Frequency markets and the problem of predictability

EPRG Working Paper 2220

Cambridge Working Paper in Economics CWPE2306

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Abstract

Ancillary services markets (ASMs) are gaining higher importance in renewable-based power systems. They, however, remain less explored than the energy markets (EMs) of different regions. For limited energy units, such as battery energy storage systems (BESSs), it is vital to investigate the relative predictability of the two markets as suitable bidding hours of a less predictable product are more challenging to identify, thus entailing less certain revenues. This paper develops forecast models of the two markets of three Nordic countries – Denmark, Finland, and Norway – to quantify the difference in their predictability. Frequency containment normal reserves (FCR-N) are considered as a case of the Nordic ancillary service product. The dataset of 315648 datapoints contains three years (2019 – 2021) of their hourly FCR-N, and spot market revenues. Generalized additive models (GAMs) are used to develop week-ahead forecasts using smooth curves of hourly and daily patterns. The forecast allows both inter country – between same markets of different countries – and intra country – between different markets of the same country – comparison. The results show that the FCR-N markets of the Nordic countries are less predictable than their respective spot markets except for the case of Denmark due to its fixed hourly volumes. Moreover, the smoothing curves of FCR-N forecast models differ for each Nordic country despite their similar market requirements. This is in contrast to the Nordic spot markets where the smoothing curves indicate similarity in inter-country market behaviors. Considering market predictability differences in addition to their hourly prices is thus vital for BESS units performing multi-market bidding.

Keywords Ancillary services, Spot markets, Forecast, Battery energy storage

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Publication December 2022

Financial Support BOSS: Bornholm Smartgrid Secured by grid-connected battery systems, contract no. 64018-0618

1 INTRODUCTION

In 2019, the Nordic countries issued a joint declaration to make the Nordic region carbon neutral by 2050 [1]. Higher integration of renewable energy sources (RES) in the energy sector lies at the heart of achieving carbon neutrality. From 2005 to 2018, the RES share in the Nordic electricity consumption increased from 63% to 73% [2]. Projections for 2050 show a five-fold increase in the wind production in the Nordic generation mix. However, RES intermittency and its synchronous inertia inadequacy affects the grid stability, reliability, and security. Ancillary service products (ASPs) including frequency regulation services (FRSs), voltage control services, and system restart services are thus becoming more important in the modern RES-based power systems [3][4].

Traditionally ASPs were procured by transmission system operators (TSOs) from gas or coal-fired power plants, as by-products of their energy at administered prices [5]. Nowadays, new players such as battery energy storage systems (BESSs) and electric vehicles (EVs) are entering the ancillary services markets (ASMs) [6]. FRSs are the greatest value applications of BESSs in the Nordics due to their fast response and flexible control [7], [8]. They are also one of the most feasible services driven from the Nordic EVs [9]–[14]. However, unlike conventional power plants, the limited energy reservoir of BESSs and EVs prevents them from retaining a fixed energy capacity for ancillary services (ASs). Instead, they must rely on forecast techniques to identify suitable bidding hours. Since Nordic countries have unique pricing and procurement mechanisms – despite having same ASPs – it is vital for BESS owners with international assets to assess the applicability of similar forecast models for different countries. It is also important to compare the revenue potential in different countries by quantifying relative predictability. The question of relative predictability is important as identifying the suitable bidding hours of a less predictable product is challenging and entails less certain future revenues. Moreover, since ASMs are relatively new as compared to the energy markets (EMs) – being mainly available in Europe, North America, and Oceania – benchmarking their predictability against the latter is an obvious point of comparison that can help market participants quantify market differences and identify relative business risks.

Studies so far have mainly focused on price behaviors of ASPs of a particular region – Midcontinent Independent System Operator (MISO) in [15], and Electricity Reliability Council of Texas (ERCOT) in [16] and [17]. Since ASPs revenues depend on a country's procurement methods, remuneration methods, participating entities, environmental policies, and operational conditions, a comparative study is important, especially in BESS-business context [18]. Moreover, considering procured volumes in addition to the price behavior is also crucial to get a true understanding of the overall revenues. [19] showed the revenues earned by the same pumped storage hydro facility from providing FRSs in the New England ISO were one eighth of what it would earn in the MISO area. However, such studies have not been conducted for the Nordics. A few studies have also compared the behavior of ASMs and EMs. [20] found FRSs prices to be more volatile than underlying energy prices in Ontario, New York and ERCOT, and [21] found them to be more exaggerated than energy market prices in Nord Pool. However, so far, their relative predictability has not been quantified based on a single model for different markets. Even though both statistical and artificial intelligence models are extensively applied to forecast behavior of EM products, similar work on ASPs is scarce [22]–[25].

For the above-recognized reasons, this paper investigates three main research questions: a) Can similar ASPs of different Nordic countries be represented using a single model, b) Are revenues from Nordic ASPs less predictable than corresponding EM products, c) Does a particular ASP differ significantly in terms of predictability in each Nordic country. To answer to these questions, we develop a forecast model for ASMs and EMs of Denmark, Sweden, Finland, and Norway using three years of hourly data of their respective ASP prices, ASP volumes, spot market prices, and MW-consumption. The forecast is based on generalized additive modeling (GAM), which applies smooths – splines along with their smoothing parameters – to fit the data. Two weeks of hourly data is used for data fitting, and assessing the key determinants of the fitted model, while the next one week is used to compute the forecast accuracy. The process is repeated for all three years. Relative differences in the predictability among different countries and different markets are assessed based on the complexity and shape of the smooths of their respective GAM models, the differences in the model fit, and the percentage error of the forecast. Moreover, considering the weekly price forecast, the revenues an 1MW/1MWh BESS unit may earn when deployed in different Nordic countries are also estimated. The analysis presented in this paper is vital for investors, financiers, policy makers and researchers to investigate the relative business potential of bidding in the Nordic ASMs and compare the difference in their behavior with EMs.

This paper has six sections. Section II overviews the Nordic ASPs. Section III discussed the modeling approach, while section IV applies the proposed approach to forecast revenues of the Nordic ASMs and EMs. Section V discusses the results and the paper ends with concluding remarks in section VI.

2 OVERVIEW OF NORDIC ASPS

ASPs can be procured in three ways. First, via a mandatory response which is required as a condition of being connected to the power network. Second, via a long-term bilateral contract between the TSO and the ancillary service provider, and third, via a market-based procurement mechanism on the basis of invited bids [5]. Moreover, the name, the operational conditions, and the regulations requirements associated with ASPs vary for different synchronous areas (SAs). The SAs are a group of power systems that are connected and operate under the same frequency. The European network of transmission system operators (ENTSO-E) has five SAs, namely, the Continental Europe Area, the Nordic Area, the Baltic Area, the United Kingdom Area, and the Ireland Area. These SAs are illustrated in Fig.1a. The Nordic SA and the Continental Europe SA are represented in light and dark green colors, respectively. The SA are further divided into bidding zones. A bidding zone is the largest geographical area within which market participants can exchange energy without capacity allocation. The bidding zones of Nordic SA are also shown in Fig.1b. Denmark has two, Sweden and has four, Finland has one, and Norway has five bidding zones. In the Nordic SA, voltage control is compulsory for all large-scale units directly connected to the grid and system restart and recovery services are procured as long-term contracts from specific suppliers. Depending on the system needs, generation and consumption units can increase or decrease their electric power to supply FRS and participate in market-based procurement. Five main FRSs exist in the Nordic SA as shown in Fig.2a. This includes two types of frequency containment reserve (FCR) products, namely frequency-controlled normal operation reserve (FCR-N) and frequency-controlled disturbance reserve (FCR-D), two types of frequency

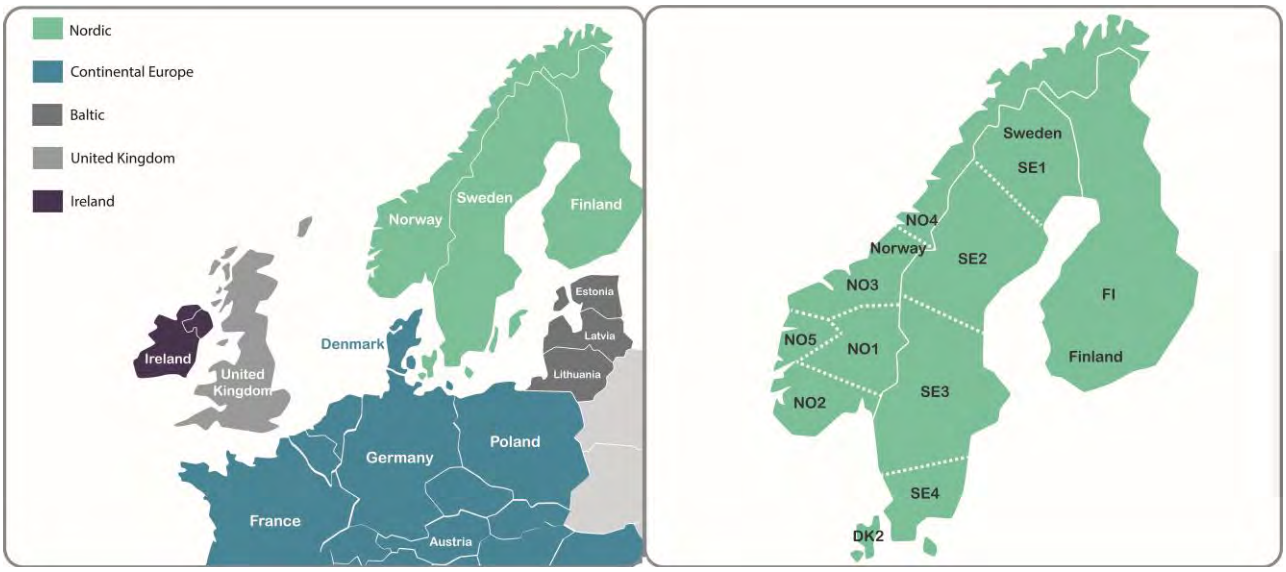


Fig. 1: a) The five synchronous areas (SA) under ENTSO-E, b) Bidding zones in Nordic SA

