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Can Energy Communities Provide Ancillary Services? A Stochastic Program for Aggregated Bidding in the Nordic Ancillary Markets

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***Abstract*—With the volume of ancillary services required in the Nordic synchronous grid expected to grow in the next ten years, more ancillary services will need to be procured from smaller consumers. This work proposes a two-stage stochastic program that considers bidding a variety of flexible assets into the ancillary markets of the Nordic synchronous grid. The first stage determines optimal bid quantities in the various ancillary markets, while the second stage includes activation and delivery of the ancillary services. An in-sample and out-of-sample analysis based on historical data from the Nordic synchronous grid is performed to evaluate the model's performance and assess which markets are most beneficial in the current market framework. The results show that the community decides to bid almost exclusively into Frequency Containment Reserve (FCR-N and FCR-D) markets, with a small amount of bidding into the Manual Frequency Recovery Reserve (mFRR). Additionally, an out-of-sample analysis shows that with an in-sample size of only 100 scenarios, ancillary services can be reliably delivered in 96.8% of out-of-sample scenarios.**

***Index Terms*—Ancillary Services, Energy Communities, Flexibility, Stochastic Optimization**

I. INTRODUCTION

As the world begins to enact the changes necessary for a carbon-free future, power systems are experiencing an increasing penetration of variable renewable energy sources into the system. Due to the increased volatility stemming from these sources and the loss of operational flexibility from phasing out of conventional fossil fuel-based generation, the need for ancillary services will become more pronounced. For example, in Denmark, where 44% of annual energy production comes from wind power [1], the TSO projects that ancillary service market quantity requirements could increase by as much as 300% by 2032 [2]. Meeting this demand will require significantly increasing the number and variety of actors providing ancillary services. One key actor that still needs to be successfully integrated into the ancillary market framework is flexible prosumers and consumers on the distribution level. This has not been realized on a large scale due to many challenges, such as the minimum bid size requirements of the ancillary markets and the complexities of asset control. To resolve these challenges, novel ideas and roadmaps, such as Market Model 3.0 in Denmark [3], look to remove barriers to the entry of smaller local consumers into power markets. One framework for integration of smaller consumers mentioned in [3] is the energy community. Energy communities were first introduced by the European Union (EU) in [4] as a means to foster local participation in the green transition. Part of the goal of energy communities is to enable greater consumer participation in power markets by aggregating energy community members' demand and production profiles. The EU's support for energy communities was further strengthened in [5], where new rules were established to put energy communities on equal footing with larger market players. With these regulations being implemented across Europe, the participation of local energy actors in the larger grid, especially ancillary markets, will grow significantly in the coming years. Therefore, this paper investigates the optimal bidding strategy of an energy community within the ancillary service market structure of the Nordic Synchronous Area.

A. Literature review

Local energy system trends have been the subject of much research over the past years. In [6], an overview of the different trends and categories of local energy usage is presented. [6] groups the local energy framework into three categories, namely peer-to-peer (P2P), transactive energy (TE), and community self-consumption (CSC). The traditional implementation of energy communities, namely the aggregation and shared trading of community members' consumption and production profiles for economic benefits, aligns directly with the CSC framework. In [6], only 6 of the 139 studied papers look at CSC. The CSC research identified in [6] focuses on reducing energy costs by using the synergies created by bundling load and production profiles together and buying/selling this electricity on the wholesale power market. None of these studies examine grid and system reliability or the added revenue possible from offering such services, specifically bidding and providing ancillary services.

Various works can be found that investigate bidding for ancillary services from different kinds of assets and demand profiles. For example, [7] looks at a supermarket freezer and investigates whether shifting load to avoid high prices or offering an ancillary service is more profitable. Furthermore, [8] looks at the participation of a single zinc furnace in both primary and tertiary reserves to determine how much additional profit can be obtained by offering these services with optimal control. Outside of single assets, [9] looks at a

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portfolio of profiles and improve their aggregated bidding into an ancillary service market to increase the collective revenue through synergistic effects.

