Model of Water Needs for Energy Production

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Abstract

Thermoelectric power plants need large amounts of cooling water. The energy sector is responsible for the largest annual volume of water withdrawals in the Czech Republic. The issues related to water demand and its determinants were considered in several earlier studies of thermoelectric water use. For regression model determinants describing the natural, operational and socio-economic conditions were selected. In this study, we used econometric models of water needs for energy production in thermoelectric power plants in the Czech Republic. The main purpose was to obtain a model suitable for predictions. Annual data on electricity and heat production and on water use were available for sample of 33 operational units.

Keywords	***JEL code***
Linear regression model, water consumption, water withdrawals, energy production	*C30, Q25, Q49*

INTRODUCTION

Energy production is very water-intensive. Meeting ever-growing demands for energy will generate an 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, p. 4). 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, p. 33). Water is required not only in thermoelectric power plants but also for production of nearly all forms of energy. For primary fuels, water is used in resource extraction, irrigation of biofuel 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, p. 505).

Globally, about 4 000 km3 of fresh water is withdrawn each year for human use. Of that, about 70% is withdrawn for agriculture and around 10% for the power industry (Williams, Simmons, 2013, p. 10). There is a completely different situation in the Czech Republic. As shown in the annual report on water

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management in the Czech Republic in the period 2004–2013, the energy sector withdrew an average of 45% of all withdrawals from water resources in the Czech Republic and 56% 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, Bik (2006). The group of operational conditions can include, in particular, the technology of boilers, type of cooling systems and the means 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, p. 51), 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). The third cooling system with the pond is not used in the Czech Republic.

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

Social and economic conditions are very important in a longer perspective because they form the basis for investment decisions on the improvement of technology of current plants, the 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, 2013, p. 2).

1 DATA AND METHODOLOGY

1.1 Data

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

For the study presented in this paper, we collected data from the 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 with complete data were selected (see Table 2). 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 the data are only available on net electricity production, gross electricity generation was imputed by using average ratio gross and net electricity generation from records with both data.

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

1.2 Model

We assumed that water demand per energy unit is a function of direct and indirect determinants (explanatory variables). These explanatory variables could describe different conditions specified in the introduction herein. Overview of the selected variables is given in Table 1.

As explanatory variables describing natural conditions, we selected average annual temperature and the average temperature from June to September representing the summer period with most intensive demand on cooling. We used regional data from Czech hydrometeorological institute (CHMI, 2014). The average temperature from June to September was calculated as the average value of monthly temperature in this period each year.

As the explanatory variables 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. We used data provided by Energy Regulatory Office. 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 the explanatory variable describing the socio-economic conditions, we selected payments for water withdrawals. Payment for water withdrawals is one of the typical instruments of management and sustainable way of managing water resources. Other instruments are discussed in Slavíková et al. (2012). For this variable, we collected data from Reports on water management in the Czech Republic (MoA, 2015).

The type of cooling equipment was the only (purely) qualitative determinant and we grouped the operational units accordingly. The remaining seven determinants are quantitative and served as explanatory variables in the regression analysis described below.

Table 1 Summary of explanatory variables used in models

Explanatory variable	Units of measurement	Expected sign
Avg. temperature: June-Sept.	°C	+
Avg. annual temperature	°C	+
Energy production	MWh / year	-
Heat energy to total energy	<0 ; 1>	-
Capacity factor–electricity	<0 ; 1>	?
Capacity factor–heat	<0 ; 1>	?
Price for withdrawal	CZK / m3	-

Source: Own computation

As the main target of the study is the connection between the thermoelectric sector as a whole and water withdrawal, we also took into account the relative energy production of individual operational units. That means that each operation received a weight equal to its share on the sum of energy produced by all operational units included in the relevant model. This approach contributes to the (total) error reduction 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 operational units than 0.1 m^3/MWh concerning small operational units. However, we also tried to estimate the effect of the explanatory variables without weighting the individual observation. This approach can be useful for predicting the withdrawals of smaller operational units, 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 observations by practically the same variable.