restoration reserve (FRR) products, namely, automatic FRR (aFRR) and manual FRR (mFRR), and the fast frequency reserve (FFR) product. Their response time, response duration and droop control requirements are the same for each Nordic country, however, their procurement and pricing mechanisms differ.

2.1 Procurement Mechanisms

Energinet of East Denmark (DK2) – DK2 is henceforth called Denmark – Fingrid of Finland, Statnett of Norway, and Svenska Kraftnat of Sweden constitute the Nordic TSOs. The Nordic TSOs dimension their ASPs together that defines the total amount of reserves required in the system and their distribution between the individual countries. The total Nordic reserve requirements for FFR, FCR- D, FCR-N, and aFRR in 2022 was 300 MW, 1450 MW, 600 MW, and 300 MW respectively [26], [27]. The volume distribution of FCR-N reserves among the four Nordic TSOs depends on the generation and consumption profile of the previous year in their respective areas and the total Nordic generation and consumption profile. The equation is as follows:

$$FCRN_{TSO1} = \frac{Generation_{TSO1} + Consumption_{TSO1}}{\sum_{i=1}^{4}(Generation_{TSOi} + Consumption_{TSOi})}$$

Of the total 600MW Nordic requirement, FCR-N volumes to be delivered by Denmark, Finland, Norway, and Sweden were 2.74%, 19.88%, 39.05%, and 35% respectively in 2022 as shown in Fig.2d. Energinet and Svenska Kraftnat produce their respective shares via common Danish-Swedish hourly day-ahead market. The pricing mechanism is pay-as-bid. There is no restriction on exchange of FCR-N reserves between the two countries within the limits of the transmission capacity. Moreover, since FCR-N reserves are auctioned via one market only, their procured volumes are at minimum the combined Danish-Swedish need, that remains same per year. Contrarily, Fingrid procures its required share via two markets: hourly day-ahead market and hourly year-ahead market, both operating on pay-as-clear mechanism. Providers with year-ahead contracts submit plans to Fingrid for all hours of the following day on the capacity they can maintain. The maintained capacity can be maximum the contracted volume. The remaining volumes are procured from day-ahead market. Statnett, imposes droop control requirements for frequency control on all synchronous generators. It also procures FCR-N reserves through hourly day-ahead and two-day-ahead markets per bidding zone operating on a pay-as-clear mechanism. The FCR-D procurement in all four Nordic countries is handled in the same way as their respective FCR-N procurement [26]. It is important to note, that only Norway's FCR-N and FCR-D markets have different prices per bidding zone. This is not true for the case for Sweden and does not apply for the case of Denmark and Finland.

FFR is a relatively new service in the Nordic SA, the procurement of which started in May 2020. Each Nordic TSO has implemented a national FFR market. Energinet and Fingrid procure FFR via their separate hourly day-ahead markets. The procured volumes depend on forecasted hourly need, and the pricing mechanism is pay-as-clear. Fingrid may also procure FFR via interconnectors from Estonia if needed. Svenska Kraftnat procures FFR twice a week and procures volume based on the forecasted hourly need via pay-as-clear mechanism. Statnett has a seasonal FFR market with two different types of FFR products operating from May – September [26]. FFR profil allows provision of a fixed capacity over the season for certain hours. While FFR flex allows guaranteed delivery hours during which Statnett can order required volumes on request.

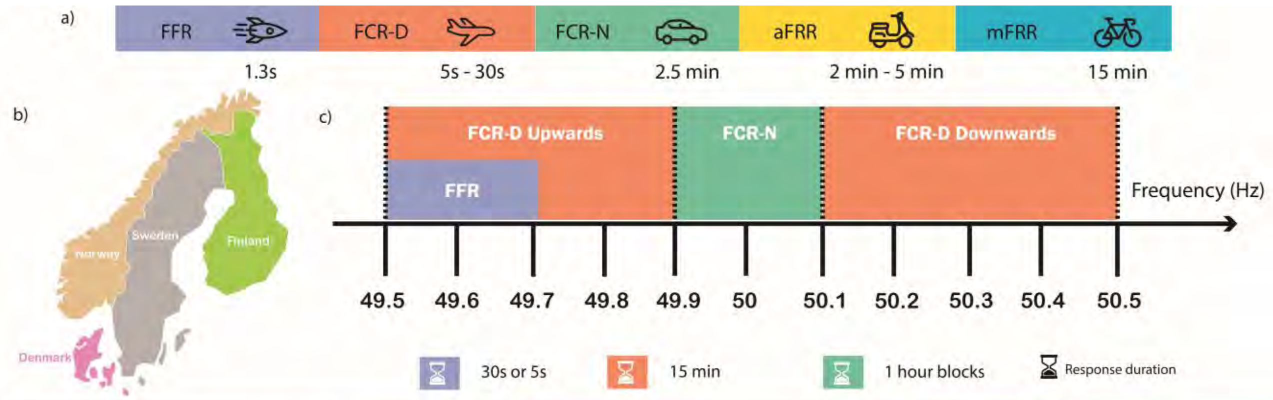
For aFRR reserves, Finland, Norway, and Sweden procure their required volumes in their respective aFRR national capacity markets. The providers are paid according to the most expensive accepted bid, i.e. pay-as-clear mechanism. Norway's aFRR market has different hourly prices per bidding zone similar to its FCR-N, and FCR-D markets. Denmark (DK2) on the other hand buys aFRR from DK1 via HVDC interconnectors. According to ENTSO-E, in near future, a common aFFR Nordic capacity market is anticipated. So is a common mFRR Nordic capacity market. At the moment, the mFRR energy bids for each country are combined in the common Nordic energy activation market that opens fourteen days before the day of operation and is based on marginal pricing mechanism. For mFRR, in addition to the common Nordic energy activation market, Denmark has long term contracts with reserve providers, Statnett has a national capacity market, and Fingrid has reserve power plants [26]. Fig.2d. details the Nordic procurement mechanisms.

2.2 Provision Requirements

FCR-N reserves keep the frequency close to 50 Hz in the event of frequency deviations [28]. At frequency deviations between 0 to 100 mHz, FCR-N reserves must be supplied linearly by the participating units. At frequencies equal to or above 50.1 Hz, 100% of FCR-N downward capacity must be activated. While at frequencies equal to or below 49.9 Hz, 100% of FCR-N upward capacity must be activated. The activation must be supplied within 2.5 minutes [28]–[32]. On the other hand, FCR-D reserve is divided into two separate products. FCR-D-upwards and FCR-D-downwards for sudden frequencies under 49.9 Hz, and higher than 50.1 Hz respectively. Participating units must maintain the regulation for at least 15 minutes [28]–[31].

Fast frequency reserves (FFR) are used to regulate the system frequency when there is a major system disturbance in low inertia situations[33]. FFR was introduced in the Nordic SA in May, 2020, because the response of the primary frequency reserves was not enough to ensure frequency stability in low inertia situations given the reference incident [34]. The low inertia situation was more likely during periods of low demands in summers. A feasibility study was conducted to address the challenge, and FFR was deemed to be the most promising solution in contrast to reducing the size of the reference incident by reducing the limit of the largest generator or increasing system inertia through synchronous condensers. Since FFR was aimed to help low inertia situations, it is designed to be activated when the frequency of the system is lower than specific limit. There are three possible timeframes for FFR activation. It can be activated at frequency dips below 49.7, 49.6, or 49.5 Hz. The maximum time for full activation is 1.3 seconds, 1.0 seconds, and 0.70 seconds respectively. The activation durations of FFR can either be long or short, which are 30 seconds, and 5 seconds respectively. Participating unit must stay active as long as the frequency is below 49.8 Hz [33][35].

