



Research article

Hydropower market dynamics in Norway: Evaluating the market value and volatility in the electricity sector

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ABSTRACT

Energy markets are evolving to meet environmental challenges, such as the European Union's (EU) ambition to become the first net-zero continent by 2050. A critical component in this transition is the decarbonization of the electricity sector, which requires a significant shift towards renewable energy sources. Hydropower stands out among these sources due to its flexibility and storage capabilities, which can mitigate the intermittency of wind and solar power. This paper examines the market value and market value volatility of hydropower in Norway, a country where hydropower plays an important role in electricity generation and is a significant contributor to Europe's reservoir storage capacity. We use linear regression models to understand the relationships of various energy sources on hydropower market value and volatility, followed by a quantile regression to explore effects under different market conditions. Our findings reveal that Run-of-River and water reservoir hydropower have different impacts on market value. Run-of-River negatively affects market value in both regions, while water reservoirs positively impact NO2 and negatively impact NO1. When it comes to the volatility of hydropower in both regions, we find that almost all generation sources reduce market value volatility, including variable sources, such as wind generation. Additionally, the quantile regression analysis highlights that the different hydropower sources have varying impacts on the hydropower distribution. Despite the different generation mixes and market dynamics in the two regions, it seems that the electricity systems remain reliable due to the availability and complementarity of various sources in the electricity system. Market participants can utilize this information in developing profitable strategies that can enhance their overall market performance. On the other hand, the results can guide policy makers in designing regulations that support hydropower producers while including higher renewable generation in the electricity mix in Europe.

1. Introduction

Electricity markets have continuously evolved to meet the challenges posed by changing dynamics and environmental concerns. The European Union's (EU) goal of becoming the first net-zero continent by 2050 (European Commission, 2019) underlines the important role of the electricity sector in achieving this objective. Electricity is an essential commodity in societies, that powers homes, businesses, and industries but the generation of electricity can result in significant emissions of greenhouse gases. The EU's emphasis on decarbonization requires a significant shift towards renewable energy sources, which already account for a substantial portion of electricity generation across Europe. However, the high variability of renewable sources, and the limited storage opportunities of electricity, present multiple challenges for governments and market participants.

Hydropower, unlike other renewable sources, offers flexibility and storage opportunities that can help balance the intermittency of wind

and solar power (Graabak et al., 2017). The literature has shown that hydropower can support the deployment of renewable energy sources such as wind and solar power not only in Norway but also in Europe. It has also been shown that increased interconnection capacity among Norway and Northern European countries provides more potential to utilize the storage capabilities and flexibility of Norwegian hydropower and help integrate renewable sources in Europe that result into an increase in social welfare (Zakeri et al., 2018; Graabak et al., 2019). Thus, hydropower plays an important role in the decarbonization of the electricity sector and the development of a secure and reliable electricity system that can increase social welfare. Focusing on Norway, Jåstad et al. (2022) showed that wind and solar power are unlikely to exceed their Levelized Cost of Electricity (LCOE), making them less attractive investments. Hence, large-scale deployment of wind and solar may not be viable options in Norway in 2040. This highlights the crucial role of

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hydropower in ensuring the reliability of the power sector in Northern Europe, supporting the expansion of renewable energy sources and fostering the decarbonization not only of the electricity sector but also of other industries such as transportation.

Norway's electricity mix consists mainly of hydropower production and high reservoir capacity. In 2022, Norway produced 88.2% of electricity from hydropower while wind contributed to 10%. Additionally, Norwegian hydropower contributes to 50% of Europe's total reservoir storage capacity (NVE, 2021b). Norway exports a significant amount of electricity to neighboring countries and is expected to experience increased demand in the coming years (NVE, 2021b). Several of the largest hydropower production plants and reservoirs are located in the southern part of Norway. The southern regions of Norway, particularly NO1 and NO2, are of particular interest due to their connection to central European electricity markets, highlighting the importance of understanding the impact of different electricity generation sources on the hydropower market value and its volatility.

Reservoir-based hydropower plays a crucial role in optimizing social welfare by enabling the strategic management of water resources to maximize both economic and societal benefits. By storing water during periods of low demand and releasing it when electricity prices are higher, producers can generate electricity more efficiently, ensuring a stable supply while maximizing income. This process is supported by market mechanisms that provide financial incentives aligned with the physical realities of water availability and demand (NVE, 2021a). These incentives encourage producers to balance their operations in a way that optimizes resource use across the year, contributing to both economic efficiency and security of electricity supply. Thus, the market not only drives effective water management but also plays a vital part in ensuring that hydropower contributes to broader social goals, such as affordable energy.

Despite the essential role of hydropower, there has been limited focus on empirically investigating its market value compared to other renewable sources. Investigating how different sources influence the market value of hydropower is crucial for stakeholders, especially in countries heavily reliant on hydropower production. Previous studies have mainly concentrated on wind and solar power, leaving a gap in understanding hydropower's market value and volatility. Therefore, this paper aims to address this gap by exploring the market value and volatility of hydropower in Norway. We estimate the market value and the market value volatility of hydropower in the southern Norwegian bidding zones, NO1 and NO2, and investigate the impact of other renewable energy sources from NO1, NO2 and neighboring countries such as Denmark and Sweden. We have distinguished hydropower production into Run-of-River (ROR) and water reservoirs/pumped-up storage. ROR generates electricity by using the natural flow of rivers while water reservoirs store large volumes of water behind dams, allowing for controlled and flexible electricity generation based on demand. Pumped-up storage, on the other hand, operates by pumping water to an elevated reservoir during periods of low electricity demand and releasing it during peak demand, effectively functioning as a large-scale energy storage system¹. This allows for a more detailed analysis of how these different sources impact the market value of hydropower. Previous studies have often considered hydropower generation as a whole, overlooking the information associated with the nature of the hydropower source.

First, we construct the indices that represent the market value of hydropower and its volatility and after we perform different estimations to investigate the impact of various sources on hydropower market value and market value volatility. In addition, we perform a quantile regression to take into account the extremes of the market

value distribution, especially during the energy crisis period. By analyzing the ongoing changes and dynamics in the electricity sector, including increased interconnection and the integration of higher levels of renewables in Norway, this research aims to provide insights into how various electricity generation sources impact the market value of hydropower and its volatility, particularly in southern Norwegian regions. Understanding these interactions is essential for optimizing the role of hydropower in the transition to a sustainable energy future, not only in Norway but also in Northern Europe as a whole. Additionally, as countries relying heavily on hydropower production face risks associated with water inflow shortages, a diversified energy mix that includes renewable energy generation becomes increasingly important (Haddeland et al., 2022). Therefore, investigating the market value of hydropower in conjunction with different renewable energy sources can provide valuable insights for Norwegian stakeholders and contribute to the sustainable development of the energy sector.

There is increasing interest in the literature on the revenue and market value of renewable sources in electricity markets. Hirth (2013) was the first to explore the revenues and market value of renewable energy sources and highlighted that previous literature focused on various aspects of renewable sources such as the curtailment and technical constraints but not the economic consequences and price effects for renewable generators. They discovered that higher penetration of renewable generation in the electricity generation mix in Germany can result in lower values of wind and solar power. Tveten et al. (2016) examined the interconnection between thermal and hydro and the impact on the revenues and value of variable renewable energy. They found that the market value of renewable sources decreases in hydro-dominated countries while it increases in thermal power-dominated regions. Additionally, Hirth (2016) has found that in hydro-dominated regions, the wind power market value diminishes at a lower rate than regions dominated by thermal plants. More recently, Prol et al. (2020) created two indices that represent the revenues and market value of wind and solar in the Californian market and found that both sources reduce their own and each other's revenues and market values. They called this effect the cannibalization and cross-cannibalization of renewable energy sources. Lastly, Peña et al. (2022) analyze the relationship between the market value of various generation technologies such as wind, hydropower, coal, etc. and the penetration of different electricity generation sources. They discover that higher renewable energy penetration reduces the market value of all generation technologies involved in the papers.