More specifically, many have looked at battery systems and their role in ancillary service markets, as the characteristics of batteries make them very suitable for ancillary service provision. For example, there have been investigations into how battery systems should be placed to most optimally deliver grid services [10] and the feasibility of providing ancillary services from batteries. Others have investigated the feasibility of revenue stacking using ancillary services and conventional load shifting [11], while others have also done in-depth data analysis to determine the best business cases for providing ancillary services from batteries [12]. These studies do not consider the bidding side, but this has also been considered in other studies such as [13] and [14]. [13] presents a market design for the trade of ancillary services and devises an algorithm for bidding into the proposed market framework but does not look at a concrete real-world example of providing ancillary services. The closest work to this paper is [14], which looks at bidding into all primary reserves in the Nordic synchronous system. However, [14] only looks at the modelling of battery systems and no other type of asset or consumer, nor does he consider bidding into the tertiary markets. Additionally, this paper does not devise a model which bids into multiple markets, but rather assumes a forecast of which market will be most profitable and only bids into that market.

B. Contributions

Given the above literature review, a research gap has been identified for community self-consumption models that consider multi-market ancillary bidding. While many works investigate the participation of either single loads or aggregated portfolios in the Nordic ancillary markets, none of these works look at this from the community self-consumption perspective. To the authors' knowledge, this paper presents the first two-stage stochastic program looking at community self-consumption with simultaneous ancillary service bidding and provision from 4 different ancillary markets.

The remainder of this paper is structured as follows: Section II provides a brief overview of the Nordic ancillary service markets. Section III presents the different elements of the two-stage stochastic program. Section IV presents an overview of the scenario generation and data used in the case study and presents results. Lastly, Section V draws conclusions based on the results and presents some future work.

II. BACKGROUND

A. Nordic ancillary service markets

In the Nordic synchronous grid there are 5 ancillary services responsible for maintaining the frequency of the power system. Listed from fastest to slowest response time, these are the Fast Frequency Reserve (FFR), Frequency Containment Reserve for disturbances (FCR-D) and normal operation (FCR-N), automatic Frequency Restoration Reserve (aFRR), and manual Frequency Restoration Reserve (mFRR). The faster services aim to stop the initial frequency drop due to a fault, while the slower reserves aim to return the frequency back to its nominal state. For the reader's convenience, a general overview of the four relevant ancillary service markets is given in Table I. A more in-depth overview of the Nordic ancillary markets can be found in both [12] and [15]. As aFRR is the only service that is not procured daily, it is not considered in the two-stage model developed in this paper.

III. FORMULATION

This section introduces the base community model, before subsequently introducing the constraints and variables used to model the different markets one by one.

A. Base Community Model

The base model is given in (1). This model considers three different types of prosumers: inflexible prosumers, $n \in N$, shiftable prosumers, $f \in F$, and battery prosumers, $e \in E$. These groups are all part of the set of community members, $c \in C$. It is worth noting that the base community model does not have any first-stage decisions, as it only looks at operation throughout the day. For continuity, as first-stage bidding decision variables are introduced later, all variables and parameters have been denoted with a scenario index $s \in S$.

$$\min \sum_{s \in S} \pi_s \left[\sum_{t \in T} \lambda^{\text{im}}_{t,s} p^{\text{im}}_{t,s} - \lambda^{\text{ex}}_{t,s} p^{\text{ex}}_{t,s} \right] \tag{1a}$$

$$\text{s.t} \sum_{c \in C} p_{c,t,s} - p^{\text{im}}_{t,s} + p^{\text{ex}}_{t,s} = 0 \qquad \forall t \in T \tag{1b}$$

$$p^{\text{ex}}_{t,s} \geq 0 \qquad \forall t \in T \tag{1c}$$

$$p^{\text{im}}_{t,s} \geq 0 \qquad \forall t \in T \tag{1d}$$

The objective function of the base community model, (1a), is a simple scenario weighted cost minimization function for the daily consumption of the community considering day-ahead prices. The imported power from the grid, $p^{\text{im}}_{t,s}$ is multiplied by the import power prices, $\lambda^{\text{im}}_{t,s}$, and subtract the product of the exported energy $p^{\text{ex}}_{t,s}$ and the export price $\lambda^{\text{ex}}_{t,s}$ and then sum over the scenarios while weighting these for their probability π_s. The import and export prices are different due to different import and export tariffs imposed by the transmission and distribution system operators. (1b) ensures that the sum of power consumption, $p_{c,t,s}$ is equal to the power exchanged with the grid at any point in time, while (1c) and (1d) ensure that the capacity of the grid connection is not exceeded. To model the different kinds of prosumers mentioned before, three sets of constraints are introduced. Firstly, all inflexible consumers are subject to a single constraint (1e), which ensures that their power consumption is equal to the difference in their solar production, $PV_{n,t,s}$, and demand, $D_{n,t,s}$ at any time.