The activation of an aFRR unit is based on a control signal sent every 10s by the connecting TSO. It is activated continuously, with a full activation time between 2 and 5 minutes depending on the country. mFRR activations on the other hand are ordered by the regional TSOs to reduce existing imbalances or because of forecasted imbalances in the near future. The full activation time is 15 minutes. Fig.2a. shows the response time for Nordic FRS products. The fastest response time is for FFR of 1.3 seconds, followed by FCR-D of 5 – 30 seconds, FCR-N of 2.5 minutes, aFRR of 2 – 5 minutes, and mFRR of 15 minutes. Fig.2c. shows the activation frequency range of FCR-N, FCR-D, and FFR reserves.



d)

Country	TSO	FFR		FCR-D		FCR-N		aFRR		mFRR
Denmark (DK2)	Energinet	8 %	24 MW	3 %	43 MW	2.74 %	17 MW	10 %	30 MW	
	Procurement	Hourly day-ahead market		Hourly day-ahead market		Hourly day-ahead market		Interconnectors		Long-term contracts
	Price	Pay-as-clear		Pay-as-bid		Pay-as-bid		Pay-as-clear		Pay-as-clear
	Volume	Forecasted		Min DK2+Sweden need		Min DK2+Sweden need		Fixed		Fixed
Finland	Fingrid	18 %	54 MW	20 %	290 MW	19.88 %	119 MW	20 %	60 MW	
	Procurement	Hourly day-ahead market Interconnectors to Estonia		Hourly day-ahead market Hourly year-ahead market		Hourly day-ahead market Hourly year-ahead market		Hourly day-ahead market		Reserve power plants, Capacity market
	Price	Pay-as-clear		Pay-as-clear in day-ahead Pay-as-clear in year-ahead		Pay-as-clear in day-ahead Pay-as-clear in year-ahead		Pay-as-clear		Pay-as-clear
	Volume	Forecasted need		Variable in day-ahead Max contracted in year-ahead		Variable in day-ahead Max contracted in year-ahead		Fixed		Fixed
Norway	Statnett	39 %	117 MW	37 %	537 MW	39.04 %	234 MW	35 %	105 MW	
	Procurement	Seasonal market		Hourly day-ahead per zone, Compulsory droop control		Hourly day-ahead per zone, Compulsory droop control		Hourly day-ahead per zone		National capacity market, Nordic energy market
	Price	Pay-as-clear		Pay-as-clear		Pay-as-clear		Pay-as-clear		Pay-as-clear
	Volume	FFR profil, FFR flex		Variable in day-ahead market		Variable in day-ahead market		Fixed		Fixed
Sweden	Svenska kraftnät	35 %	105 MW	40 %	580 MW	38.33 %	230 MW	35 %	105 MW	
	Procurement	Hourly week-ahead market		Hourly day-ahead market		Hourly day-ahead market		Hourly week-ahead market		Voluntary energy bids, Long term contracts
	Price	Pay-as-clear		Pay-as-bid		Pay-as-bid		Pay-as-bid		Pay-as-clear
	Volume	Forecasted need		Min DK2+Sweden need		Min DK2+Sweden need		Fixed		Fixed
	Total	300 MW		1450MW		600 MW		300 MW		

Fig. 2: a) ASPs in the Nordic region b) Nordic countries map c) Response time and response duration requirements of Nordic ASPs d) Availability pricing mechanism, and volume requirements of ASPs

3 METHOD

In this paper, we use generalized additive models (GAMs) to develop the revenue forecasts of FCR-N reserves of Denmark, Norway, and Finland as a case of Nordic ASPs. One bidding zone is considered for each country as market participants can in general submit bids in the one bidding zone where their unit is physically located. The forecast models developed are thus applied to compare the revenues BESS owners can earn in different regions while considering a case of the country's bidding zone. DK2 (henceforth called Denmark, or DK) is considered for Denmark as it is the only bidding zone of the country in Nordic SA, FI (henceforth called Finland, or FI) for Finland as the whole country is one bidding zone, and NO2 (henceforth called Norway, or NO) for Norway as its prices are most fluctuating. Sweden is not considered separately since the FCR-N prices of Denmark and Sweden are the same – due to the common Danish-Swedish market.

3.1 Generalized Additive Model

GAMs are semi-parametric, additive models that relax the linearity assumption of linear models [36]. When the regression line of linear models is unable to capture the non-linear trajectory between the explanatory variables (henceforth called predictors) and response variables, it creates systematic patterns in the model residuals, thereby making the p-values and the causal inferences unreliable [37]. GAMs allow the relationships between the predictors and the response variable to be described by smooth curves and take the general form [38]:

$$g\big(\mathbb{E}(Y)\big) = \beta_0 + \sum_{j=1}^{J} f_j\,(x_j) \qquad (2)$$

Here, where $\mathbb{E}(Y)$ is the expected value of the response Y. f_j is a smooth function (henceforth called smoother) of the predictor x_j, and β_0 is an intercept term. Each smoother f_j is represented by a sum of K simpler, fixed basis functions $b_{j,k}$ multiplied by corresponding coefficients $\beta_{j,k}$, which need to be estimated:

$$f_j\big(x_j\big) = \sum_{k=1}^{K} \beta_{j,k} b_{j,k}(x_j) \qquad (3)$$

Here, K is the basis size – also known as knots – and represents the maximum complexity of the smoother. Higher K results in more wiggly smoothers which may result in overfitting. This is counteracted by a penalty term in the model fitting process controlled by the smoothing parameter λ. The penalized log-likelihood used to fit the model is thus given by:

$$L - \lambda\beta^T S\beta \qquad (4)$$

Here, $\beta^T S\beta$ is the penalty term, L is the model log-likelihood, and λ controls the tradeoff between model accuracy its complexity (wiggliness). λ is selected using restricted maximum likelihood (REML). K mainly sets the upper limit to the degree of the smoother wiggliness.

3.2 Market Predictability Comparison

In this paper, two GAM models are developed per country: GAM_1 for FCR-N revenues ($GAM_1^{DK}, GAM_1^{NO}, GAM_1^{FI}$), and GAM_2 for spot market revenues ($GAM_2^{DK}, GAM_2^{NO}, GAM_2^{FI}$). Hourly FCR-N revenues are calculated as a product of hourly FCR-N prices and volumes and are considered in their logarithmic form to avoid the higher volume requirements of larger countries affect the comparative results. Similarly, spot market revenues – also considered in their logarithm form – are calculated as a product of the country's hourly spot prices and net consumption as follows:

$$FCRNrev_h^{NC} = \log_e(FCRNprice_h^{NC} \times FCRNvolume_h^{NC}) \quad (5)$$

$$SPOTrev_h^{NC} = \log_e(SPOTprice_h^{NC} \times Consumption_h^{NC}) \quad (6)$$

Here, $NC = DK, NO, FI$.

For intra-country (different markets of the same country) and inter-country (same markets of different countries) predictability comparison, GAM_1 and GAM_2 are developed considering the smoothers of the hours of the day and days of the week only. Doing so, quantifies the market predictability based only on the patterns in the historical data. Interaction between the two smoothers is also modeled by a tensor product ti. ti creates a new set of basis functions that allow for each marginal function to have its own marginal smoothness penalty. Mathematically the models are written as:

$$FCRNrev_i^{NC} = f(hours_i) + f(days_i) + f(hours_i \times days_i) + \varepsilon_i \quad (7)$$

$$SPOTrev_h^{NC} = f(hours_i) + f(days_i) + f(hours_i \times days_i) + \varepsilon_i \quad (8)$$

Here, $f(hours_i)$ is the smoother for the hours of the day, $f(days_i)$ is the smoother for days of the week, and $f(hours_i \times days_i)$ is the interaction between the two. The R representation of the models is as follows:

$$\begin{aligned} GAM_1^{NC} <- \text{gam}\ (&FCRNrev^{NC} \sim s\ (hours, bs = 'cr', k = 24) \\ &+ s(days\ , \quad bs = \text{'ps'}, \quad k = 7) \\ &+ ti\big(hours, days\ k = c(24,7), bs = c(\text{cr}, \text{ps})\big), \\ &data = NC,\ family = gaussian) \quad (9) \end{aligned}$$

$$\begin{aligned} GAM_2^{NC} <- \text{gam}\ (&SPOTrev^{NC} \sim s\ (hours, bs = 'cr', k = 24) \\ &+ s(days\ , \quad bs = \text{'ps'}, \quad k = 7) \\ &+ ti\big(hours, days\ k = c(24,7), bs = c(\text{cr}, \text{ps})\big), \end{aligned}$$

$$data = NC, family = gaussian) \quad (10)$$

Here, s stands for smoothers, bs for basis function, k for knots, cr and ps for cubic spline and P-spline respectively that are types of basis functions.

To compare the predictability of the two markets of the three countries, GAM_1^{NC} and GAM_2^{NC} are used to forecast the spot market and FCR-N revenues. The forecast accuracy is measured by computing mean-absolute-percentage-error (MAPE), mean-squared-error (MAE), and root-mean-squared-error (RMSE). They are called, 'accuracy measures,' and given by the following equations:

$$MAPE = \frac{1}{H}\sum_{h=h0}^{H}\left|\frac{A_h - F_h}{A_h}\right| \quad (11)$$

$$MAE = \frac{\sum_{h=h0}^{H}|F_h - A_h|}{H} \quad (12)$$

$$RMSE = \sqrt{\frac{\sum_{h=h0}^{H}(F_h - A_h)^2}{H}} \quad (13)$$

In the above equations, A_h, is the actual value at hour h, and F_h is the forecasted value at hour h . H are the total hourly observations. As one week of hourly data is predicted in each round, $H = 168$ in each iteration.