This paper makes several contributions to the power market literature. Firstly, it examines hydropower production empirically, filling a gap in previous research that has predominantly focused on wind and solar generation. Secondly, we follow Peña et al. (2022), and quantify the volatility of hydropower market value, which has been less explored in previous literature compared to electricity price volatility. Thirdly, we differentiate between run-of-river and water reservoir production², providing detailed insights into the type of hydropower and its impact on market value and volatility. Fourthly, we concentrate on Southern Norwegian hydropower, particularly the NO1 and NO2 bidding zones, which play a crucial role in balancing electricity supply and demand in central Europe. To the best of our knowledge, there is limited literature investigating the interaction of these regions with neighboring countries, with a specific emphasis on Norwegian hydropower rather than Danish wind power. Lastly, we employ quantile regression to examine extreme values in the market value distribution, providing valuable insights into market uncertainty, a method previously used in exploring extreme cases of electricity prices.

¹ The distinction lies in the independent variables in the model. Nevertheless, we maintain the use of total hydropower production data to compute both the hydropower market value and its volatility at a specific region.

² By water reservoir production we refer to production of electricity by hydropower storage reservoirs which store water and release it when needed.

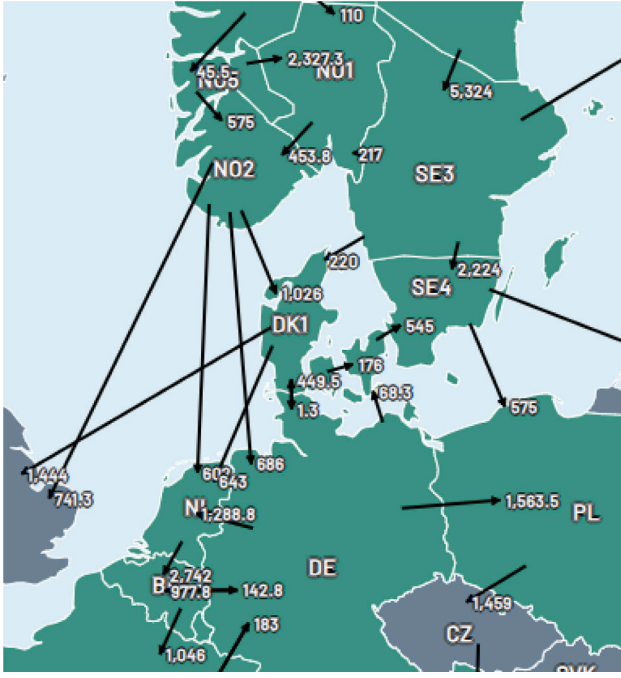


Fig. 1. Map of the electricity bidding zones and interconnections from Nord Pool Group (2024).

2. Data and descriptive statistics

We use hourly data from the Southern Norwegian regions, NO1, NO2, and from neighboring countries such as Denmark (DK1), Sweden (SE3), and Germany (DE) for the period from 2021 until 2024. We obtain day-ahead electricity prices (€/MWh), various renewable energy sources (in GWh) such as hydropower production, wind and solar generation as well as electricity demand (GWh) from the ENTSO Transparency platform.³ We focus on hydropower production in the NO2 and NO1 bidding zones since both have high electricity production from hydropower but different generation mixes and interconnections. Fig. 1 illustrates a map of the NO1 and NO2 bidding zones, along with their interconnected regions. The NO1 bidding zone is interconnected with Sweden (SE3) and the neighboring Norwegian zones NO2, NO3, and NO5. In contrast, the NO2 bidding zone, which is characterized by higher water reservoir production, is connected to Denmark (DK1), Germany (DE), the Netherlands (NL), and the United Kingdom (GB) as well as the Norwegian zones NO1 and NO5.⁴

2.1. Hydropower market value and volatility

We follow Hirth (2013, 2015), and Peña et al. (2022) and calculate the market value of hydropower in NO1 and NO2 as the ratio of income to generation. The hourly revenue on day t from NO1 or NO2 hydropower production is:

$$r_{h,t}^{NO1,NO2} = p_{h,t} q_{h,t}^{NO1,NO2} \quad (1)$$

where $r_{h,t}^{NO1,NO2}$ is the revenue for day t and hour h in NO1 and NO2, respectively. $p_{h,t}$ is the day-ahead price and $q_{h,t}^{NO1,NO2}$ is the overall hydropower production in NO1 and NO2.

We are using the hourly revenue to calculate the market value of hydropower in NO1 and NO2 regions. We define the hourly market remuneration (€/MWh) as the ratio of hourly revenue divided by the

daily production.

$$MV_{h,t}^{NO1,NO2} = \frac{r_{h,t}^{NO1,NO2}}{\sum_{h=1}^{24} q_{h,t}^{NO1,NO2}} \quad (2)$$

where $MV_{h,t}^{NO1,NO2}$ represents the hourly market value of hydropower in the NO1 and NO2 region.

We calculate the daily hydropower market value $MV_t^{NO1,NO2}$ by summing the hourly market value for each day.

$$MV_t^{NO1,NO2} = \sum_{h=1}^{24} MV_{h,t}^{NO1,NO2} \quad (3)$$

In this paper, we also investigate the impact of renewable energy sources on the volatility of the hydropower market value in Norway. This approach allows us to analyze not only the impact of various generation technologies on the market value but also their influence on the uncertainty in electricity markets. We follow Peña et al. (2022) that base their volatility measure on Rintamäki et al. (2017) and measure the hydropower market value volatility $V_t^{NO1,NO2}$ for NO1 and NO2 as follows:

$$V_t^{NO1,NO2} = \sqrt{\frac{1}{24} \left(MV_{h,t}^{NO1,NO2} - \frac{1}{24} \sum_{h=1}^{24} MV_{h,t}^{NO1,NO2} \right)^2} \quad (4)$$

2.2. Descriptives

In Fig. 2, we plot the hydropower generation in the Norwegian NO1 and NO2 bidding zones. The main sources of hydropower production in the two regions include water reservoirs, pumped-up storage and run-of-river and poundage (ROR). Water reservoirs and pumped-up storage enable the storage of energy in the form of water, allowing for flexible electricity generation. On the other hand, ROR rely on the natural flow of rivers to generate electricity. Therefore, the distinct characteristics of these hydropower sources can have diverse effects on market dynamics in the electricity sector. The figure illustrates the significant diversity in the hydropower generation mixes between the two regions. While water reservoir generation dominates in the NO2 region, the NO1 region exhibits higher dependence on run-of-river hydropower production. This suggests that each region may encounter different challenges and uncertainties within the market. Additionally, we notice that the NO2 electricity production exceeds that of NO1, indicating a higher capacity in NO2 compared to NO1.

Our next step involves plotting and analyzing the evolution of market value and market value volatility of hydropower production in the NO1 and NO2 regions. We aggregate the hydropower production from all sources within each region, and derive a measure for the market value of the entire hydropower. Fig. 3 demonstrates the development of market value in both Norwegian regions. The market values exhibit high variability, particularly with evident spikes in 2022. This period corresponds to significant challenges faced by electricity markets due to the energy crisis in Europe (Fabra, 2023). Furthermore, we observe a similar pattern in market values until 2023, with a slight divergence thereafter.

