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Determinants of Regulated Hydropower Supply in Norway

Mariann Birkedal[a,*], Torjus Folsland Bolkesjø[b]*

[a]E-CO Energy, Oslo, Norway
[b]Norwegian University of Life Sciences (NMBU) / Thomson Reuters Point Carbon, Oslo, Norway

Abstract

Having an average annual production of about 130 TWh and close to 31 GW installed capacity, Norway is among the world's largest hydropower producers. The majority of the hydro production capacity comes from regulated hydro power plants, and the large volumes imply that the supply of hydro power play a vital role in the price setting in the Nordic power market. In this study, we analyse the hydro scheduling decisions made by hydro producers based on historic observations. The objective is to quantify how different economic factors that are relevant in hydro scheduling have affected the actual hydro dispatch. The data consist of weekly observations of hydro generation as well as information on market drivers and factors affecting the water values. We estimate parameters for statistical models where the weekly hydro power generation is modelled as a function of the hydrological balance, inflow, temperature and the short term marginal costs for coal power generation. The current and expected power price are also included in alternative model specifications and we test for seasonal and regional differences in the supply response by estimating models that are specific for each season and for three different regions. The results show that both the hydro balance, inflow, temperature, short run marginal costs (SRMC) of coal power generation and power prices significantly affect the short run hydro power supply. We estimate an average increase in the weekly supply of 52 GWh when the hydro balance increases by 1 TWh for Norway in total. The estimated models have, in general, a good ability to predict the hydro power generation. The predictive power increases when regional models are applied. One main reason for this is the varying degree of regulation in the different regions. Overall, the results confirm that a major part of the variation in the weekly hydro power supply may be explained with a few, predicable determinants, and this knowledge may be utilized both by market participants and energy market modellers.

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* Corresponding author. Tel.: +47 995 10 258
E-mail address: mariann.birkedal@e-co.no

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1. Introduction

In a normal hydrological year, hydro power has a share of about 98% of the Norwegian and 50% of the Nordic total power production. The total installed generation capacity is about 31 GW, the annual generation volume is about 130 TWh and the majority of the Norwegian hydro resource is storable for shorter or longer periods [1]. The large volumes and the storability imply that increased insight in hydro power supply is of particular interest for two reasons. First, the behaviour of hydro power suppliers is a crucial factor for the short- and medium term price development in the power market, and for market participants and system operators the supply behaviour is hence of interest for commercial and system security reasons. Second, the storability and easy regulation of the hydro resource imply that hydro power is an excellent source of flexibility in the energy system since the hydro resource may be dispatched in periods with little variable renewable energy (VRE) supply and saved for later periods when there is much VRE generation in the market. Flexibility on the supply side will likely be a much demanded property in the future energy system with large shares of VRE (e.g [2]). Studies by Hirth et al [3], Hirth [4] and Tveten [5] highlight the lack of studies on the flexibility potential of hydro power as a major shortcoming in the existing literature on the flexibility options for integration of large shares of VRE. Previous studies of hydro power supply has mainly applied stochastic dynamic programming (SDP) (e.g. [6]) or Stochastic Dual Dynamic Programming (SDDP) approaches to forecast the behaviour of hydro power suppliers under assumptions of perfectly competitive markets, and uncertainty related to future inflow and/or prices [7]. These studies are of great value and the success of such approaches is demonstrated in the fact that most hydro power producers and also other market participants apply such models for their production planning and power market forecasts. In contrast to the substantial research within model simulations and forecasting of hydro power supply, very few studies have addressed hydro power supply based on observed data through e.g. econometric modelling. One exception is [8] who estimate the price of power in Norway using hydro power supply and a set of other economic data as explanatory variables. The purpose of the present study is to analyse factors that have affected Norwegian hydro power supply, *ex post*. Such an approach is useful to verify or reject established views on drivers for hydro power supply, to assess the relative importance of various drivers and, if well specified, an econometric model may also be used as a prediction tool for the future hydro power supply.