$$p_{n,t,s} + \text{PV}_{n,t,s} + \text{D}_{n,t,s} = 0 \qquad \forall n \in N, t \in T \tag{1e}$$

Meanwhile, the shiftable prosumers in the community are subject to a set of three constraints. (1f) is their power balance

TABLE I
SUMMARY TABLE OF CHARACTERISTICS OF THE DIFFERENT ANCILLARY SERVICES IN THE NORDIC SYNCHRONOUS GRID, SPECIFICALLY DK2.

Characteristic	**FFR**	**FCR-D**	**FCR-N**	**mFRR**
Response time	0.7s / 1.0s / 1.3s	50% in 5s, 100% in 30s	150s	15min
Reservation payment	Marginal Pricing	Pay-as-Bid	Pay-as-Bid	Marginal Pricing
Activation payment	No	No	Yes	Yes
Activation frequency	49.5 Hz / 49.6 Hz / 49.7 Hz	≤49.9Hz	between 49.9 - 50.1Hz	N/A
Last gate closure	15:00 D-1	15:00 D-1	15:00 D-1	9:30 D-1

constraint, where $d_{f,t,s}$ is their demand at any time. Constraint (1g) ensures that the total energy consumed in the flexible time window, T_{flex}, is equal to the total demand that would have occurred in that time window without any load shifting. Lastly, constraint (1h) ensures that any consumption outside of the flexible time window is the same as the consumption in the baseline demand scenario.

$$p_{f,t,s} + \mathrm{PV}_{f,t,s} - d_{f,t,s} = 0 \qquad \forall f \in F, t \in T \tag{1f}$$

$$\sum_{t \in T_{\text{flex}}} d_{f,t,s} - \sum_{t \in T_{\text{flex}}} \mathrm{D}_{f,t,s} = 0 \quad \forall f \in F \tag{1g}$$

$$d_{f,t,s} = \mathrm{D}_{f,t,s} \qquad \forall f \in F, t \in T \backslash T^{\text{flex}} \tag{1h}$$

Lastly, the battery prosumers must be considered. (1i) is similar to the power balance equation for other consumer types but now includes battery charge, $b^{\text{ch}}_{e,t,s}$, and discharge, $b^{\text{dis}}_{e,t,s}$. Constraints (1j) - (1l) track the state of charge of the battery, $\mathrm{SOC_{e,t,s}}$ throughout the day, while constraints (1m) - (1o) ensure that neither the maximum charge/discharge rating nor the maximum energy storage capacity of the battery is exceeded at any point.

$$\begin{aligned} p_{e,t,s} + PV_{e,t,s} - D_{e,t,s} \\ - b^{\text{ch}}_{e,t,s} + b^{\text{dis}}_{e,t,s} = 0 \qquad \forall e \in E, t \in T \end{aligned} \tag{1i}$$

$$\begin{aligned} \mathrm{SOC}_{e,t,s} = \mathrm{SOC}_{e,t-1,s} \\ + \eta b^{\text{ch}}_{e,t,s} - \frac{1}{\eta} b^{\text{dis}}_{e,t,s} \qquad \forall e \in E, t \in T \backslash 1, T^{\max} \end{aligned} \tag{1j}$$

$$\begin{aligned} \mathrm{SOC}_{e,t=1,s} = 0.5 \cdot \bar{S}_e \\ + \eta b^{\text{ch}}_{e,t=1,s} - \frac{1}{\eta} b^{\text{dis}}_{e,t=1,s} \quad \forall e \in E \end{aligned} \tag{1k}$$

$$\mathrm{SOC}_{e,t=T^{\max},s} = 0.5 \cdot \bar{S}_e \qquad \forall e \in E \tag{1l}$$

$$b^{\text{ch}}_{e,t,s} \leq \bar{b}_e \qquad \forall e \in E, t \in T \tag{1m}$$

$$b^{\text{dis}}_{e,t,s} \leq \bar{b}_e \qquad \forall e \in E, t \in T \tag{1n}$$

$$\mathrm{SOC}_{e,t,s} \leq \bar{S}_e \qquad \forall e \in E, t \in T \tag{1o}$$

Together, all of (1), with objective function (1a) and constraints (1b)-(1o) make up a simple single-stage linear program that optimizes community self-consumption without considering ancillary markets. This model will now be extended to account for the different ancillary markets.