Fig. 4 shows the market value volatility in NO1 and NO2. It is evident that the market value volatility of hydropower in NO2 exhibits greater variability than NO1. This pattern can be attributed to the differences in the generation mixes and the interconnections between the two regions. Given that both regions are experiencing higher electricity prices due to the energy crisis and new interconnections between Southern Norway, Germany, and the UK, the main reason for the difference in variability is likely that hydropower production in NO2 is higher than the NO1.

In Table 1 we present the descriptive statistics of the included variables in the model. The average market value in NO2 is 149€/MWh, showing high variability, with a wide range from −3 to 700. On the other hand, NO1's market value is slightly lower, averaging 131€/MWh, yet still showing a wide range spanning from −5.8 to 669. Furthermore,

³ <https://transparency.entsoe.eu/>

⁴ Due to data constraints and methodological issues, we chose to focus on the interaction of specific bidding zones and interconnections rather than investigate the entire system.

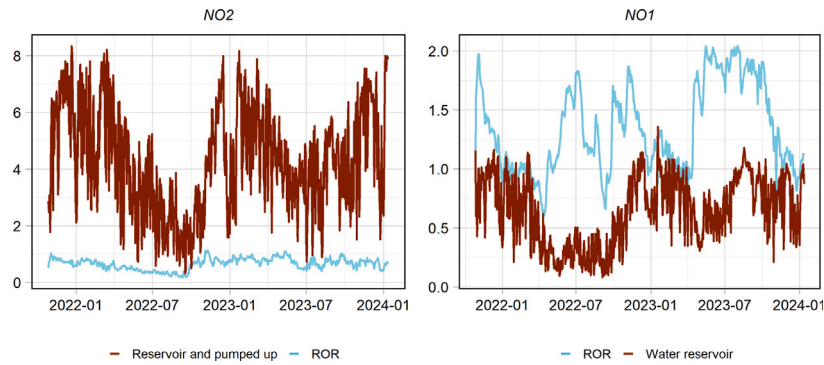


Fig. 2. Hydropower generation in NO1 and NO2 in GWh.

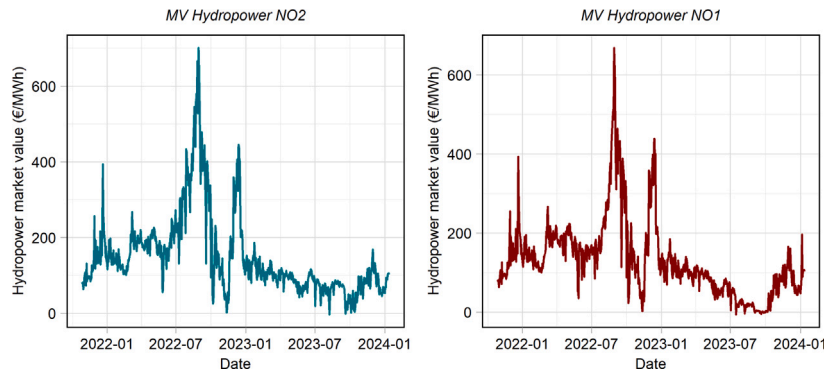


Fig. 3. Market value of hydropower in NO1 and NO2.

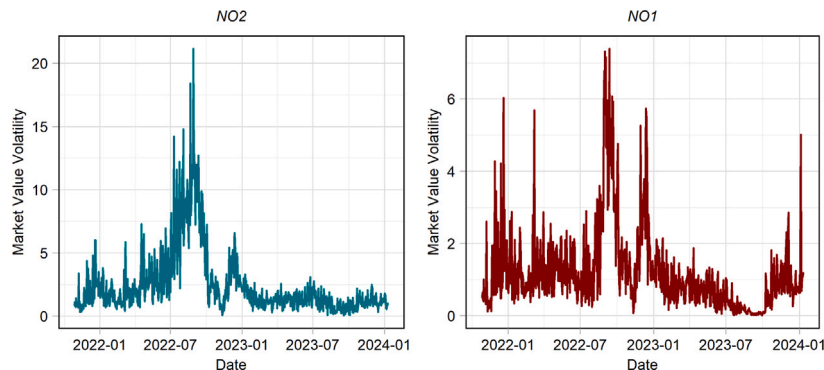


Fig. 4. Market value volatility of hydropower in NO1 and NO2.

the volatility of market value in NO2 exceeds that of NO1, indicated by its broader range of values. Both NO1 and NO2 exhibit high positive kurtosis in their market value distributions, revealing the presence of extreme outliers. This characteristic supports our modeling strategy, which involves estimating the distribution mean first, followed by applying a quantile regression. This approach allows us to account for distribution extremes and emphasizes the impact of different sources on the hydropower market value in NO1 and NO2 across varying market dynamics.

3. Econometric approach

3.1. Linear regression models

Once we have calculated the market value and market value volatility for NO1 and NO2, we proceed to test the stationarity of the data. We use the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) tests (see Table A.1), incorporating a trend, with lags selected based

on the Akaike Information Criterion (AIC)⁵. Our tests indicate that all variables are stationary, allowing us to estimate our models without requiring any further modifications.

We then model the market value $MV_t^{NO1,NO2}$ and its volatility $V_t^{NO1,NO2}$ for the two regions as functions of Run-of-River hydropower generation ($HROR_t$), water reservoir hydropower production ($HRES_t$), wind power (W_t), solar power (S_t), hydropower production from neighboring countries (H_t), and load (L_t). The region

⁵ We also employed the Schwarz Information Criterion (SIC) to validate the unit root test results, confirming that our time series remain stationary.

⁶ We consider hydropower production to be exogenous for several reasons. First, previous research has shown that hydropower producers are typically price takers in the electricity market, meaning they are not able to influence market prices (Rasmussen et al., 2016; Fodstad et al., 2017). Second, electricity prices in Norway are shaped by the dynamics of the broader European and Nordic markets. Finally, the Norwegian electricity market is highly competitive, further limiting the ability of individual producers to affect prices (Fodstad et al., 2017; NVE, 2021c).

Table 1
Descriptive statistics.

	Mean	Std. Dev.	Min	Max	Skew	Kurt
$MV_{t,NO2}^H$ (€/MWh)	149	110	-3	700	1.9	7.324
$MV_{t,NO1}^H$ (€/MWh)	131	99	-5.8	669	1.7	7.096
$V_{t,NO2}^H$	2.4	2.6	0.057	21	2.7	11.819
$V_{t,NO1}^H$	1.2	1.2	0.01	7.4	2.3	9.504
$HROR_{t,NO2}$ (GWh)	0.66	0.2	0.18	1.1	-0.32	2.487
$HRES_{t,NO2}$ (GWh)	4.3	1.9	0.32	8.3	0.094	2.136
$HROR_{t,NO1}$ (GWh)	1.3	0.37	0.61	2	0.27	1.831
$HRES_{t,NO1}$ (GWh)	0.64	0.29	0.08	1.4	-0.14	1.911
$W_{t,NO2}$ (GWh)	0.53	0.34	0.0033	1.3	0.35	2.041
$W_{t,DK1}$ (GWh)	1.6	1	0.066	4.6	0.45	2.299
$S_{t,DK1}$ (GWh)	0.19	0.17	0.0016	0.75	0.98	3.282
$W_{t,DE}$ (GWh)	15	10	0.83	48	0.84	2.864
$W_{t,SE3}$ (GWh)	1	0.64	0.094	3	0.81	3.016
$L_{t,NO2}$ (GWh)	4.1	0.69	2.5	6	0.34	2.033
$L_{t,NO1}$ (GWh)	4	1.2	2.1	7.6	0.32	2.03

of the electricity source generation is indicated by the subscript of each variable. For instance, $HROR_{t,NO1}$ represents hydropower Run-of-River production in NO1, while $HRES_{t,NO2}$ represents water reservoir hydropower production in NO2. In each model for NO1 and NO2, we incorporate electricity production from both the respective region and from neighboring countries with which the regions exchange electricity. When analyzing the bidding zone NO1, we include electricity production from NO2 and SE3. On the contrary, when examining the bidding zone NO2, we consider electricity production from NO1, DK1, and DE.