2. Behaviour model

Inspired by [9] we use the supply of *regulated hydro power* (RegHP) as response variable (Y_1) while the explanatory variables included in the analysis are *inflow, temperature, hydrological balance, short run marginal costs* (SRMC) *for coal power generation, power prices* and *price expectations*.

The structural equation of the estimated models is as follows:

$$RegHP_{rt} = \beta_0 + \beta_1 lnPowerPrice_{rt} + \beta_2 HydBal_{rt} + \beta_3 Temp_{rt} + \beta_4 lnInflow_{rt} + \beta_5 lnSRMC_{rt} + \beta_6 PriceExp_{rt} + u_{rt}$$

where $\beta_{1\text{-}6}$ are the unknown regression coefficients of the explanatory variables on Norwegian regulated hydro power. u_{rt} is the stochastic error term, and r and t represent region and time. All explanatory variables are regarded exogenous in the ordinary least squares (OLS) regressions.

2.1 Endogenous variable and two stage least squares estimation

A simultaneous relationship between the power price and the regulated hydropower generation can often occur, and hence the *power price* should be regarded as possibly endogenous. The Durban-Wu-Hausman test is applied to uncover whether there exists a problem of endogeneity, and two-stage least squares (2SLS) regressions is applied if the test shows endogeneity. The structural equation is estimated in two steps in the 2SLS regressions.

Step 1:

$$lnPowerPrice\ (Y_2) = \beta_1 HydBal_{rt} + \beta_2 Temp_{rt} + \beta_3 lnInflow_{rt} + \beta_4 lnSRMC_{rt} + \beta_5 PriceExp_{rt} + \beta_6 lnGermanPowerPrice_{rt} + e_{rt}$$

where the exogenous variables from the structural equation in the introduction of *Section 2* and the German power price are included as instrument variables on the endogenous Norwegian *power price* (Y_2). *e* is the error term for the regression in Step 1.

Step 2**:** In the second step the endogenous explanatory variable, Y_2, from the structural equation is replaced by the predicted values from Step 1, $ln\widehat{PowerPrice}_2$:

$$RegHP_{rt} = \beta_0 + \beta_1 ln\widehat{PowerPrice}_{rt} + \beta_2 HydBal_{rt} + \beta_3 Temp_{rt} + \beta_4 lnInflow_{rt} + \beta_5 lnSRMC_{rt} + \beta_6 PriceExp_{rt} + u_{rt}$$

where β are the adjusted regression coefficients of the exogenous and endogenous variables.

All explanatory variables but *power price* are regarded as exogenous variables, since they all influence the supply of hydro power without being directly influenced in return. It can be argued that the *hydrological balance* in fact is not exogenous – since the reservoir levels will decrease as the supply of regulated hydro power increase. This is however disregarded in this context. Also *price expectation* is regarded as being exogenous, although price expectations in reality are highly affected by the amount of supplied hydro power. In order to research the variability in seasonal supply, three dummy variables are included in each of the four models: $D_{1t}=1$ if winter, $D_{2t}=1$ if spring, $D_{3t}=1$ if summer and 0 if otherwise. The German power price was used as instrument variable (IV) for the endogenous variable *power price*. In accordance with the requirements of an IV, the German power price is correlated with the national and regional supply of hydro power in Norway, without having a direct influence on the supply. Hence it is neither endogenous nor included in the structural equation. Tests of the relevance of the instrument (F-statistic) show that the German power price performs well as an IV on yearly basis in all four models, but less in the seasonal models.

The correlation between the explanatory variables has been tested, and shows no multicollinearity problem.

3. Data

The data set analyzed consist of weekly data for the years 2004 to 2013, summing up to 522 observations. The seasonal pattern, and variations between years is shown in Figure 1.