In addition to the actual hourly revenues, denoised revenues are also considered. This is achieved by using Fourier analysis. Fourier analysis is a method used for expressing a function as a sum of its periodic components, and for recovering the function from those components. When both the function and its Fourier transform are replaced with discretized counterparts, it is called the discrete Fourier transform (DFT). One of the algorithms used to calculate DFT is fast Fourier transform (FFT). By applying FFT to the revenue time series, a vector of fourier coefficients is computed. This vector is multiplied by its conjugate and divided by its total size to calculate power spectral density (PSD). The PSD helps to assess the power in each of the frequencies of the fourier coefficients with the peaks showing most powerful frequencies. Fourier coefficients with PSD within certain range of the peaks are retained while the rest are considered 'noise,' and removed. By taking inverse fourier transform, the denoised timeseries is reconstructed. The resulting timeseries – henceforth called denoised timeseries – is thus less noisy than original logarithmic timeseries – henceforth called original timeseries. The predictability of original and denoised timeseries is also compared for each country.

3.3 BESS Revenue Comparison

In the Nordics, two types of payments are associated with FCR-N provision. All accepted FCR-N bids receive offered price as availability payments (APs). APs are paid to the participating units for availability per power capacity (€/MW) per hour. The units also receive payments corresponding to the MWh of energy provided or absorbed in response to the system frequency deviations which are known as energy payments (EPs). EPs are thus paid as €/MWh per hour. The revenues earned by providing FCR-N ($FCRN_p$) from hour $h0$ to hour H can thus be written as:

$$FCRN_p = \sum_{h=h0}^{h=H} AP_h^{fcrn} + \sum_{h=h0}^{h=H} EP_h^{fcrn} \qquad (14)$$

To estimate the approximate revenue a BESS owner can earn by bidding in FCR-N markets of Denmark, Finland, and Norway, a BESS unit of 1 MW power capacity and 1MWh energy capacity is considered. Since FCR-N market of Denmark work on pay-as-bid mechanism, all submitted bids lower than the highest accepted bids receive APs for each hour based on the MW capacity. However, Energinet only publishes mean availability prices and not the marginal price per hour. On the other hand, FCR-N market of Norway and Finland works on pay-as-clear mechanism, the published prices are the marginal prices per hour. For 1 MW BESS unit, the hourly forecast revenues obtained from the GAM_2 model are divided by hourly volumes. The resultant hourly prices are considered the price of the submitted bids. It is assumed that all submitted bids are accepted.

The EPs are calculated by estimating the MWh energy delivered by the 1 MWh BESS unit per hour. This is done by applying droop control signal (DCS). DCS determines the power set point of the BESS inverter [39]. It controls the power output of the BESS at different grid frequencies. For Nordic SA, it is set by ENTSO-E as below:

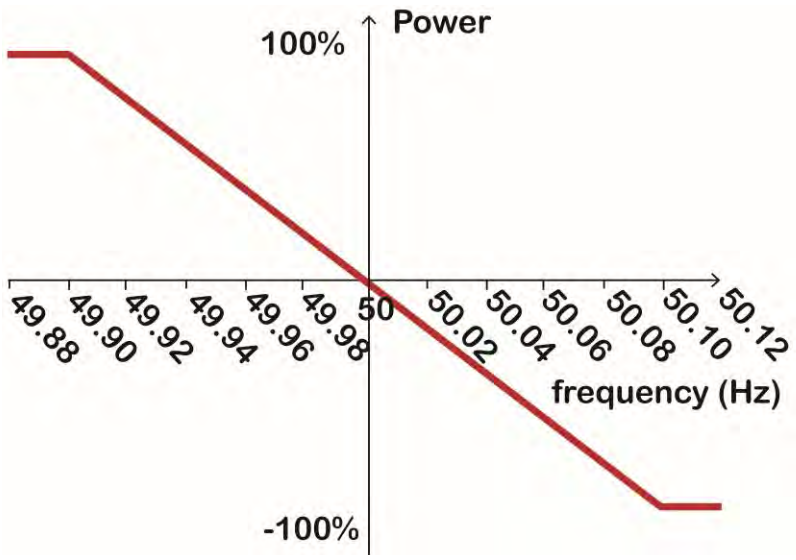


Fig. 3: Droop control signal for FCR-N in the Nordics

The DCS thus governs the response of the participating unit to changes in system frequency and is the follows the same equation for FCR-N provision in all Nordic countries:

$$P_i = \begin{cases} -P_{\max} & f_{\mathrm{i}} > 50.1 \\ \frac{-2\,(f_i - 49.9)+1}{0.2} & 49.9 \le f_{\mathrm{i}} \le 50.1 \\ +P_{\max} & f_{\mathrm{i}} < 49.9 \end{cases} \qquad (15)$$

In the equation, f_{i} is the power system frequency at i[th] second of the day. And P_i is the MW-power of the BESS unit at the i[th] second calculated according to the (15). $+P_{\max}$ is 1 MW, while $-P_{\max}$ is -1 MW. Based on P_i the per second energy (E_i) and per-hour energy content (E_h) that must be supplied or absorbed by the BESS unit is computed. E_h when multiplied by hourly regulation-up (p^{reg-up}) or regulation-down (p^{reg-dn}) prices of each country gives hourly energy payment (EP_h) . For the hour h , EP_h is given by equation 16 when E_h is positive and equation 17 when E_h is negative:

$$EP_h = E_h \times p_h^{reg-up} \qquad (16)$$
$$EP_h = -E_h \times p_h^{reg-dn} \qquad (17)$$

To calculate E_h, P_i for each second of each year is calculated from equation 15, which gives us 1.89x10^8 values. Since FCR-N is a symmetrical product – both up and down regulation must possible – it is assumed that the initial energy content (E_{bat}) is 0.5 MWh. At each second, there is an increment or decrement in the energy-content of the BESS ($E_{bat} \pm E_i$). This results in continuous charging and discharging of the BESS unit. Here, E_i is calculated per second by dividing P_i by 3600 and it is ensured that $E_{bat} \pm E_i$ is maintained within its operational range of the BESS, such that:

$$E_{max} \le E_{bat} \pm E_i \le E_{min} \qquad (18)$$

Here, $E_{min} = 0$ and $E_{max} = 1$. P_i values are summed for each hour and divided by 3600 to calculate E_h for the hour h :

$$E_h = \sum_{i=h}^{i=h+3600} \frac{P_i}{3600} \qquad (19)$$

4 RESULTS AND DISCUSSION

For 2019 – 2021, hourly data on FCR-N prices in – €/MWh – and volumes – in MWh, spot market prices – in €/MWh – and gross consumption – in MWh – is used from [40] for Denmark, [41] for Finland, and [42] for Norway. For Denmark, the hourly volumes remain unchanged throughout the year. For Finland both day-ahead, and year ahead market revenues are considered. Finland's hourly revenues are thus the sum of the revenues from the two markets. The spot market revenues and FCR-N market revenues – in € – of the three countries are calculated in the logarithmic form following equations (5) and (6) and illustrated in Fig.4. in pink for Denmark, green for Finland, and orange for Norway. The grey timeseries on top is the denoised version of the logarithmic timeseries. Moreover, in Table 1, the mean, minimum, and maximum values of spot market and FCR-N market prices, volumes and revenues are shown for the three countries. The overall standard deviation (std), within country std ($wstd$), and between different countries std ($bstd$) is also shown. In most cases, $bstd > wstd$, indicating that the cross-sectional variations in prices, revenues and volumes are higher than the time variations.