The first model aims to estimate the market value (MV) of electricity in bidding zone NO2. The specification is:

$$MV_{t,NO2}^H = \beta_0 + \beta_1 HROR_{t,NO2} + \beta_2 HRES_{t,NO2} + \beta_3 W_{t,NO2} + \beta_4 H_{t,NO1} + \beta_5 W_{t,DK1} + \beta_6 S_{t,DK1} + \beta_7 W_{t,DE} + \beta_8 L_{t,NO2} + \beta_9 MV_{t-1,NO2}^H + C_{t,NO2} + \epsilon_{t,NO2} \quad (5)$$

The model specification for NO1 is:

$$MV_{t,NO1}^H = \beta_0 + \beta_1 HROR_{t,NO1} + \beta_2 HRES_{t,NO1} + \beta_3 W_{t,NO2} + \beta_4 H_{t,NO2} + \beta_5 W_{t,SE3} + \beta_6 L_{t,NO1} + \beta_7 MV_{t-1,NO1}^H + C_{t,NO1} + \epsilon_{t,NO1} \quad (6)$$

In this paper, we have also estimated the effect of various renewable sources on the volatility of the NO1 and NO2 hydropower market value. We follow Rintamäki et al. (2017) and Peña et al. (2022) to model the market value volatility. The second model aims to estimate the volatility (V) of the market value of electricity in bidding zone NO2. The equation is as follows:

$$V_{t,NO2}^H = \alpha_0 + \alpha_1 HROR_{t,NO2} + \alpha_2 HRES_{t,NO2} + \alpha_3 W_{t,NO2} + \alpha_4 H_{t,NO1} + \alpha_5 W_{t,DK1} + \alpha_6 S_{t,DK1} + \alpha_7 W_{t,DE} + \alpha_8 L_{t,NO2} + \alpha_9 MV_{t-1,NO2}^H + C_{t,NO2} + u_{t,NO2} \quad (7)$$

The model specification for the market value volatility for bidding zone NO1 is:

$$V_{t,NO1}^H = \alpha_0 + \alpha_1 HROR_{t,NO1} + \alpha_2 HRES_{t,NO1} + \alpha_3 W_{t,NO2} + \alpha_4 H_{t,NO2} + \alpha_5 W_{t,SE3} + \alpha_6 L_{t,NO1} + \alpha_7 MV_{t-1,NO1}^H + C_{t,NO1} + u_{t,NO1} \quad (8)$$

In all the models we include a vector of control variables such as weekend and monthly dummies, as well as a lag variable of the dependent variable to control for short-term dynamics.

We use three different estimation methods to validate our results. First, we apply an Ordinary Least Square (OLS) but we find both autocorrelation and heteroskedasticity, thus we use heteroskedasticity and autocorrelation consistent standard errors. We then apply a Feasible Generalized Least Squares (FGLS) with Prais–Winsten estimator as in Clò and D'Adamo (2015) and Prol et al. (2020). In the FGLS we exclude the lagged variable since the Prais–Winsten estimator assumes that the residuals follow a first order autoregressive

process AR(1). We also estimate Eqs. (5) and (7) as two panels using a cross-section Seemingly Unrelated Regression Equations (SURE) model, as in Peña et al. (2022), correcting for heteroskedasticity and cross-sectional correlation.

3.2. Quantile regression

The mean regressions provide valuable insights into the relationships between our chosen independent variables and the market value of hydropower in NO1 and NO2, but the descriptive statistics indicate that the distribution of the market value of hydropower in both regions is leptokurtic. Additionally, macroeconomic events during the investigated period such as the energy crisis, suggest the need for a method that not only offer more robust results in extreme observations but also contributes to more detailed information on how market dynamics affect the relationships between various renewable energy sources and the hydropower market value. Therefore, we apply a quantile regression. Quantile regression was introduced by Koenker and Bassett Jr. (1978) and has been widely used in various economic applications. There have been numerous studies in the electricity market literature that have used quantile regression to investigate market dynamics and their implications for market participants, including Cludius et al. (2014), Bunn et al. (2016), Sapio (2019), Maciejowska (2020), and Tselika (2022) among others.

The quantile regression model for the NO2 bidding zone takes the following form:

$$MV(\tau)_{t,NO2}^H = \beta_{0,\tau} + \beta_{1,\tau} HROR_{t,NO2} + \beta_{2,\tau} HRES_{t,NO2} + \beta_{3,\tau} W_{t,NO2} + \beta_{4,\tau} H_{t,NO1} + \beta_{5,\tau} W_{t,DK1} + \beta_{6,\tau} S_{t,DK1} + \beta_{7,\tau} W_{t,DE} + \beta_{8,\tau} L_{t,NO2} + \beta_{9,\tau} MV_{t-1,NO2}^H + \beta_{10,\tau} C_{t,NO2} \quad (9)$$

The model is similar to the linear specification but consider the entire distribution of the market value. This approach allows us to connect the τ quantile (where $\tau = 0.1, \dots, 0.9$) of the NO2 hydropower market value $MV(\tau)_{t,NO2}^H$ with different electricity production sources. In this way, we can examine the impact on hydropower market value under extreme market conditions, whether the market value is low or high. This information is crucial for efficiently managing the market value of hydropower in Norway and ensuring its long-term sustainability. The model is estimated using the autoregressive quantile regression method by Koenker and Xiao (2006).

The quantile model for the NO1 bidding zone is:

$$MV(\tau)_{t,NO1}^H = \beta_{0,\tau} + \beta_{1,\tau} HROR_{t,NO1} + \beta_{2,\tau} HRES_{t,NO1} + \beta_{3,\tau} W_{t,NO2} + \beta_{4,\tau} H_{t,NO1} + \beta_{5,\tau} W_{t,SE3} + \beta_{6,\tau} L_{t,NO1} + \beta_{7,\tau} MV_{t-1,NO1}^H + \beta_{8,\tau} C_{t,NO1} \quad (10)$$

As in NO2, the model is similar to the linear specification but explore not only the mean of the market value distribution, but also the extremes of the distribution.

4. Empirical results

4.1. Linear regression models results

4.1.1. NO2 region

Table 2 presents the results of the linear models, including OLS, Prais–Winsten and SURE models, for the market value of hydropower in NO2. We observe that the hydropower run-of-river (ROR) in NO2 has a negative impact on the hydropower market value in the same region, while hydropower from water reservoirs and pumped-up storage positively impacts the market value. Although an increase in water reservoir hydropower production in NO2 raises the market value, the results are not statistically significant.

Table 2

The market value of hydropower in the NO2 region.

MV hydropower NO2			
Variables	OLS	Prais-Winsten FGLS	SURE
$H ROR_{t,NO2}$	-27.155***	-33.351***	-36.053***
$H RES_{t,NO2}$	0.356	0.892	0.373
$W_{t,NO2}$	-9.212***	-11.694**	-10.752**
$H_{t,NO1}$	-14.808***	-17.308***	-19.868***
$W_{t,DK1}$	-6.303**	-3.787*	-3.746**
$S_{t,DK1}$	16.748*	15.97	13.202
$W_{t,DE}$	-0.601***	-0.793***	-0.878***
$L_{t,NO2}$	0.289	-0.128	-1.172
Control dummies	Yes	Yes	Yes
Standard errors	HAC	HAC	HC

Note: *, ** and ***, respectively denote rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels.