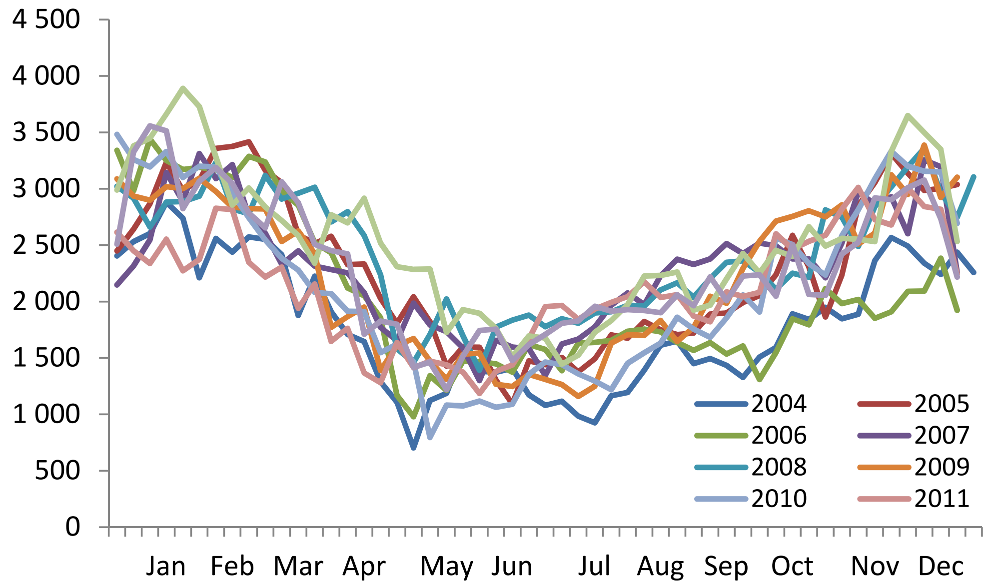

Figure 1. Weekly regulated hydro power generation 2004-2013 (TWh)

Models for each of the seasons winter, spring, summer and fall were estimated in addition to the all-year models. Data for the dependent variable was obtained by taking total hydro power generation minus estimated generation in run-of-river plants from Point Carbon Thomson Reuters's hydrological HBV models. (a description of HBV models is provided in [10]). Data for the hydrological balance were also collected via the HBV models. Short term marginal costs of coal and German power prices were obtained via Point Carbon Thomson Reuters' database, while Nordic power price data was collected from www.nordpoolspot.com and temperature data from www.eklima.no.

4. Results

The OLS regression model for the whole sample – i.e. using data for all seasons and taking the sum of all regions - are in Table 1. All coefficients, except the coefficient for SRMC coal are significantly different from zero at 1%-level. SRMC coal has no significant effect on the supply according to this model specification. R-squared is quite high at 88.3%. The endogeneity tests indicate simultaneity of power prices and hydro production for the all-year, winter and fall models as well as in the regional all-year models. In case of endogeneity, the use of OLS causes biased and inconsistent estimates of the regression coefficients. For this reason we present 2SLS results for these models which address the endogeneity using instrumental variables for the power price. The results of the OLS model are, broadly speaking, confirmed by the 2SLS model (Table 2), but the sensitivities are somewhat different – in particular, the price sensitivity is much higher in the 2SLS models. According to the model results for the full sample, a 1 TWh improvement in the hydrological balance would increase the current week's hydro power supply by 52 GWh, while a 1 percent increase in the power price would increase the supply by 16,8 GWh.

Most coefficients have the expected sign, except for inflow, which has a negative sign. The inflow variable is likely reflecting that when inflow increases, run-of-river generation increases while regulated hydro power producers choose to store the inflow for production at a later time when price expectations are higher. It might also reflect some inertia in hydro producer's response time to update/reduce water values, and hence the supply of regulated hydro power is decreased.

4.1 All year model results

Table 1. OLS regression model results for all regions and seasons aggregated.