The operational units listed in Table 2 were divided into three groups. The first group represents operational units with the once-through cooling system. The second group represents operational units with the recirculating cooling system, and the third represents hybrid cooling systems. This study

Table 2 Summary of operational units – average data for period 2004–2013

Operation	Cooling system	Gross energy generation [MWh/year]	Ratio between power and heat generation	Water withdrawals [m^3/MWh]	Water consumption [m^3/MWh]
HPs Brno Sever+Špitálka	R	825 510	0.168	1.337	0.798
HP České Budějovice	R	1 024 075	0.193	1.321	1.175
HP Dvůr Králové	OT	154 163	0.132	21.584	2.399
HPs Energetika Třinec	R	2 166 807	0.449	4.983	2.622
HP Kolín	OT	415 099	0.135	18.443	0.616
HP Krnov	R	187 789	0.185	1.238	No data
HP Liberec	R	280 130	0.101	1.181	0.992
HP Náchod	R	211 293	0.334	2.575	No data
HP Olomouc	OT+D	832 410	0.319	0.539	0.388
HP Ostrov	R	123 615	0.105	3.105	2.086
HP Otrokovice	R	780 256	0.360	1.207	0.914
HP Písek	R	155 836	0.099	0.437	0.372
HP Planá nad Lužnicí	R	337 921	0.871	2.873	2.486
HP Plzeň	R	1 576 252	0.634	1.658	1.402
HP Přerov	R	672 558	0.687	3.643	3.031
HP Strakonice	OT	365 548	0.483	13.915	0.625
HP Trmice	R	1 439 117	0.407	3.626	1.411
HP Varnsdorf	R	74 440	0.079	5.370	2.156
HP Zlín	R	683 066	0.411	1.004	0.918
PPs Alpiq Kladno	R	2 188 569	2.675	2.163	1.011
PP Dětmarovice	R	2 646 007	14.048	2.043	1.346
PP Hodonín	OT	607 782	1.793	114.772	0.424
PP Chvaletice	R	3 125 041	60.779	3.082	2.104
PP Ledvice	R	2 338 291	6.091	3.281	1.352
PP Mělník	OT+R	7 637 173	1.887	53.242	1.602
PP Opatovice	OT	3 514 978	1.529	50.719	0.503
PP Počerady	R	6 699 537	143.422	2.475	1.934
PP Poříčí	R	1 098 995	1.323	2.066	0.930
PPs Prunéřov	R	8 803 992	20.030	2.341	1.841
PP Tisová	R	1 869 319	4.533	2.342	0.841
PP Tušimice	R	4 021 132	19.425	2.032	1.674
PP&HP Komořany	R	1 520 382	1.122	1.778	1.106
PP&HP Vřesová	R	7 057 527	1.043	1.805	0.581
NP Dukovany	R	14 426 350	108.981	3.376	2.079
NP Temelín	R	13 295 602	86.429	2.553	1.979

Abbreviations: HP – heat power plant, NP – nuclear power plant, PP – fossil (coal or nature gas) power plants, OT – once through, R – recirculation, D – dry cooling system.
Source: Own computation based on Water balance evidence data and data from the Energy Regulatory Office

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 operational units with recirculating cooling systems and 5 records for once-through cooling system. These two groups of records were analysed with SPSS statistical software (SPSS, 1999). 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 observations, 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 this section. We used the traditional linear regression model for an operation unit in a given year in the form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \varepsilon \,, \tag{1}$$

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 were generated with the procedures known as forward selection, backward selection and stepwise selection (Zvára, 2008, p. 110). Multicollinearity of individual explanatory variables was tested by variance inflation factor (VIF). Multicollinearity of an explanatory variable is high when VIF of the given variable is higher than 10.

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 showed the lowest AIC of the models which we examined in each segment and which met the signs requirement.