Additionally, we find that wind power in NO2, DK1, and DE as well as hydropower production in NO1 reduce the market value of hydropower in NO2. All renewable electricity generation sources, including ROR hydropower in NO2 and hydropower production in NO1 (which primarily consists of ROR), tend to lower electricity prices, resulting in reduced hydropower market value. Run-of-river hydropower is particularly dependent on water flow, making it highly variable and influenced by weather conditions. The recent connection of southern Norway with Germany has resulted in higher prices in Norway and increased revenues for electricity producers. However, in the long run, as electricity prices stabilize to a new average level, higher wind penetration in Germany may lower the market value for hydropower producers. On the contrary, solar power from DK1 appears to increase the market value of hydropower, although the estimates are statistically insignificant. It has been shown that solar generation can increase the market value of other generation sources due to its availability during peak hours when electricity prices are high (see Clò and D'Adamo, 2015; Prol et al., 2020). Our results are robust throughout all the estimation methods.

Analyzing the volatility of the hydropower market value in NO2 (see Table 3), we find some interesting results. Although hydropower ROR reduces the NO2 hydropower market value, it also decreases the market value volatility. This means that an increase in electricity production by hydropower ROR reduces the market value volatility of hydropower in NO2. Similarly, hydropower production from water reservoirs reduces the market value volatility. Both hydropower types are quite stable electricity generation sources. Although hydro ROR is more variable than water reservoir production due to its dependence on water flow, it can be predictable, especially in regions with consistent precipitation patterns. Additionally, both hydropower sources cover most of the electricity demand in NO2, which reduces the need for more volatile and expensive electricity sources. Hydropower from the NO1 region also contributes to reducing market value volatility.

Concerning the other renewable energy generation technologies, the only statistically significant variable identified is wind power from Germany, despite its relatively low estimate. Increasing wind power in Germany results to reduced volatility in the market value of hydropower. One might anticipate that a renewable generation source like wind would increase market value volatility by increasing electricity price volatility. However, considering the stability of the Norwegian electricity system, which is characterized by high levels of hydropower, wind generation can serve as potential storage capacity through the hydropower water reservoirs, thus complementing the existing Norwegian electricity infrastructure.

4.1.2. NO1 region

Table 4 shows the estimates for the hydropower market value model in NO1. Both hydropower ROR generation and water reservoir in NO1 reduce the hydropower market value. The water reservoir estimate is

Table 3

The volatility of market value of hydropower in the NO2 region.

Volatility MV hydropower NO2			
Variables	OLS	Prais-Winsten FGLS	SURE
$H ROR_{t,NO2}$	-1.119**	-0.797**	-1.407***
$H RES_{t,NO2}$	-0.265***	-0.179***	-0.272***
$W_{t,NO2}$	-0.141	-0.131	-0.292
$H Y_{t,NO1}$	-0.721***	-0.464***	-0.9***
$W_{t,DK1}$	-0.139	-0.004	-0.033
$S_{t,DK1}$	0.369	0.357	0.359
$W_{t,DE}$	-0.047***	-0.038***	-0.057***
$L_{t,NO2}$	0.261	0.197	0.208
Control dummies	Yes	Yes	Yes
Standard errors	HAC	HAC	HC

Note: *, ** and ***, respectively denote rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels.

Table 4

The market value of hydropower in the NO1 region.

MV hydropower NO1			
Variables	OLS	Prais-Winsten FGLS	SURE
$H ROR_{t,NO1}$	-33.722***	-39.003***	-41.821***
$H RES_{t,NO1}$	-10.13	-9.135	-20.683**
$W_{t,NO2}$	-8.399**	-8.921**	-8.495**
$H Y_{t,NO2}$	1.086	1.119	1.087
$W_{t,SE3}$	-5.922***	-6.295***	-7.927***
$L_{t,NO1}$	1.422	1.133	2.211
Control dummies	Yes	Yes	Yes
Standard errors	HAC	HAC	HC

Note: *, ** and ***, respectively denote rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels.

only statistically significant in the SURE estimation. We can see that these results are different than the NO2 region. This could be due to the differences in the electricity generation mix between the two regions. In NO1, ROR hydropower is the primary source of electricity production. Furthermore, the interconnections with other regions play a significant role. A high and consistent supply of electricity from hydropower can create less scarcity in the market. This abundance can lead to lower prices overall, affecting the hydropower market value negatively. Additionally, in regions where hydropower is the dominant source of electricity, the market can become saturated for this type of energy. This can lead to the marginal value of hydropower to decrease, leading to the negative effect we find.

The estimates for wind power generation in regions NO2 and SE3 are as expected negative, and statistically significant, with similar magnitudes. In contrast, the impact of NO2 hydropower generation is positive but not statistically significant. This positive impact can be attributed to the fact that the main source of hydropower production in NO2 is from water reservoirs.

Table 5 presents the hydropower market value volatility in the NO1 region. The only significant estimates are for hydropower ROR in NO1 and wind generation in SE3. Both estimates are negative, indicating that increases in hydropower ROR in NO1 and wind generation in SE3 reduce hydropower market value volatility in NO1. Although hydropower ROR is variable due to its dependency on water flow, it still provides a relatively stable source of electricity generation, thus reducing market value volatility. Additionally, an increase in wind power production in SE3 leads to greater electricity availability in NO1, potentially stabilizing electricity prices and reducing hydropower market value volatility. Wind generation from SE3 contributes to a diversified generation mix in NO1, helping to mitigate weather-related variability, such as periods of low rainfall. Therefore, wind power from other regions can provide an alternative source of electricity generation, improving the overall electricity market stability.

The results for hydropower market value and market value volatility provide important insights into how hydropower systems interact

Table 5

The volatility of market value of hydropower in the NO1 region.

Volatility MV hydropower NO1			
Variables	OLS	Prais-Winsten FGLS	SURE
$H ROR_{t,NO1}$	-0.619***	-0.471***	-0.669***
$H RES_{t,NO1}$	0.025	0.072	-0.010
$W_{t,NO2}$	-0.075	-0.062	-0.084
$H Y_{t,NO2}$	-0.045	-0.039	-0.049
$W_{t,SE3}$	-0.225***	-0.173***	-0.241***
$L_{t,NO1}$	-0.053	-0.047	-0.048
Control dummies	Yes	Yes	Yes
Standard errors	HAC	HAC	HC

Note: *, ** and ***, respectively denote rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels.

with other renewable energy sources. By distinguishing between hydropower ROR and water reservoirs, we can assess whether these sources offer stability to electricity systems capable of integrating higher volumes of variable renewable generation, such as wind and solar, while maintaining system security. Norway is considered the “battery of Europe” and is set to play a crucial role in first, decarbonizing the European electricity sector; and second, reducing Europe’s dependence on fossil fuels from non-EU countries.

4.2. Quantile regression results

Figs. 5 and 6 illustrate the quantile regression results for the hydropower market value in NO2 and NO1 regions, respectively. These findings offer detailed insights into how different generation sources influence the market value of hydropower across varying market conditions.

In the NO2 region, hydropower ROR exhibits a negative impact on the entire distribution of the hydropower market value, with statistical significance observed only in the upper quantiles. On the contrary, hydropower from water reservoirs shows a positive and statistically significant effect in lower quantiles. This corroborates our linear regression findings, indicating that the two hydropower sources have distinct impacts on the market value and can balance the varying market effects. Furthermore, the results highlight that these impacts are significant across different parts of the market value distribution, suggesting varying effects under different market conditions. These insights emphasize the importance of considering both hydropower ROR and water reservoirs in understanding the dynamics of hydropower market value and forming policy decisions adapted to different market scenarios.