Variable	Coefficient		Newey-West std.error	T	P>|t|	[95 % Confidence Interval]	
ln Power Price NOK/MWh	0,401	***	0,073	5,52	0,000	0,259	0,544
Hydrological Balance TWh	0,028	***	0,002	16,66	0,000	0,025	0,032
Temperature	-0,037	***	0,003	-10,89	0,000	-0,044	-0,030
ln Inflow TWh	-0,340	***	0,027	-12,81	0,000	-0,392	-0,288
ln SRMC coal NOK/MWh	-0,002		0,070	-0,02	0,982	-0,139	0,135
Price Expectations	0,001	***	0,000	4,97	0,000	0,001	0,001
Constant	0,529	*	0,313	1,69	0,091	-0,085	1,143
N	522						
R^2	88,3%						

Significant at *p<0,10, **p<0,05, ***p<0,01

Table 2. 2-SLS regresion model results for all regions and seasons aggregated.

Variable	OLS regression for Y1: RegHP		2SLS First step for Y2: ln Power Price		2SLS Second step for Y1: RegHP	
ln Power Price NOK/MWh	0,401	***			1,680	***
Hydrological Balance TWh	0,028	***	-0,020	***	0,052	***
Temperature	-0,037	***	-0,011	***	-0,023	***
ln Inflow TWh	-0,340	***	-0,012		-0,292	***
ln SRMC coal NOK/MWh	-0,002		0,348	***	-0,860	***
Price Expectations	0,001	***	-0,001	***	0,003	***
ln German Power Price			0,293	***		
Constant	0,529	*	1,949	***	-1,783	**
R^2	88,3%					
F-statistic					45,37	

Significant at *p<0,10, **p<0,05, ***p<0,01

4.2 Seasonal models

Since both demand, prices and inflow follow a clear seasonal pattern separate models for each season were estimated in addition to the all-year models. 2SLS results are presented for winter and fall, while OLS results are presented for spring and summer as no endogeneity was uncovered in the two seasons. The estimated effect of power price, hydrological balance and inflow have the same signs in all seasons and are all significantly different from zero at 10% level. Temperature shows significance in all seasons but winter, while SRMC coal and price expectations are significantly different from zero at 10% level during winter and fall. The elasticity of temperature is quite similar for the different seasons while there are somewhat larger differences in elasticities of price, hydrological balance and SRMC coal. R^2 is above 0.80 for the winter and spring models, while it is 0.64 for the summer model.

Table 3. Regression results for all regions divided in different seasons.

Variable	Winter (Nov-Jan)		Spring (Feb-Apr)		Summer (May-July)		Fall (Aug-Oct)	
ln Power Price, NOK/MWh	5,437	***	0,569	***	0,248	***	1,971	***
Hydrological Balance, TWh	0,104	***	0,030	***	0,031	***	0,048	***
Temperature, Deg C.	0,064		-0,020	***	-0,025	***	-0,029	*
ln Inflow, TWh	-0,432	***	-0,323	***	-0,471	***	-0,223	*
ln SRMC coal, €/MWh	-2,162	***	-0,095		-0,057		-0,874	*
Price Expectations, €/MWh	0,008	***	0,000		0,000		0,003	***
Constant	-15,655	***	-0,165		1,763	***	-3,463	
N	129		132		130		131	
R^2	81,2%		85,7%		64,6%		75,6%	
F-statistic	4,23		-		-		9,95	

Significant at *p<0,10, **p<0,05, ***p<0,01

4.3 Regional models

Estimation results for the regional models are shown in Table 4. All coefficients, except the coefficient for inflow in Mid-Norway are significantly different from zero at 5%-level. The main reasons for the variation in elasticities of price, hydrological balance, inflow and SRMC coal are the large differences in storage and regulation capacities in the three regions.

Table 4. 2SLS regression model result for regions with seasons aggregated.