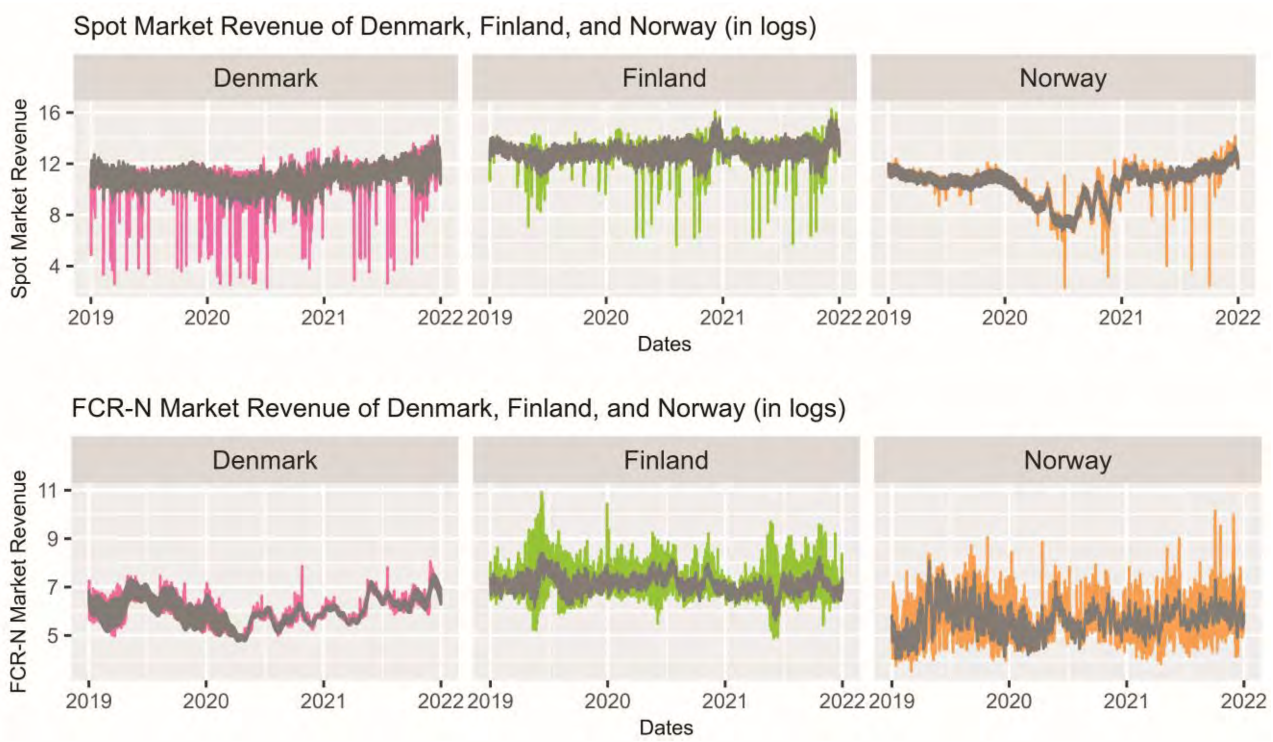


Fig. 4: a) Spot market revenues (in logs) of Denmark, Finland, and Norway, b) Ancillary market revenues (in logs) of Denmark, Finland, and Norway

Table. 1: Summary statistics of data used in the GAMs model

		Denmark			Finland			Norway			Std		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Overall	Within	Between
Spot market	Price	3.67	0.009	6.43	3.90	0.02	6.90	3.22	0.009	6.39	1.04	1.00	0.35
Consumption	Volume	7.31	6.80	7.81	9.12	8.58	9.58	9.62	9.12	10.13	1.01	0.19	1.21
Spot Market	Revenues	10.94	2.29	14.17	13.01	5.62	16.23	10.51	2.29	14.14	1.52	1.05	1.34
FCRN market	Price	3.16	1.93	5.23	2.55	0.0	6.21	1.54	0.18	6.65	1.02	0.77	0.82
FCRN market	Volume	2.83	2.83	2.83	3.29	-2.30	4.72	4.06	1.94	5.01	0.72	0.50	0.62
FCRN market	Revenues	6.0	4.77	8.07	7.13	4.88	10.92	5.61	3.51	10.16	0.92	0.65	0.79

To compare the predictability of the two markets of the three countries, six models are developed, namely: GAM_1^{DK}, GAM_1^{NO}, GAM_1^{FI}, GAM_2^{DK}, GAM_2^{NO}, GAM_2^{FI} based on equations $(7) - (10)$. Two weeks of hourly data is used for fitting these models. Adjusted R-squared – R-sq.(adj) – is recorded as a measure of model-fit accuracy. The fitted model is applied to hourly data of the next week to forecast the respective revenues of each country for each market. MAPE, MAE, and RMSE are recorded to measure the forecast accuracy. Fig.5. illustrates the model-fit of GAM_1^{NC} and GAM_2^{NC} for weeks 3 and 4. The left side of the Fig.5. shows the fitted and forecast model of the original data while the right-hand side shows for the denoised data. For spot markets – upper figures – R-sq.(adj) of Denmark, Finland and Norway is 0.77, 0.67, and 0.79. for original and 0.76,0.95, and 0.99 for the denoised time series. However, for their respective FCR-N markets – bottom figures, it is 0.92, 0.46, and 0.06 for original 0.99, 0.94, and 0.72 for the denoised time series. In addition to the model fit, Fig.5. also illustrates the forecast of the next week – week 5 – obtained from the fitted models GAM_1^{NC} and GAM_2^{NC}. The MAPE for the spot market of Denmark, Finland and Norway is 0.91%, 0.74%, and 0.94% respectively. However, it is relatively higher, i.e. 1.52%, 2.26% and 4.34% for their respective FCR-N markets.

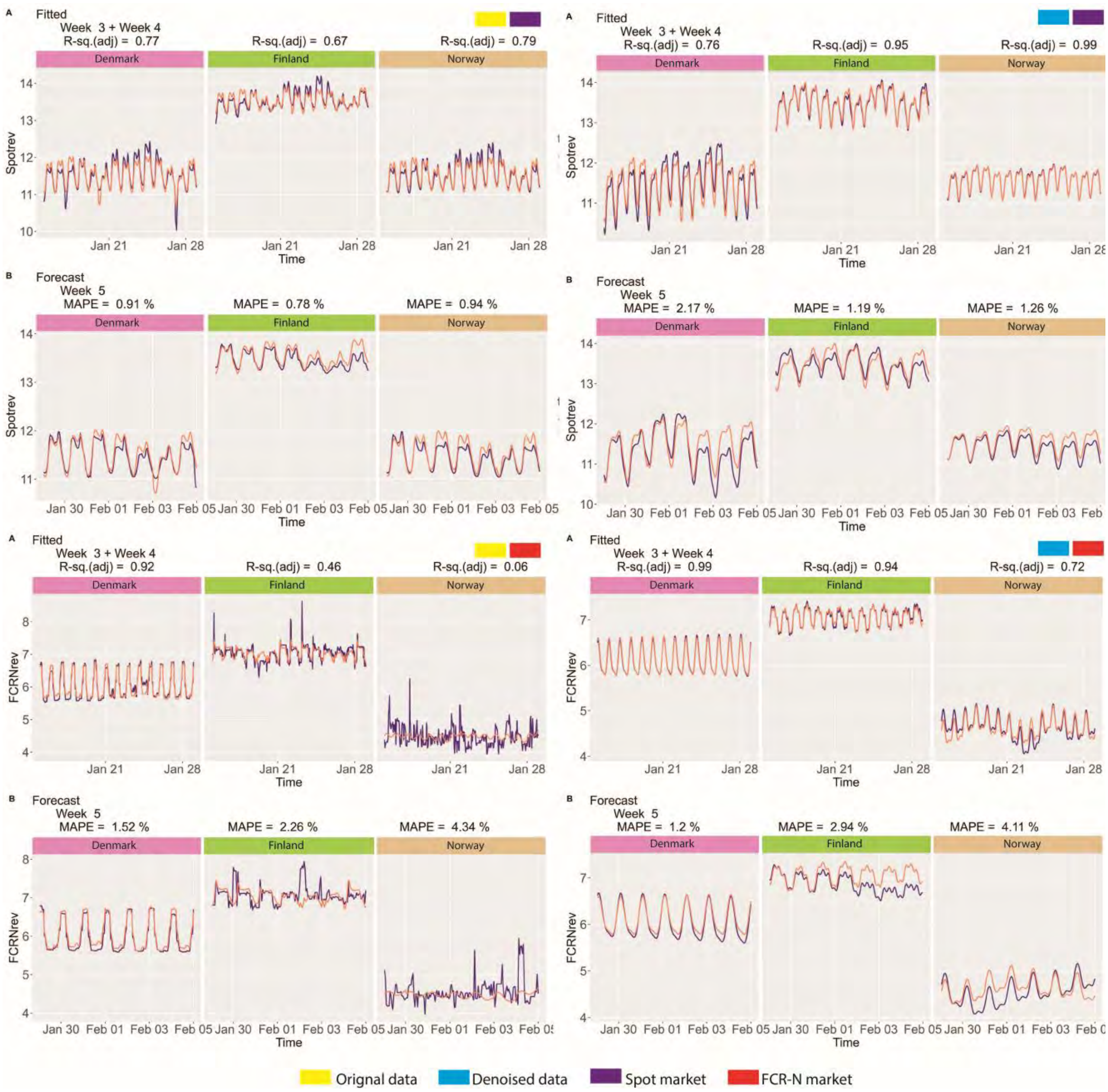


Fig. 5: Fitted and forecast revenues of week 3 – 5 using original and denoised data of spot and FCR-N markets of Denmark, Finland and Norway