Regarding the other variables in the model, hydropower from the NO1 region diminishes the market value of hydropower in NO2, with a more pronounced effect observed in lower and intermediate levels of the market value. Similarly, wind generation in NO2 influences negatively the market value, with statistically significant estimates found in lower and intermediate quantiles. Additionally, wind power from Germany (DE) demonstrates a negative impact across the entire distribution of the market value, with the effect being particularly pronounced in upper quantiles. It is noteworthy that the estimates for DE wind are relatively low compared to the other variables in our model.

In the case of NO1, the results reveal that ROR hydropower has a negative effect on the hydropower market value across the entire distribution, with statistically significant estimates. Particularly, the strongest effect is observed in lower market value quantiles, representing a contrast to the NO2 region. On the other hand, hydropower from water reservoirs demonstrates a positive and significant impact, albeit only in the highest quantile of the market value. The differences observed in the effects of ROR hydropower and water reservoirs between NO1 and NO2 highlight the significant influence of various factors, such as the type of hydropower, cross-border interconnections, and the generation mix, on electricity market dynamics. These results underscore the importance of considering the diverse interactions among different

variables and emphasize the need for distinct policy frameworks to address the challenges of hydropower markets across different regions.

Focusing on the other renewable energy sources in our model, wind power from NO2 has a significant and negative influence across all quantiles of the hydropower market value, with the effect being more pronounced at the tails of the distribution. This indicates that wind power from NO2 has a stronger impact under more extreme market conditions. Wind power from SE3 also shows a negative impact across almost the entire distribution, with the strongest effect observed in the lower market value quantiles. In contrast, hydropower from NO2 has a positive influence across all quantiles, with the strongest effect seen in the lower market values. Overall, the results suggest that although the electricity market dynamics in NO1 differ from those in NO2, the system’s reliability is supported by the complementarity of different generation sources and the availability of various generation technologies.

4.3. Robustness analysis

The robustness of the results is verified by employing different model specifications. In the linear regression model, we explore robustness by using various sets of control variables, such as excluding weekend controls. For the quantile regression model, we incorporate gas prices as an additional explanatory variable. We use the Dutch TTF Natural Gas Continuous Contract prices from Market Watch⁷ as a benchmark and run the quantile regressions for the NO1 and NO2 regions. Thus, Eqs. (9) and (10) become:

$$MV(\tau)_{t,NO2}^H = \beta_{0,\tau} + \beta_{1,\tau} H ROR_{t,NO2} + \beta_{2,\tau} H RES_{t,NO2} + \beta_{3,\tau} W_{t,NO2} + \beta_{4,\tau} H_{t,NO1} + \beta_{5,\tau} W_{t,DK1} + \beta_{6,\tau} S_{t,DK1} + \beta_{7,\tau} W_{t,DE} + \beta_{8,\tau} L_{t,NO2} + \beta_{9,\tau} G_t + \beta_{10,\tau} M V_{t-1,NO2} + \beta_{11,\tau} C_{t,NO2} \quad (11)$$

$$MV(\tau)_{t,NO1}^H = \beta_{0,\tau} + \beta_{1,\tau} H ROR_{t,NO1} + \beta_{2,\tau} H RES_{t,NO1} + \beta_{3,\tau} W_{t,NO2} + \beta_{4,\tau} H_{t,NO1} + \beta_{5,\tau} W_{t,SE3} + \beta_{6,\tau} L_{t,NO1} + \beta_{7,\tau} G_t + \beta_{8,\tau} M V_{t-1,NO1} + \beta_{9,\tau} C_{t,NO1} \quad (12)$$

The only difference between these equations and the main models is the inclusion of gas prices (G_t). The detailed robustness results can be found in Appendix B.

The findings indicate that the main conclusions of the paper remain robust under the new specifications. Although there are some quantitative differences compared to the original results, the overall qualitative interpretations are consistent.

5. Conclusion

The European Commission (2019) has set a goal of decarbonizing the European continent by 2050. To achieve this, the power sector must undergo significant changes to accommodate higher levels of variable renewable energy, which is crucial for decarbonizing European societies. Norway is contributing to these efforts as part of the EU’s internal energy market through the Agreement on the European Economic Area (EEA) (Norwegian Ministry of Energy, 2024). Electricity markets play a crucial role in decarbonizing the energy sector. Increasing renewable energy is essential in reducing emissions from electricity production and promoting the use of clean electricity in other sectors, such as transportation. Therefore, investigating the European electricity system can provide critical insights into overcoming the challenges posed by high levels of variable sources in the electricity grid.

Norway has a stable electricity production system primarily based on high hydropower capacity. However, the forecasted higher levels of future electricity demand and the need for an integrated system with other countries necessitate increased renewable generation. This may introduce higher uncertainty for renewable energy producers, including

⁷ <https://www.marketwatch.com/investing/future/ttfc00>

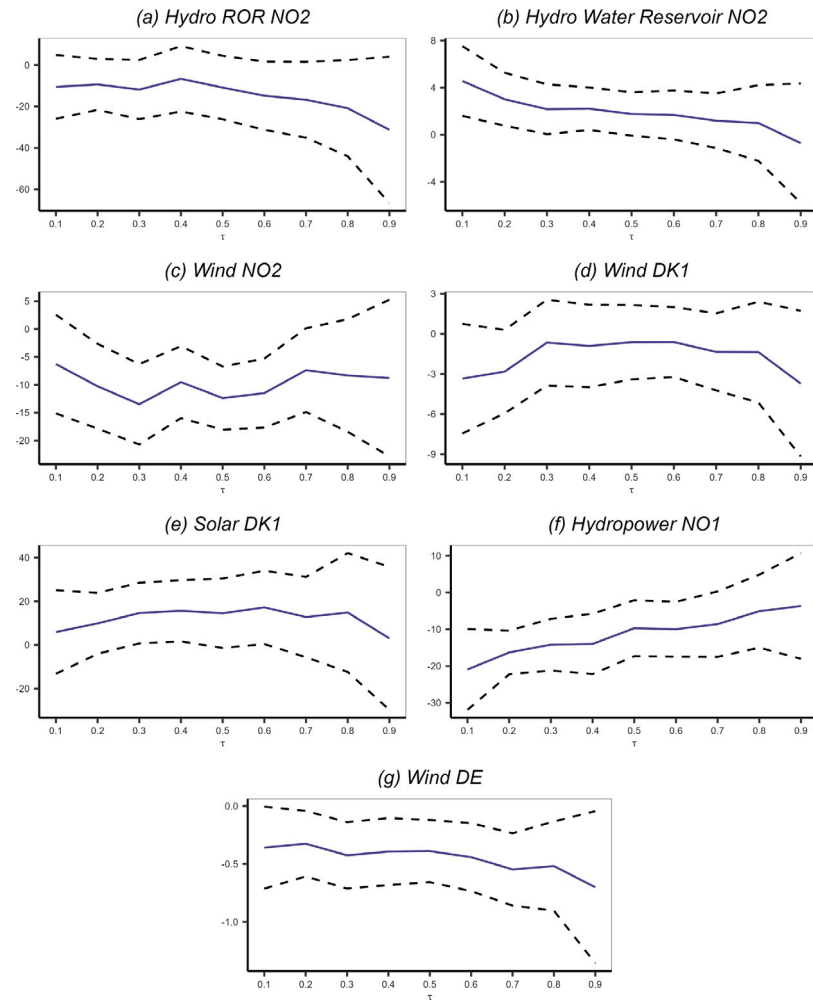


Fig. 5. The estimates of the quantile regression for $\tau = 0.1, \dots, 0.9$ with 95% confidence intervals (dashed line) for the market value of hydropower in NO2.

hydropower producers. Hydropower, the main source of electricity production in Norway, not only generates electricity but also stores it in the form of water (Graabak et al., 2017). This capability has led to Norway being characterized as the "battery of Europe", aiding in the development of a reliable electricity system in Europe.