The first group included 10 observations (each observation for the particular year of the period 2004–2013) for each of the 28 operational units with recirculating cooling. Therefore, the regression parameters related to the already mentioned explanatory variables were estimated from 280 observations during the regression analysis. The second group included 10 observations for each of the 5 operational units, making the size of the sample including 50 observations.

2 RESULTS

The results of analyses of operational water withdrawals and consumption for energy generation shown in Table 2 are similar to the published results of other studies. Macknick et al. (2012, Table 2 and 3) processed the information from several studies and states that real observed water consumption is between 1.491 and 4.164 m^3/MWh for coal power plants with recirculating cooling systems, and between 0.242 and 1.200 m^3/MWh for coal power plants with once-trough cooling systems. The value interval of water consumption for nuclear power plants with recirculating cooling system is between 2.199 and 3.199 m^3/MWh. Water withdrawal is between 1.775 and 5.485 m^3/MWh for coal power plants with recirculating cooling systems, between 75.708 and 189.271 m^3/MWh for coal power plants with once-trough cooling systems, and between 3.028 and 9.842 m^3/MWh for nuclear power plants with recirculating cooling system.

For each category of cooling systems, we identified three best-weighted models and three best no weighted models with lowest AIC. Only for category of recirculating cooling – weighted by energy production of individual operational units we found best five models because the best three models contained the variable price for withdrawal and its parameter's interferes with its expected sign. Table 3 shows the statistics of the models as a whole. The p-values of the F-tests of all of the models listed in table 3 are <0.02.

Table 3 The statistics of the models as a whole for best models in all categories

Model	Number of explanatory variables	R^2_{adj}	Std. Error of the Estimate	RSS	AIC
Recirculating cooling – weighted by energy production of individual operational units					
5re,w,f	5	0.204	0.042	0.474	–1 776.8
4re,w,b	4	0.201	0.042	0.478	–1 776.7
6re,w,f	6	0.204	0.042	0.472	–1 775.8
3re,w,f	3	0.195	0.042	0.483	–1 775.4
5re,w,b	3	0.194	0.042	0.484	–1 775.1
Recirculating cooling – equal weight assigned to each of the operational units					
1re,f	1	0.023	1.181	387.7	93.1
2re,f	2	0.024	1.181	386.0	93.9
3re,f	3	0.025	1.180	384.4	94.8
Once-through cooling – weighted by energy production of individual operational units					
3ot,w,b	5	0.944	0.931	38.2	–3.5
6ot,w,f	6	0.943	0.941	38.1	–1.6
7ot,w,f	7	0.941	0.952	38.1	0,4
Once-through cooling – equal weight assigned to each of the operational units					
2ot,b	6	0.964	7.448	2385.5	205.3
1ot,b	7	0.963	7.536	2384.9	207.2
3ot,b	5	0.960	7.765	2652.8	208.6

Abbreviations in model name: re – recirculating cooling system; ot – once through cooling system; w – weighted by energy production of individual operational units; f – forward selection; b – backward selection.
Source: Own computation

2.1 Operation units with recirculation cooling

Table 4 shows the estimated regression parameters, standard error of the estimation, standardised coefficients, t value of relevant variable and its statistical significance and collinearity statistics VIF. 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.

Table 5 shows the best three models and their parameters if the operational units receive equal weight. We can see that the models again include the capacity factor of electricity production and also of heat production. 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 Table 5 (i.e. models which take into account the size of individual operational units) 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 the model estimated from equally weighted observations with the model estimated from differently weighted observations.

Even though the VIFs (Variance Inflation Factor) of the explanatory variables are relatively low, the models are not suitable for quantification of the influence of individual variables because the R^2_{adj} is low.