The process of fitting GAM_1^{NC} and GAM_2^{NC} on two consecutive weeks and forecasting the revenues of the next week is repeated for all weeks of 2019 – 2021. In Fig. 6. the hourly forecasted and actual values are compared for each week based on equations (11). The percentage of weeks showing a MAPE within the range of 0-5%, 5-10%, and 10-15% is shown. For Denmark, the MAPE of 60.65% of the weeks lies within 0-5% for its spot market, while MAPE of 87.1% of the weeks lie within that range for its FCR-N market. Thus, showing a higher predictability of its FCR-N market revenues. Contrarily, for Finland and Norway, MAPE of 85.16% of the weeks is in the range of 0-5% for their respective sport markets, while for their FCR-N market, the MAPE of 53.55% and 7.1% lies within that range, thus showing lower predictability of their FCR-N market. Moreover, the mean, minimum, and maximum values of R-sq.(adj), MAPE, MAE, and RMSE are also recorded in the table in Appendix A. The table shows that the mean R-sq.(adj) is lower for FCR-N markets of Finland and Norway as compared to their spot markets. The values also show that in the denoised timeseries, the predictability of FCR-N markets of Finland, and Norway improves more than their spot markets. Moreover, in appendix B, 2-D plots of hourly and daily smoothers $f(hours_i), f(days_i)$ and 3-D plots of the interaction smoothers $f(hours_i \times days_i)$ are also shown for the two markets. The shapes of these smoothers are similar for the spot markets of the three countries. They show relatively higher values at mid-day, and mid-week with two prominent humps for all three countries. The beginning and end of the day shows decreasing trends in the smoothers, while beginning and end of the week show increasing trend. However, for FCR-N markets, interaction smoothers are different for each country. For Denmark, contrary to its spot market smoothers, FCR-N market smoothers show relatively lower values mid-day, and mid-week. FCR-N smoothers of Finland, and Norway however do not show this behavior.

Based on these results the following conclusions can be drawn:

1. Spot markets of Finland and Norway are relatively more predictable based on the smoothers $f(hours_i), f(days_i)$ and $f(hours_i \times days_i)$ as compared to their FCR-N markets.

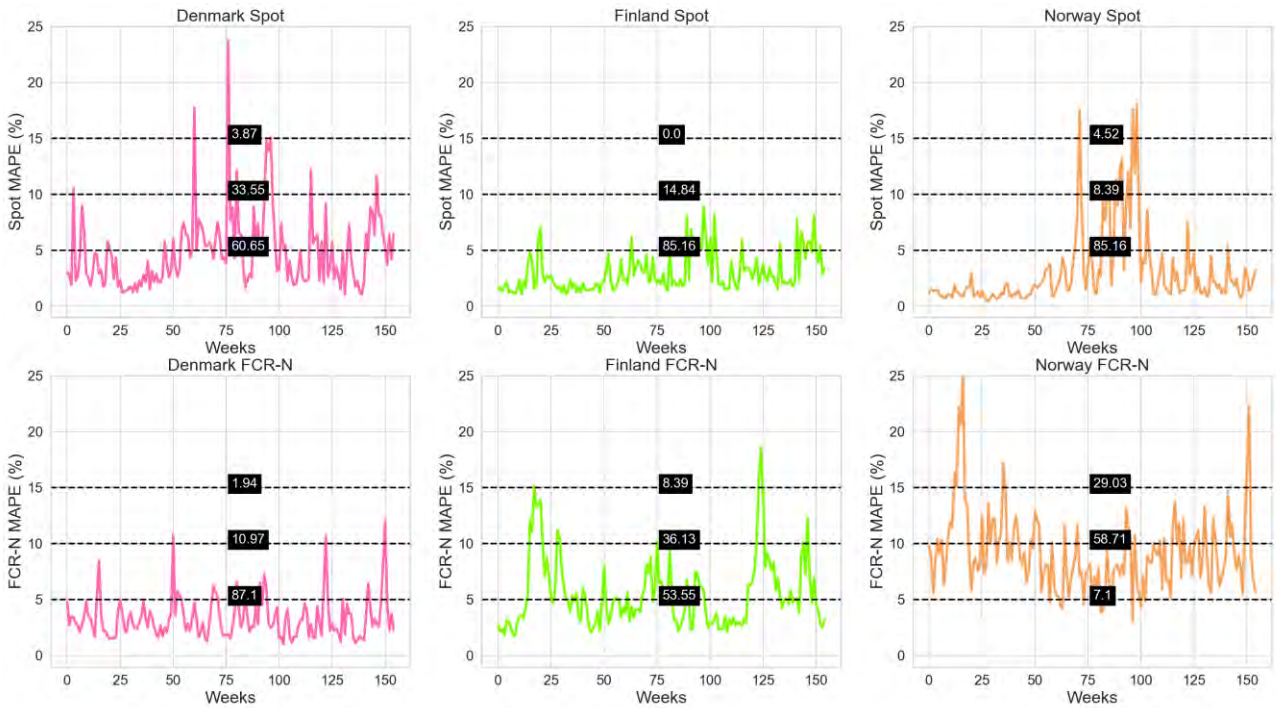


Fig. 6: Percentage of weeks with MAPE falling between 0-5%, 5-10%, and 10-15% for spot and

2. Spot markets of Denmark, Finland, and Norway show relatively similar hourly and weekly behavior. FCR-N market of Denmark is relatively more predictable than FCR-N markets of Finland, and Norway
3. FCR-N markets of Denmark is relatively more predictable than its spot market
4. A higher percentage of weeks show lower MAPE for the spot markets of Norway and Finland as compared to their FCR-N markets, thus indicating higher predictability of the former.
5. Denoised FCR-N revenue timeseries of Denmark, Finland, and Norway show higher improvement in predictability as compared to their denoised spot market timeseries thus implying FCR-N markets in general are noisier than spot markets

It is important to note that since the main driver of FCR-N market is the frequency of the power grid, the fluctuations of which are highly unlikely to be predicted accurately, this makes FCR-N markets less predictable. In the Nordics, main providers of FCR-N reserves are hydro-power plants [43]. The fluctuations in the stored MWh of hydro reserves therefore are one of the drivers of Nordic FCR-N prices as shown in Appendix C.

In addition to the predictability comparison, the total revenues earned from the two markets of the three countries are also compared. Fig.7. shows a comprison of their log-reveneus. Since spot markets fulfill the total energy demand of the country their yearly log-revneues are higher than that of FCR-N markets – that fulfill only the frequency control demand. However, the log-revenues of spot markets of the three Nordic countries are similar, so are their FCR-N market revenues. Finland's revenues are relatively higher than Denmark's and Norway's for all three years in both markets. However, the Denmark's FCR-N market revunes would be slightly higher than that shown in Fig.5. its recorded APs are the mean value of accepted bids per hour, while that of the Finland, and Norway are the maximum value. Fig.7. also shows that if the discrepancy in revenues due to the size difference of the countries are ignored, their spot and FCR-N markets generate similar revenues. For indivudal entities bidding in FCR-N markets of these countries, trends in per unit revenues may not essentially be compareable to the trends in overall market revenues.

Fig.7. Yearly revenue comparison of spot and FCR-N markets of Denmark, Finland, and Norway

To determine the approximate revenues a 1MW/1MWh BESS owner may earn from FCR-N markets of each country equations $(14) - (19)$ are used. A relative comparison between potential earnings in different Nordic countries is shown in Fig.8. The charge/discharge cycles of the BESS unit following equations $(15) - (19)$. are shown in Appendix D. The potential earnings for a 1 MW/1MWh BESS are relatively higher in Denmark, as compared to the other two countries. Contrarily, they are significantly lower in Norway. Denmark's higher revenues can be attributed to the higher predictability and higher availability payments of its FCR-N market. On the other hand, lower availability payments in Norway lead to lower BESS revenues. This is in contrast to Norway's total FCR-N market revenues of Fig.7. which are comparable to the other two countries. This difference is due to the fact that Norway's hourly FCR-N market volumes are higher than its hourly availability prices thereby increasing its total market revenues but not the in-

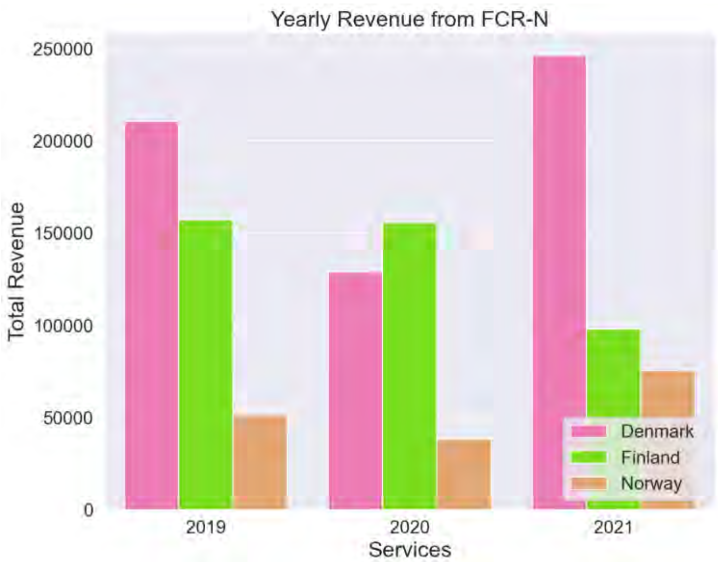


Fig. 8: Revenue comparison for 1MW/1MWh BESS in Nordic FCR-N markets

dividual revenues of a BESS unit – since availability payments mainly depend on market prices and not the volumes. The revenues shown in Fig.8. are a sum of revenues from availability payments and energy payments. However, energy payments revenues are in general quite lower as shown in Appendix E.