Previous literature has primarily focused on the effects of renewable generation, such as wind and solar power, on electricity markets. Despite the critical role of hydropower in balancing the intermittent nature of wind and solar power, there has been limited research on empirically investigating the economics of hydropower production. Therefore, we employ empirical methods to investigate the impact of various renewable energy sources on the hydropower market value and its volatility in Norway. Our focus is on the two southern regions, NO1 and NO2, which have high levels of hydropower and are also connected to central Europe and other Nordic countries.

The results demonstrate that run-of-river (ROR) hydropower and water reservoirs have different effects on the hydropower market value in NO1 and NO2. While ROR hydropower negatively impacts the market value in both regions, water reservoirs have a positive impact in NO2 and a negative effect in NO1. This discrepancy may be due to the different generation mixes and interconnections in the two regions. Additionally, all other sources in our NO2 model negatively influence the hydropower market value. On the other hand, in the NO1 model, hydropower from NO2, which is primarily water reservoir production, increases the NO1 hydropower market value. Regarding the volatility of hydropower in both regions, we find that almost all generation sources reduce market value volatility. Even variable sources, such as

wind generation, reduce hydropower market value volatility, which could be attributed to hydropower's ability to balance the variability of renewable sources by storing energy.

The quantile regression results reveal that different hydropower sources have varying influences on the hydropower market value distribution. In NO2, ROR production reduces stronger the market value in the upper quantiles, while water reservoirs increase the value in the lower quantiles. This effect is reversed in NO1. These results illustrate that the type of hydropower as the main source of electricity production in a region, the availability of other generation technologies, and the interconnections with other countries are important factors in the operation of electricity markets and shaping market dynamics. Overall, despite the different generation mixes and market dynamics in the two regions, the electricity systems remain reliable due to the availability and complementarity of various sources.

The results of this paper are important for practitioners and policy-makers because they illustrate the impact of variable generation sources on the hydropower market value and volatility, which is crucial for the decarbonization of the European electricity system. The findings can be used in several ways. First, market participants can use the information on market value and its volatility to identify profitable strategies. For instance, knowledge that wind power from regions like NO2 and SE3 significantly reduces hydropower market value, particularly during high wind generation periods, can help hydropower producers optimize their production schedules, such as increasing production when wind generation is low to maximize market value. Second, the results provide useful insights for electricity producers and regulators regarding

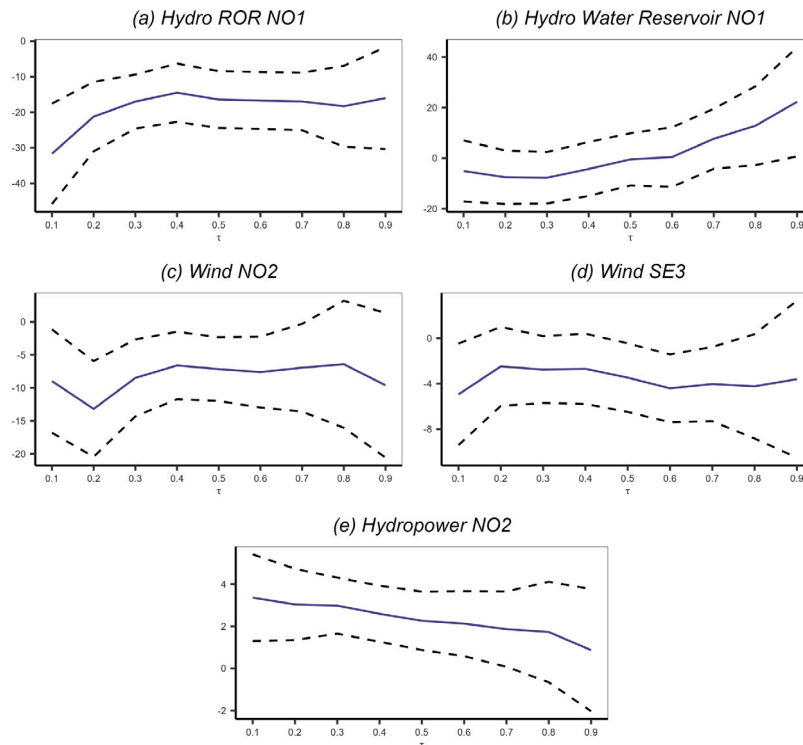


Fig. 6. The estimates of the quantile regression for $\tau = 0.1, \dots, 0.9$ with 95% confidence intervals (dashed line) for the market value of hydropower in NO1.

how different market dynamics influence the economic performance of producers in the market. This can guide regulators in designing policy schemes that support hydropower producers while incorporating higher levels of renewable energy into the system. For example, the negative impact of run-of-river (ROR) hydropower on market value, coupled with its ability to reduce market volatility, suggests that differentiated support mechanisms could be designed to incentivize the use of reservoir hydropower during peak demand periods while also stabilizing prices. This could involve policies that encourage the use of water reservoirs for load balancing, thus ensuring that hydropower remains competitive and sustainable amidst increasing wind and solar penetration. Lastly, understanding the dynamics and interaction of different sources, including generation from neighboring countries, can help governments develop strategies for creating a reliable yet profitable electricity market in Europe. For instance, access to various generation technologies can complement Norwegian hydropower production, benefiting both Norwegian producers and contributing to a secure and sustainable electricity system in Europe. Policymakers could utilize these insights to strengthen cross-border energy collaboration by optimizing interconnection capacities and developing more integrated market frameworks.

This research provides valuable insights into hydropower systems and electricity markets, particularly through a focused analysis of Norway's NO1 and NO2 regions. These regions are characterized by high hydropower generation and play a critical role in ensuring energy security in Europe. However, this focused approach may limit the generalization of findings to other hydropower systems or the broader dynamics of European electricity markets. Moreover, due to data constraints, we analyze a three-year period (2021–2024), which provides a snapshot of recent trends but may not fully capture long-term shifts or the broader implications of climate change. These considerations highlight the need for further research while underscoring this study's contributions to understanding hydropower in the Norwegian context.

Future research could expand on these findings by exploring several key areas. A comparative analysis of other hydro-dominated regions, such as France, Switzerland, and Spain, could validate our conclusions and provide a broader perspective on hydropower dynamics across Europe. Additionally, studies examining the overall European electricity system could offer more generalized recommendations for policymakers and industry stakeholders. Future research could also investigate the hydropower market value under diverse scenarios of renewable energy integration, such as increased solar or wind generation. This would enhance understanding of how hydropower interacts with other renewable sources, supporting grid stability, energy security, and decarbonization efforts. Finally, investigating the effects of regulation, such as carbon pricing, on hydropower value and market volatility could provide critical insights into the sector's performance under varying market conditions.

CRediT authorship contribution statement

Kyriaki Tselika: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Stefan Jaehnert:** Writing – review & editing, Validation, Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

(see Table A.1)

Table A.1

Unit root tests.

	$HROR_{t,NO2}$	$HRES_{t,NO2}$	$HROR_{t,NO1}$	$HYRP_{t,NO1}$	$W_{t,NO2}$	$H_{t,NO1}$	$H_{t,NO2}$	$W_{t,DK1}$	$S_{t,DK1}$	$W_{t,DE}$	$W_{t,SE3}$	$L_{t,NO2}$	$L_{t,NO1}$
ADF (trend)	-4.932***	-9.111***	-3.3034***	-7.701***	-14.534***	-5.498***	-8.808***	-13.949***	-5.774***	-10.917***	-13.764***	-3.672***	-3.048***
PP (trend)	-30.142***	-133.30***	-17.013***	-94.967***	-413.917***	-37.166***	-121.83***	-368.59***	-74.514***	-247.766***	-330.648***	-12.854***	-8.967***

Notes: (i) ADF indicates augmented Dickey–Fuller; PP indicates Phillips–Perron, (ii) *, ** and *** respectively denote rejection of null hypothesis of a unit root at significance level 10%, 5% and 1%.