B. FFR

As FFR requires fast responses, it is assumed that only battery prosumers can provide this service. Bids accepted in the FFR market only receive a reservation payment [1]. Therefore a single term for the revenue from the FFR market is added to the base model objective function as shown in (2a), but only summed over the subset of battery prosumers.

$$\begin{aligned} \min \sum_{s \in S} \pi_s \sum_{t \in T} \Big[\lambda^{\text{im}}_{t,s} p^{\text{im}}_{t,s} - \lambda^{\text{ex}}_{t,s} \Big(p^{\text{ex}}_{t,s} - \sum_{e \in E} p^{\text{FFR}\uparrow}_{e,t,s} \Big) \\ - \lambda^{\text{FFR}}_{t,s} \sum_{e \in E} p^{\text{FFR}}_{e,t} \Big] \end{aligned} \tag{2a}$$

$$\text{s.t. (1b)} - \text{(1d)} \tag{2b}$$

$$p^{\text{FFR}\uparrow}_{e,t,s} = y^{\text{act,FFR}}_{t,s} p^{\text{FFR}}_{e,t} \qquad \forall e \in E, t \in T, s \in S \tag{2c}$$

There are two new variables introduced in this implementation; the first stage reserve bid quantity, $p^{\text{FFR}}_{e,t}$, which is not scenario indexed as it is the same across all scenarios, and an auxiliary variable to track the activated energy in a given scenario, $p^{\text{FFR}\uparrow}_{e,t,s}$. This is calculated based on a pre-processed scenario-specific activation factor, $y^{\text{act,FFR}}_{t,s}$, which always has a value between 0 and 1, depending on how much the service was activated in a given hour. The calculation of $y^{\text{act,FFR}}_{t,s}$ is explained in IV-A. In addition to the new FFR revenue term, the change in export to the grid at a given time due to the provided FFR service must also be considered. This results in a change in the export revenue term compared to the objective function in the base model, (1a). Additionally, the power and energy reserved and activated for FFR must be considered in the battery system. As FFR is only an up-regulation service, it is considered together with the battery discharge. The modified battery system constraints can be seen in (2d) - (2h), with the addition of the unchanged constraints (1l),(1m), and (1o) which are not shown here. Note that (2g) and (2h) use the first stage reservation variable, as opposed to the activated energy. This is done to ensure that full activation is always within the physical limitations of the battery system.

$$\begin{aligned} p_{e,t,s} + \mathrm{PV}_{e,t,s} - \mathrm{D}_{e,t,s} - b^{\text{ch}}_{e,t,s} + (b^{\text{dis}}_{e,t,s} + p^{\text{FFR}\uparrow}_{e,t,s}) = 0 \\ \forall e \in E, t \in T \end{aligned} \tag{2d}$$

$$\begin{aligned} \mathrm{SOC}_{e,t,s} = \mathrm{SOC}_{e,t-1,s} + \eta b^{\text{ch}}_{e,t,s} - \frac{1}{\eta} \Big(b^{\text{dis}}_{e,t,s} + p^{\text{FFR}\uparrow}_{e,t,s} \Big) \\ \forall e \in E, t \in T \backslash 1, T^{\max} \end{aligned} \tag{2e}$$

$$\begin{aligned} \mathrm{SOC}_{e,t=1,s} = 0.5 \cdot \bar{\mathrm{S}}_e + \eta b^{\text{ch}}_{e,t=1,s} - \frac{1}{\eta} \Big(b^{\text{dis}}_{e,t=1,s} + p^{\text{FFR}\uparrow}_{e,t,s} \Big) \\ \forall e \in E \end{aligned} \tag{2f}$$

$$b^{\text{dis}}_{e,t,s} + p^{\text{FFR}}_{e,t} \leq \bar{b}_e \qquad \forall e \in E, t \in T, s \in S \tag{2g}$$

$$\mathrm{SOC}_{e,t,s} \geq p^{\text{FFR}}_{e,t} \qquad \forall e \in E, t \in T, s \in S \tag{2h}$$

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[1] It is assumed that all bids from the community are below the marginal price of the FFR market and are therefore always accepted.