Variable	*Southern Norway*		*Mid-Norway*		*Northern Norway*	
ln Power Price NOK/MWh	0,884	***	0,340	***	0,453	***
Hydrological Balance TWh	0,035	***	0,008	***	0,008	***
Temperature	-0,020	***	-0,004	***	-0,006	***
ln Inflow TWh	-0,206	***	-0,007		-0,019	**
ln SRMC coal NOK/MWh	-0,411	***	-0,199	***	-0,288	***
Price Expectations	0,002	***	0,000	***	0,001	***
Constant	-0,654		-0,502	***	-0,535	***
N	*522*		*522*		*522*	
R^2	*88,7%*		*67,6%*		*60,8%*	
F-statistic	31,3		50,9		54,2	

Significant at *p<0,10, **p<0,05, ***p<0,01

4.4.Prediction accuracy

To test the prediction accuracy of the regression models we performed an out-of-sample prediction where the estimated OLS-model with data spanning 2004-2012 was coupled with observed explanatory variable values for 2013 to predict generation thorough 2013. The explanatory variable *power price* was excluded to avoid endogeneity problems in the model. The resulting prediction is shown in Figure 2, together with the observed actual values. The average absolute deviation is 313 GWh or 13,6%. A visual analysis of the actual versus predicted supply indicates tendencies of delay in the prediction model. A closer look into the lag structure of the model could potentially further improve the predictive power of the model.

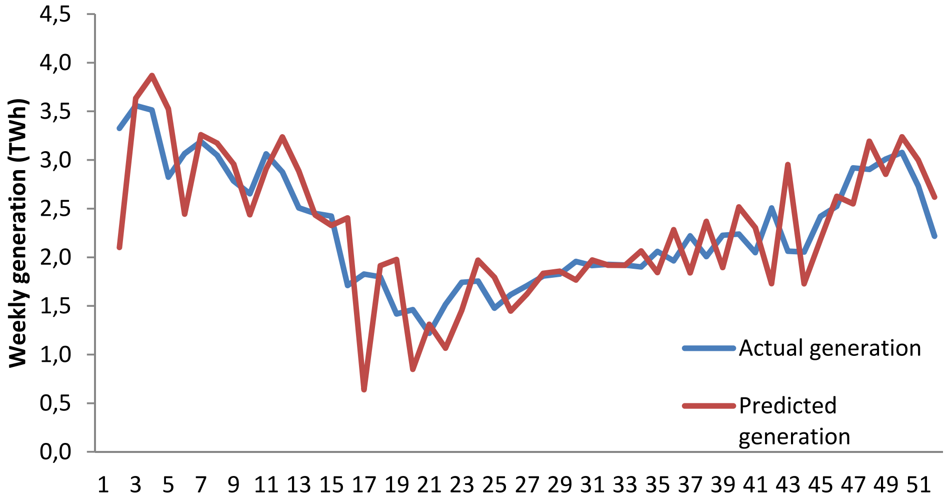

Figure 2. Actual and predicted generation for the calendar year 2013 (TWh/week).

5. Conclusions

Econometric models for the supply of regulated hydro power in Norway were estimated using OLS and 2SLS on weekly market data spanning 2004-2013. The results show that both the hydro balance, inflow, temperature, SRMC coal and power prices significantly affect the short run hydro power supply. We estimate an average increase in the weekly supply of 52 GWh when the hydro balance increases by 1 TWh for Norway in total. The estimated models have, in general, a good ability to predict the hydro power generation. The predictive power increases when regional models are applied. One main reason for this is the varying degree of regulation in the different regions. Overall, the results confirm that a major part of the variation in the weekly hydro power supply may be explained with a few, predicable determinants, and this knowledge may be utilized both by market participants and energy market modellers in the future. An out of sample prediction for 2013 showed that the average absolute prediction error was 313 GWh/week, or 13,6%.

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