5 CONCLUSIONS

In this paper we used three years of hourly data to develop forecast models of spot and FCR-N market revenues of Denmark, Finland, and Norway. Daily and weekly smoothers and their interactions are used to fit the models. The results show similar interaction smoothers capture the behavior of the spot markets of the three countries, thereby indicating similarity in market behavior and predictability. However, the smoothers differ in shape for their respective FCR-N markets, thereby indicating dissimilarity in behavior and predictability. Moreover, even though denoising the revenue timeseries of both markets, improves the predictability, however, the improvement is higher for FCR-N markets of Finland and Norway indicating higher volatility. Furthermore, Nordic FCR-N markets are found to be less predictable than spot markets. However, Denmark's FCR-N market is an exception, the higher predictability of which, may be because of the difference in its market pricing mechanism as well as volume requirements. Furthermore, a revenue comparison for 1MW/1MWh BESS operating in different Nordic countries is also conducted. It is assumed that the BESS submit bids based on the previously developed FCR-N market forecast of each country, and all submitted bids are accepted. The results show the BESS unit can earn comparable revenues in Denmark and Finland; however, they are comparatively lower in Norway.

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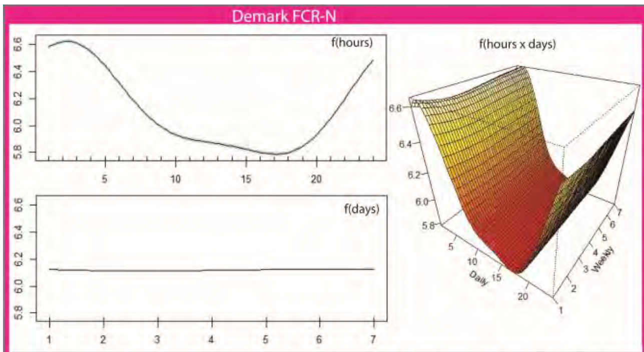
7 APPENDIX

Appendix A: Accuracy Measures of Forecast

			Denmark			Finland			Norway		
			Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum
	Spot market	R-squared	0.59	0.08	0.96	0.63	0.3	0.92	0.56	0.12	0.94
	Spot market smooth	R-squared	0.78	0.24	0.98	0.78	0.38	0.99	0.82	0.2	1
	FCR-N market	R-squared	0.58	0.04	0.98	0.34	0.07	0.86	0.32	0.04	0.79
	FCR-N market smooth	R-squared	0.79	0.24	1	0.67	0.16	0.98	0.49	0	0.95
	Spot market	MAPE	4.9	0.67	24.3	3.09	0.54	9.51	2.5	0.27	16.1
	Spot market smooth	MAPE	3.43	0.89	14.97	2.16	0.55	8.1	2.76	0.17	19.23
	FCR-N market	MAPE	3.21	0.55	14.3	5.62	1.49	18.1	9.48	2.8	24.1
	FCR-N market smooth	MAPE	2.67	0.1	9.1	2.68	0.33	10.89	6.57	1.18	22.51
	Spot market	MAE	0.46	0.07	1.66	0.38	0.07	1.35	0.31	0.03	1.93
	Spot market smooth	MAE	0.37	0.1	1.29	0.28	0.07	1.14	0.27	0.02	2
	FCR-N market	MAE	0.19	0.03	1.08	0.4	0.1	1.4	0.53	0.17	1.64
	FCR-N market smooth	MAE	0.16	0.01	0.63	0.19	0.02	0.76	0.37	0.07	1.56
	Spot market	RMSE	0.69	0.09	2.27	0.52	0.09	1.46	0.39	0.05	1.98
	Spot market smooth	RMSE	0.44	0.13	1.52	0.32	0.09	1.15	0.29	0.02	2.01
	FCR-N market	RMSE	0.22	0.04	1.15	0.5	0.14	1.74	0.67	0.22	1.77
	FCR-N market smooth	RMSE	0.17	0.01	0.63	0.21	0.03	0.77	0.42	0.09	1.6

Appendix B: GAM Smoothers

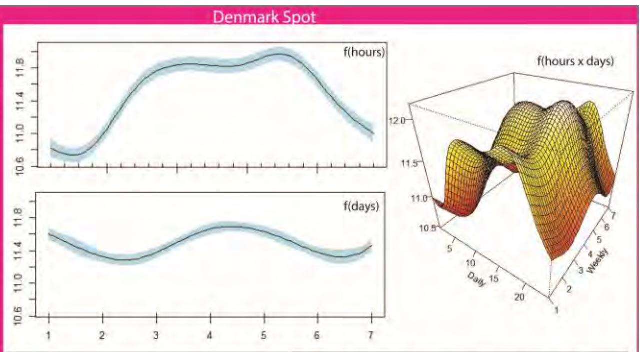
Demark FCR-N



Component	Term	Estimate	Std Error	t-value	p-value	
A. parametric coefficients	(Intercept)	6.120	0.001	4,133.260	0.0000	***
Component	**Term**	**edf**	**Ref. df**	**F-value**	**p-value**	
B. smooth terms	s(Daily)	16.571	19.631	1,986.776	0.0000	***
	s(Weekly)	2.998	3.476	3.901	0.0046	**
	ti(Daily,Weekly	7.513	10.570	2.310	0.0124	*

Signif. codes: 0 <= '***' < 0.001 < '**' < 0.01 < '*' < 0.05

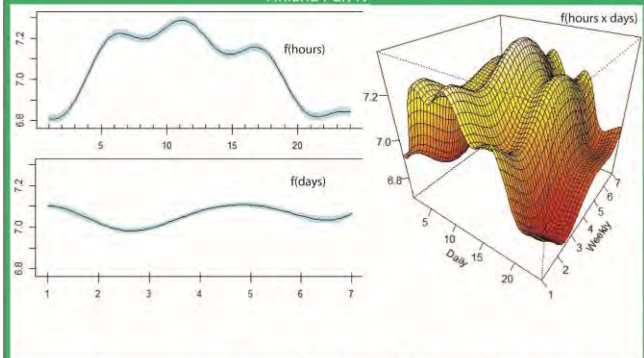
Denmark Spot



Component	Term	Estimate	Std Error	t-value	p-value	
A. parametric coefficients	(Intercept)	11.489	0.014	838.863	0.0000	***
Component	**Term**	**edf**	**Ref. df**	**F-value**	**p-value**	
B. smooth terms	s(Daily)	9.775	12.133	78.535	0.0000	***
	s(Weekly)	5.124	5.619	16.080	0.0000	***
	ti(Daily,Weekly)	3.108	3.709	1.773	0.1773	

Signif. codes: 0 <= '***' < 0.001 < '**' < 0.01 < '*' < 0.05

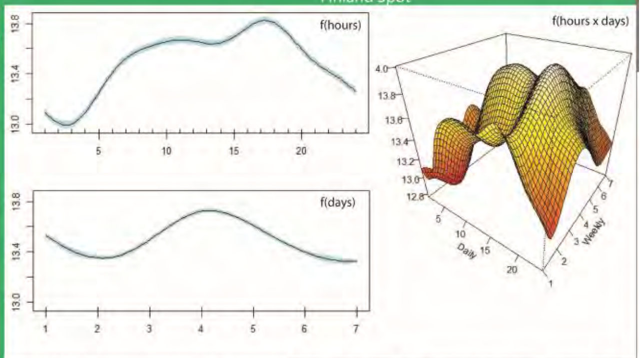
Finland FCR-N



Component	Term	Estimate	Std Error	t-value	p-value	
A. parametric coefficients	(Intercept)	7.060	0.003	2,811.299	0.0000	***
Component	**Term**	**edf**	**Ref. df**	**F-value**	**p-value**	
B. smooth terms	s(Daily)	16.529	19.593	226.444	0.0000	***
	s(Weekly)	5.599	5.914	39.540	0.0000	***
	ti(Daily,Weekly)	16.941	23.605	10.530	0.0000	***

Signif. codes: 0 <= '***' < 0.001 < '**' < 0.01 < '*' < 0.05

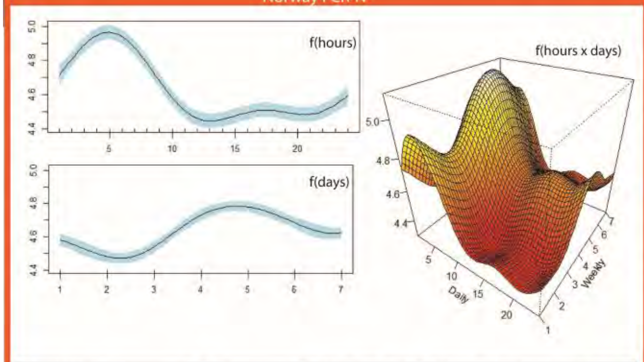
Finland Spot



Component	Term	Estimate	Std Error	t-value	p-value	
A. parametric coefficients	(Intercept)	13.491	0.004	3,697.075	0.0000	***
Component	**Term**	**edf**	**Ref. df**	**F-value**	**p-value**	
B. smooth terms	s(Daily)	14.626	17.710	261.666	0.0000	***
	s(Weekly)	5.589	5.910	228.088	0.0000	***
	ti(Daily,Weekly)	22.209	28.708	12.951	0.0000	***