C. FCR-D

The implementation of the FCR-D market is very similar to that of the FFR market, the main difference being that it is no longer a marginal pricing market, but a pay-as-bid market. In fact, the objective function and constraints presented in (2) do not change except changing from FFR denoted variables to FCR-D denoted reservation and activation variables, $p_{e,t}^{\mathrm{FCRD}}$ and $p_{e,t,s}^{\mathrm{FCRD}\uparrow}$ respectively, and implementing a small change to (2a) and (2c). As FCR-D also has fast activation times, only the subset of battery prosumers is considered, $e \in E$. The changes in (2a) and (2c) are related to the change from a marginal pricing market to a pay-as-bid market, as the model must consider whether our bid is accepted in a given scenario or not. Therefore, a new scenario-indexed binary bid acceptance parameter, denoted $y_{t,s}^{\mathrm{acc,FCRD}}$, is introduced. This parameter indicates whether the community's bid price is below the estimated clearing price of the FCR-D market[2]. This acceptance factor is multiplied into the revenue term in the objective function of the FCR-D model, resulting in (3a), which replaces the FFR revenue term from (2a).

$$\lambda_{t,s}^{\mathrm{FCRD}} y_{t,s}^{\mathrm{acc,FCRD}} \sum_{e \in E} p_{e,t}^{\mathrm{FCRD}} \tag{3a}$$

The same thing is done for the auxiliary energy tracking variable, which is now calculated according to (3b). As all of the y terms are pre-processed parameters, no bilinearities are created and a linear program is maintained.

$$p_{e,t,s}^{\mathrm{FCRD}\uparrow} = y_{t,s}^{\mathrm{acc,FCRD}} y_{t,s}^{\mathrm{act,FCRD}} p_{e,t}^{\mathrm{FCRD}} \qquad \forall e \in E, t \in T, s \in S \tag{3b}$$

Lastly, the battery limit equations are also updated to include the acceptance parameters for all FCR-D bids, resulting in (3c) and (3d).

$$b_{e,t,s}^{\mathrm{dis}} + y_{t,s}^{\mathrm{acc,FCRD}} p_{e,t}^{\mathrm{FCRD}} \leq \bar{b}_e \quad \forall e \in E, t \in T, s \in S \tag{3c}$$

$$\mathrm{SOC}_{e,t,s} \geq y_{t,s}^{\mathrm{acc,FCRD}} p_{e,t}^{\mathrm{FCRD}} \quad \forall e \in E, t \in T, s \in S \tag{3d}$$

D. FCR-N

The FCRN markets add complexity to the modelling, as now activation payments as well as symmetrical activation for ancillary services must be considered. The full linear program is given in 4. In the objective function, the energy import difference due to FCR-N down regulation is now considered, which is implemented in the first line of (4a). Lines 2 and 3 of the objective function are the same as for the FCR-D model as up-regulation must also be considered in our energy export, and the FCR-N market is also remunerated via a pay-as-bid scheme. The fourth line accounts for the activation payment that takes place for the activated FCR-N bids by multiplying the amount of activated energy in both up and down-regulation, $p_{e,t,s}^{\mathrm{FCRN}\uparrow}$ and $p_{e,t,s}^{\mathrm{FCRN}\downarrow}$ respectively, by the up and down regulation balancing price at time t in scenario s, $\lambda_{t,s}^{\mathrm{bal}\uparrow}$ and $\lambda_{t,s}^{\mathrm{bal}\downarrow}$ respectively.