Table 4 Summary of analysis for best five models in the 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				
5re,w,f	(Constant)	0.021	1.04		0.02	0.984	
	capacity factor–electricity	1.946	0.36	0.462	5.33	0.000	2.6
	avg. temperature: June-Sept.	0.088	0.06	0.084	1.43	0.153	1.2
	capacity factor–heat	−1.369	0.57	−0.194	−2.41	0.017	2.3
	total energy production	−3.2E-08	1.64E-08	−0.210	−1.96	0.051	4.0
	price for withdrawal	0.067	0.05	0.085	1.49	0.138	1.1
4re,w,b	(Constant)	1.464	0.26		5.68	0.000	
	price for withdrawal	0.083	0.04	0.105	1.89	0.059	1.1
	capacity factor– electricity	1.962	0.37	0.466	5.37	0.000	2.6
	capacity factor–heat	−1.603	0.55	−0.227	−2.94	0.004	2.1
	total energy prod.	−3.9E-08	1.56E-08	−0.259	−2.53	0.012	3.7
6re,w,f	(Constant)	−0.230	1.07		−0.22	0.830	
	capacity factor– electricity	2.006	0.37	0.477	5.42	0.000	2.7
	avg. temperature: June-Sept.	0.101	0.06	0.097	1.61	0.109	1.3
	capacity factor–heat	−1.633	0.63	−0.231	−2.59	0.010	2.8
	total energy production	−2.9E-08	1.66E-08	−0.191	−1.75	0.082	4.2
	price for withdrawal	0.056	0.05	0.071	1.20	0.231	1.2
	heat e. to total energy	0.240	0.25	0.081	0.97	0.331	2.4
3re,w,f	(Constant)	−0.657	1.00		−0.66	0.511	
	capacity factor– electricity	1.553	0.28	0.369	5.49	0.000	1.6
	avg. temperature: 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– electricity	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 production	−3.7E-08	1.56E-08	−0.245	−2.39	0.018	3.6

Abbreviations in model name: re – recirculating cooling system; w – weighted; f – forward selection; b – backward selection.
Source: Own computation

2.2 Operation units 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 very similar in the models 3ot,w,b and 6ot,w,f, which suggests that the explanatory variables, at least in the 3ot,w,b, could be very significant in the once-through cooling segment. Table 6 indicates that both models exhibit very high R^2_{adj}. According to the values of AIC (see the third part of Table 3) we recommend the model 3ot,w,b.

Table 7 shows the best three models and their parameters in case the operational units receive equal weight. The regression parameter of the variable average annual temperature of the second best model exhibited a 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. Model

Table 5 Summary of analysis for best three models in the category recirculating cooling – equal weight assigned to each of the operational units

Model	Explanatory var.	Unstandardized Coeff.		Stand. Coeff.	t	Sig.	VIF
		β_i	Std. Error				
1re,f	(Constant)	1.935	0.18		10.77	0.000	
	capacity factor– electricity	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– electricity	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	(Constant)	2.512	0.43		5.91	0.000	
	capacity factor– electricity	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 withdrawal	-0.082	0.08	–0.065	–1.07	0.287	1.1

Abbreviations in model name: re – recirculating cooling system; f – forward selection.
Source: Own computation

Table 6 Summary of analysis for best three 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 withdrawal	–41.02	7.65	–0.253	–5.36	0.000	1.9
	avg. temperature: 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– electricity	–87.11	21.45	–0.429	–4.06	0.000	9.7
	total energy production	–1.19E-05	1.96E-06	–0.614	–6.05	0.000	9.0
6ot,w,f (2ot,w,b)	(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 withdrawal	–39.73	9.04	–0.245	–4.40	0.000	2.7
	heat energy to total energy	–221.95	22.88	–1.356	–9.70	0.000	16.7
	total energy production	–1.22E-05	2.28E-06	–0.630	–5.34	0.000	11.9
	capacity factor– electricity	–90.69	25.30	–0.446	–3.59	0.001	13.3
	avg. temperature: June-Sept.	5.618	1.96	0.139	2.87	0.006	2.0
7ot,w,f (1ot,w,b)	(Constant)	163.90	44.69		3.67	0.001	
	capacity factor–heat	27.95	97.43	0.032	0.29	0.776	10.4
	price for withdrawal	–39.38	9.88	–0.243	–3.99	0.000	3.1
	heat energy to total energy	–222.58	24.09	–1.360	–9.24	0.000	18.1
	total energy production	–1.21E-05	2.33E-06	–0.628	–5.21	0.000	12.2
	capacity factor– electricity	–91.66	27.62	–0.451	–3.32	0.002	15.5
	avg. temperature: June-Sept.	5.49	2.38	0.136	2.31	0.026	2.9
	avg. annual temperature	0.19	2.04	0.005	0.09	0.925	2.2