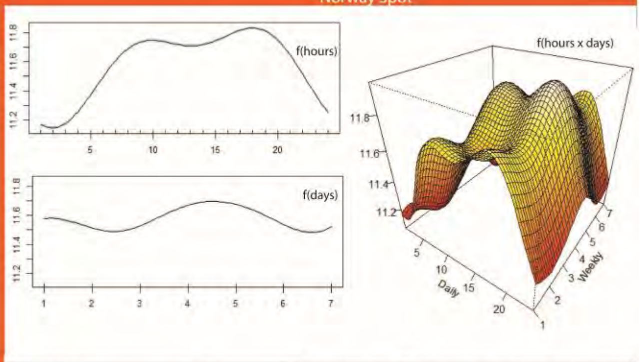
Signif. codes: 0 <= '***' < 0.001 < '**' < 0.01 < '*' < 0.05

Norway FCR-N



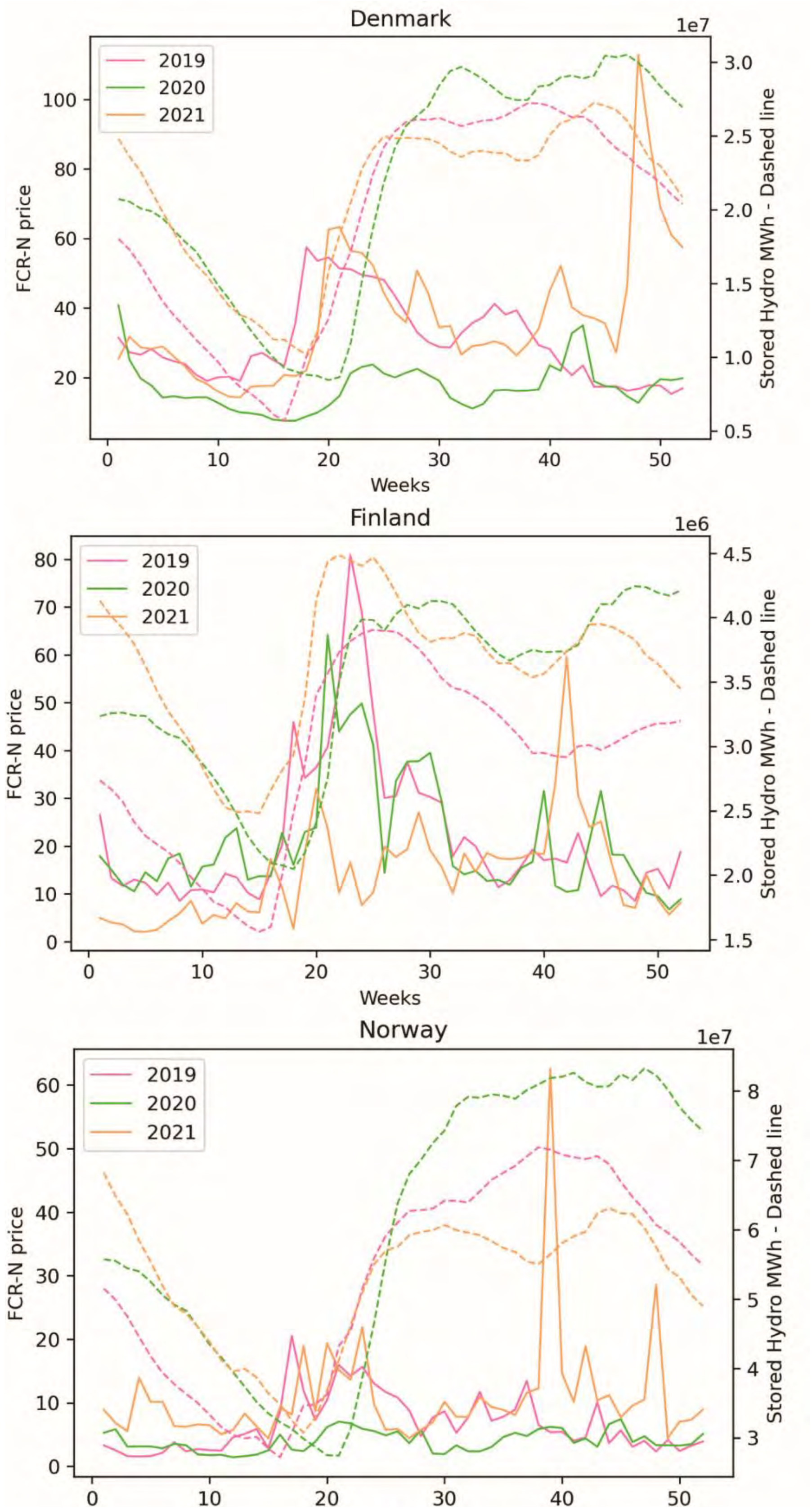
Component	Term	Estimate	Std Error	t-value	p-value	
A. parametric coefficients	(Intercept)	4.631	0.007	653.184	0.0000	***
Component	**Term**	**edf**	**Ref. df**	**F-value**	**p-value**	
B. smooth terms	s(Daily)	8.807	10.953	59.123	0.0000	***
	s(Weekly)	4.792	5.311	37.181	0.0000	***
	ti(Daily,Weekly)	3.560	4.005	5.385	0.0003	***

Norway Spot

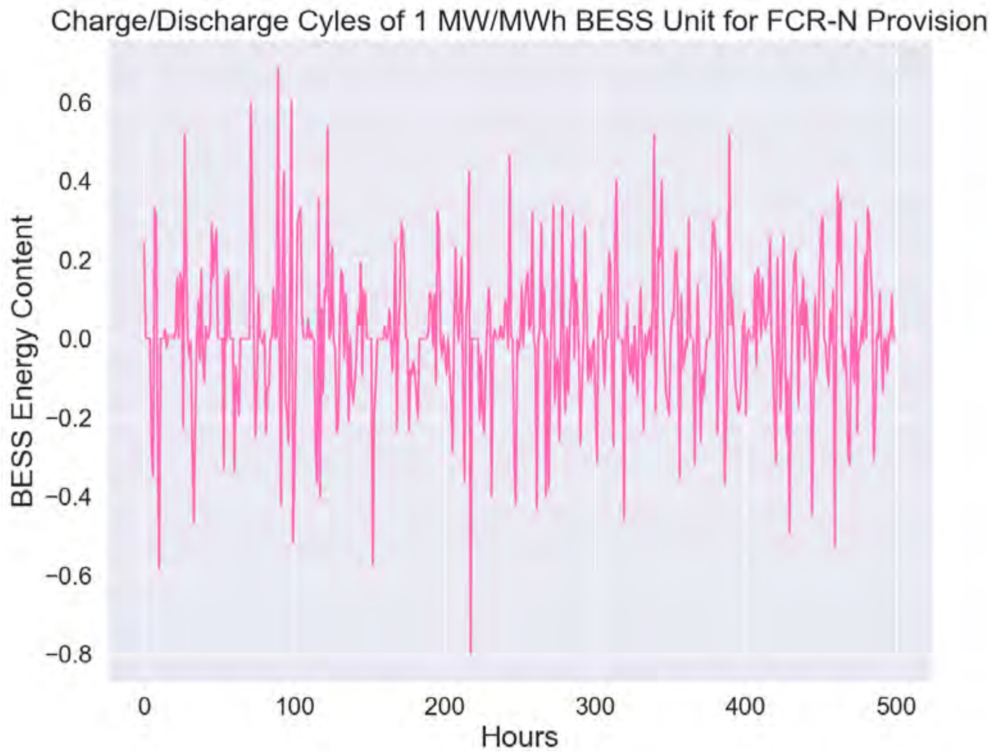


Component	Term	Estimate	Std Error	t-value	p-value	
A. parametric coefficients	(Intercept)	11.575	0.001	9,945.825	0.0000	***
Component	**Term**	**edf**	**Ref. df**	**F-value**	**p-value**	
B. smooth terms	s(Daily)	18.100	20.923	1,832.467	0.0000	***
	s(Weekly)	5.956	5.999	514.534	0.0000	***
	ti(Daily,Weekly)	12.815	16.644	33.759	0.0000	***

Appendix C: Relation b/w FCR-N prices and Stored Hydro MWh



Appendix D: Charge/Discharge Cycles of 1MW/1MWh BESS



Appendix E: Comparison b/w availability and energy payments