Appendix B

(see Figs. B.1 and B.2)

(see Tables B.1–B.4)

Table B.1

The market value of hydropower in the NO2 region without weekend controls.

MV hydropower NO2		
Variables	Prais-Winsten FGLS	SURE
$HROR_{t,NO2}$	-26.39***	-30.39***
$HRES_{t,NO2}$	2.138	1.492
$W_{t,NO2}$	-12.23**	-11.96**
$H_{t,NO1}$	-16.46***	-19.56***
$W_{t,DK1}$	-1.970	-1.914
$S_{t,DK1}$	15.10	12.42
$W_{t,DE}$	-0.489**	-0.605***
$L_{t,NO2}$	6.441	5.108
Standard errors	HAC	HC

Note: *, ** and ***, respectively denote rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels.

Table B.2

The market value volatility of hydropower in the NO2 region without weekend controls.

Volatility MV hydropower NO2		
Variables	Prais-Winsten FGLS	SURE
$HROR_{t,NO2}$	-0.879**	-1.392***
$HRES_{t,NO2}$	-0.183***	-0.257***
$W_{t,NO2}$	-0.118	-0.293
$H_{t,NO1}$	-0.469***	-0.898***
$W_{t,DK1}$	-0.018	-0.019
$S_{t,DK1}$	0.293	0.281
$W_{t,DE}$	-0.043***	-0.058***
$L_{t,NO2}$	0.114	0.214
Standard errors	HAC	HC

Note: *, ** and ***, respectively denote rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels.

Table B.3

The market value of hydropower in the NO1 region without weekend controls.

MV hydropower NO1		
Variables	Prais-Winsten FGLS	SURE
$HROR_{t,NO1}$	-39.11***	-42.45***
$HYRP_{t,NO1}$	-8.561	-20.23***
$W_{t,NO2}$	-6.932*	-6.570
$HY_{t,NO2}$	1.991*	1.906*
$W_{t,SE3}$	-4.934**	-6.635***
$L_{t,NO1}$	5.419	6.237*
Standard errors	HAC	HC

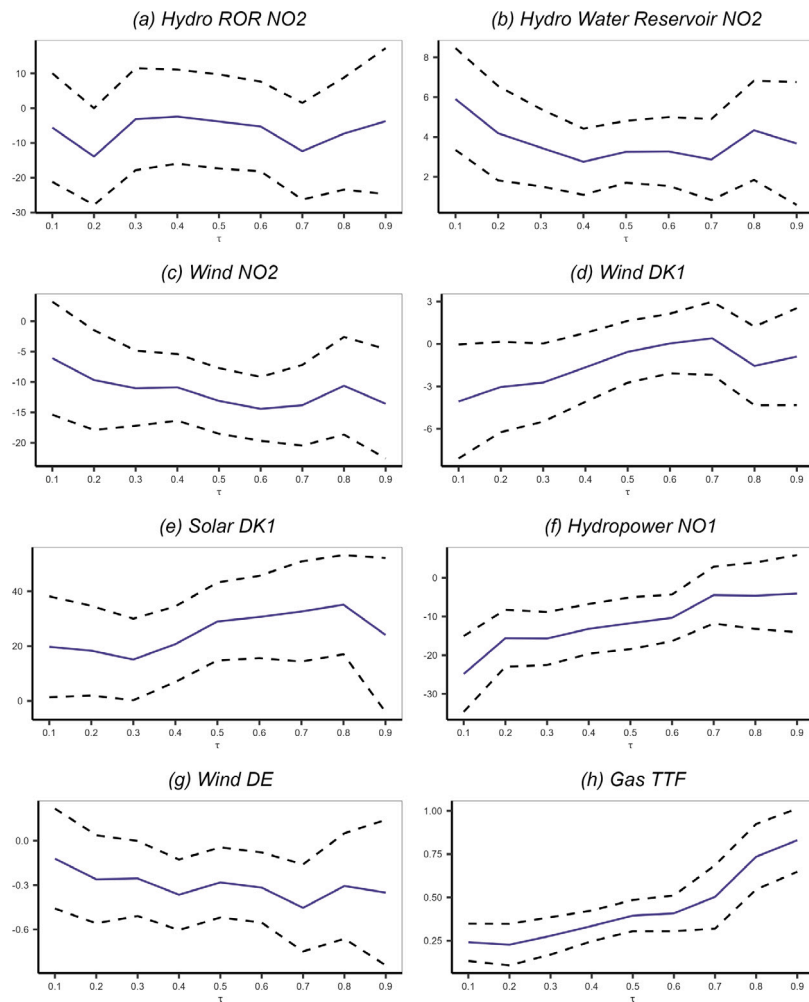
Note: *, ** and ***, respectively denote rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels.

Table B.4

The market value volatility of hydropower in the NO1 region without weekend controls.

Volatility MV hydropower NO1		
Variables	Prais-Winsten FGLS	SURE
$HROR_{t,NO1}$	-0.480***	-0.684***
$HYRP_{t,NO1}$	0.08	-0.014
$W_{t,NO2}$	-0.051	-0.061
$HY_{t,NO2}$	-0.037	-0.039
$W_{t,SE3}$	-0.168***	-0.229***
$L_{t,NO1}$	-0.019	0.005
Standard errors	HAC	HC

Note: *, ** and ***, respectively denote rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels.

**Fig. B.1.** The quantile regression results for the market value of hydropower in NO2 with gas prices.

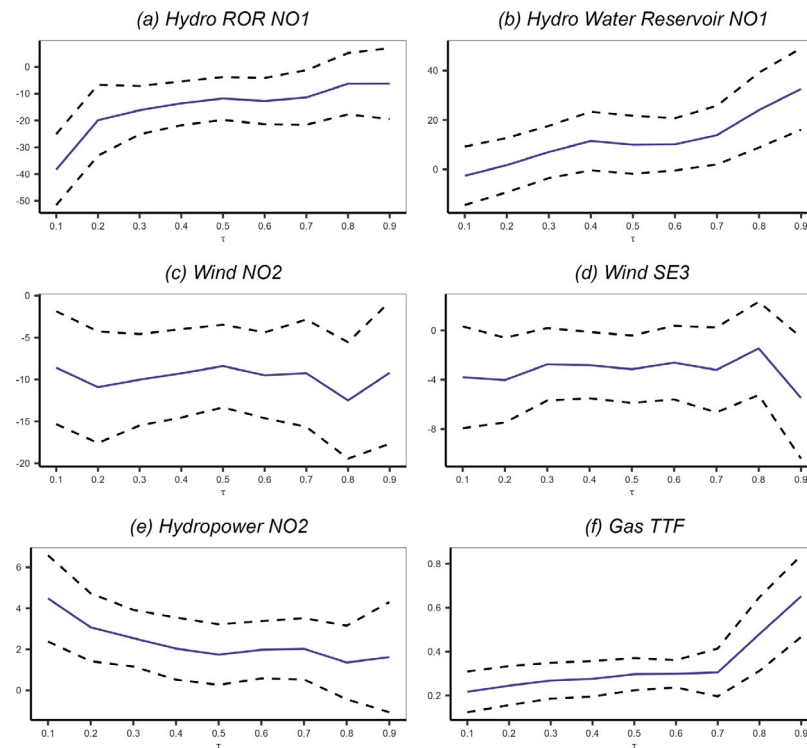


Fig. B.2. The quantile regression results for the market value of hydropower in NO1 with gas prices.

Data availability

Data will be made available on request.

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