Abbreviations in model name: ot – once through cooling system; w – weighted; f – forward selection; b – backward selection.
Source: Own computation

2ot,b is the model with the lowest AIC (see last part of Table 3) in this segment and the signs of its regression parameters are in accordance with the expectations.

Table 7 Summary of analysis for best three models in the category once-through cooling – equal weight assigned to each of the operational units

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 withdrawal	−51.46	7.54	−0.306	−6.82	0.000	2.7
	avg. temperature: June-Sept.	7.492	2.14	0.157	3.50	0.001	2.7
	heat energy to total energy	−185.40	18.85	−1.092	−9.83	0.000	16.6
	capacity factor– electricity	−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 production	−1.13E-05	1.88E-06	−0.369	−5.99	0.000	5.1
1ot,b	(Constant)	123.45	48.45		2.55	0.015	
	price for withdrawal	−51.64	7.84	−0.307	−6.59	0.000	2.9
	avg. temperature: June-Sept.	7.64	2.64	0.160	2.89	0.006	4.1
	avg. annual temperature	−0.21	2.12	−0.004	−0.10	0.922	2.4
	heat energy to total energy	−185.19	19.19	−1.091	−9.65	0.000	16.8
	capacity factor– electricity	−53.75	24.62	−0.223	−2.18	0.035	13.7
	capacity factor–heat	−131.63	60.85	−0.147	−2.16	0.036	6.1
	total energy production	−1.13E-05	1.93E-06	−0.370	−5.86	0.000	5.3
3ot,b	(Constant)	172.64	43.55		3.96	0.000	
	price for withdrawal	−44.59	7.15	−0.265	−6.23	0.000	2.2
	avg. temperature: June-Sept.	5.530	2.03	0.116	2.73	0.009	2.2
	heat energy to total energy	−220.76	10.21	−1.300	−21.6	0.000	4.5
	capacity factor– electricity	−94.61	15.82	−0.392	−5.98	0.000	5.3
	total energy production	−1.19E-05	1.94E-06	−0.390	−6.15	0.000	5.0

Abbreviations in model name: ot – once through cooling system; w – weighted; f – forward selection; b – backward selection.
Source: Own computation

For the quantification of individual explanatory variables the model 3ot,b could be used because of relatively low VIFs of its all considered variables and high statistical significance of each of its explanatory variables.

DISCUSSION AND CONCLUSIONS

For circulation plants, it is not possible to recognise 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, an unadjusted sampling of water supplies to third parties at the Planá nad Lužnicí heating plant causes an increase in demand for water per 1 MWh by 68.7% and water consumption by 79.4%. Collecting information about hot water supplies to the third parties is unfortunately very complicated.

The results of the regression analysis suggest 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 *a priori* expected signs. We suggest using the models from a group of weighted models with lowest (or close to lowest) AIC, the statistical significance of all explanatory variables lower than 0.05 and with expected signs of the estimated coefficients of explanatory variables. Model 3ot,w,b meets this conditions in the once-through cooling category and in the recirculation cooling category it is model 5re,w,b. For significantly higher prediction power of the models with non-equal weights than models with equal weights in the recirculating segment we cannot find other explanation than this is due to failure to meet the assumption of constant weights of individual observations.

Table 8 Comparison of the values of coefficients in the in both cooling categories – weighted models

Explanatory var.	Model	Unstandardized Coeff.		Model	Unstandardized Coeff.	
		β_i	Std. Error		β_i	Std. Error
(Constant)	5re,w,f	0.021	1.04	3ot,w,b	160.743	42.32
	4re,w,b	1.464	0.26	6ot,w,f	163.376	43.83
	6re,w,f	–0.230	1.07	7ot,w,f	163.898	44.69
	3re,w,f	–0.657	1.00			
	5re,w,b	1.713	0.22			
Avg. temperature: June-Sept.	3re,w,f	0.141	0.06	3ot,w,b	5.741	1.88
	5re,w,f	0.088	0.06	6ot,w,f	5.618	1.96
	6re,w,f	0.101	0.06	7ot,w,f	5.494	2.38
Avg. annual temperature				7ot,w,f	0.192	2.04
Capacity factor– electricity	6re,w,f	2.006	0.37	3ot,w,b	–87.114	21.45
	3re,w,f	1.553	0.28	6ot,w,f	–90.686	25.30
	5re,w,b	1.990	0.37	7ot,w,f	–91.664	27.62
	4re,w,b	1.962	0.37			
	5re,w,f	1.946	0.36			
Capacity factor–heat	5re,w,f	–1.369	0.57	7ot,w,f	27.950	97.43
	4re,w,b	–1.603	0.55			
	6re,w,f	–1.633	0.63			
	3re,w,f	–0.786	0.47			
	5re,w,b	–1.662	0.55			
Heat energy to total energy	6re,w,f	0.240	0.25	3ot,w,b	–216.480	11.07
				6ot,w,f	–221.950	22.88
				7ot,w,f	–222.579	24.09
Price for withdrawal	5re,w,f	0.067	0.05	3ot,w,b	–41.019	7.65
	4re,w,b	0.083	0.04	6ot,w,f	–39.733	9.04
	6re,w,f	0.056	0.05	7ot,w,f	–39.381	9.88
Total energy production	4re,w,b	–3.9E-08	1.56E-08	3ot,w,b	–1.19E-05	1.96E-06
	5re,w,f	–3.2E-08	1.64E-08	6ot,w,f	–1.22E-05	2.28E-06
	6re,w,f	–2.9E-08	1.66E-08	7ot,w,f	–1.21E-05	2.33E-06
	5re,w,b	–3.7E-08	1.56E-08			

Abbreviations in model name: re – recirculating cooling system; ot – once through cooling system; w – weighted by energy production of individual operational units; f – forward selection; b – backward selection.
Source: Table 4 and Table 6

On another side, the values of β_i coefficients in the once-through cooling category are significantly different from the same explanatory variables in recirculating cooling technology (see Table 8). We see a logical explanation only for two of the explanatory variables. For average temperature from June to September, we can assume that this is caused by the relatively stable temperature of cooling water in recirculating systems against the fluctuating temperature of water withdrawn from rivers during a year. The second remarkable variable is the price. While in the recirculating segment its regression parameters are close to 0 (which is confirmed by the low statistical significance of the variable), in the once-through segment the price was statistically very significant with its parameter around –40. That means that for the range from 0.4 to 1.22 CZK/m^3 (i.e. the range corresponding to the real minimum and maximum price for the 1 m^3 withdrawn from the surface water for the once-through cooling purposes in the investigated period) making the water more costly by 0.01 CZK/m^3 we can expect a decrease in water withdrawal by 0.40 m^3/MWh.

Possible reasons for a 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 of times the water is used in the recirculation system is not the same for all operational units with a recirculation system);
- not sufficiently complex statistical model;
- only annual data are available (while the electricity and heat production and temperature exhibits strong monthly seasonality).

ACKNOWLEDGEMENTS

The study presented within this paper was carried out as part of the project TD020113 funded by the Technological Agency of the Czech Republic. The authors would like to thank the staff of the Energy Regulatory Office, Czech Statistical Office, United Energy and ČEZ for sharing their knowledge and for providing the necessary data for this study. The authors would like to thank all unnamed colleagues from TGM WRI for their inspiring suggestions and comments. The authors also would like to thank the anonymous referees for their valuable comments which helped to improve the manuscript.

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