$$\begin{aligned} \min \sum_{s \in S} \pi_s \sum_{t \in T} \Big[& \lambda_{t,s}^{\mathrm{im}} \Big(p_{t,s}^{\mathrm{im}} - \sum_{e \in E} p_{e,t,s}^{\mathrm{FCRN}\downarrow} \Big) \\ & - \lambda_{t,s}^{\mathrm{ex}} \Big(p_{t,s}^{\mathrm{ex}} - \sum_{e \in E} p_{e,t,s}^{\mathrm{FCRN}\uparrow} \Big) \\ & - \sum_{e \in E} \Big(\lambda_{t,s}^{\mathrm{FCRN}} y_{t,s}^{\mathrm{acc,FCRN}} p_{e,t}^{\mathrm{FCRN}} \\ & + \lambda_{t,s}^{\mathrm{bal}\uparrow} p_{e,t,s}^{\mathrm{FCRN}\uparrow} + \lambda_{t,s}^{\mathrm{bal}\downarrow} p_{e,t,s}^{\mathrm{FCRN}\downarrow} \Big) \Big] \end{aligned} \tag{4a}$$

$$\text{s.t. } (1\text{b}) - (1\text{d}) \tag{4b}$$

$$p_{e,t,s}^{\mathrm{FCRN}\uparrow} = y_{t,s}^{\mathrm{acc,FCRN}} y_{t,s}^{\mathrm{act,FCRN}\uparrow} p_{e,t}^{\mathrm{FCRN}} \qquad \forall e \in E, t \in T, s \in S \tag{4c}$$

$$p_{e,t,s}^{\mathrm{FCRN}\downarrow} = y_{t,s}^{\mathrm{acc,FCRN}} y_{t,s}^{\mathrm{act,FCRN}\downarrow} p_{e,t}^{\mathrm{FCRN}} \qquad \forall e \in E, t \in T, s \in S \tag{4d}$$

In addition, the battery constraints are also updated, with the charging terms now also having an additional energy activation to consider. That means that compared to the previous battery model the term $b_{e,t,s}^{\mathrm{ch}}$, is now replaced by $(b_{e,t,s}^{\mathrm{ch}} + p_{e,t,s}^{\mathrm{FCRN}\downarrow})$. An example of this substitution is provided in form of the power balance equation, which now becomes (4e). All other state of charge constraints and battery limit constraints presented in (2) follow the same pattern.

$$\begin{aligned} p_{e,t,s} + \mathrm{PV}_{e,t,s} - \mathrm{D}_{e,t,s} - (b_{e,t,s}^{\mathrm{ch}} + p_{e,t,s}^{\mathrm{FCRN}\downarrow}) & \\ + (b_{e,t,s}^{\mathrm{dis}} + p_{e,t,s}^{\mathrm{FCRN}\uparrow}) = 0 & \\ \forall e \in E, t \in T & \end{aligned} \tag{4e}$$

E. mFRR

mFRR is the only service which can be offered by shiftable prosumers, due to the slow response time. Therefore, the not only are the objective function and the battery constraints changed, but also the shiftable prosumers constraints in this model.A new set, $m \in M$, is introduced which is the union of the shiftable and battery prosumers. It is again assumed that all community bids are acceoted. This results in the objective function shown in (5a)

$$\begin{aligned} \min \sum_{s \in S} \pi_s \sum_{t \in T} \Big[& \lambda_{t,s}^{\mathrm{im}} p_{t,s}^{\mathrm{im}} - \lambda_{t,s}^{\mathrm{ex}} \Big(p_{t,s}^{\mathrm{ex}} - \sum_{m \in M} p_{m,t,s}^{\mathrm{mFRR}\uparrow} \Big) \\ & - \sum_{m \in M} \Big(\lambda_{t,s}^{\mathrm{mFRR}} p_{m,t}^{\mathrm{mFRR}} + \lambda_{t,s}^{\mathrm{bal}\uparrow} p_{e,t,s}^{\mathrm{FCRN}\uparrow} \Big) \Big] \end{aligned} \tag{5a}$$

$$\text{s.t. } (1\text{b}) - (1\text{d}) \tag{5b}$$

$$p_{m,t,s}^{\mathrm{mFRR}\uparrow} = y_{t,s}^{\mathrm{act,FFR}} p_{m,t}^{\mathrm{mFRR}} \ \forall m \in M, t \in T, s \in S \tag{5c}$$

The battery constraints for the mFRR market are the same as for the FFR market, simply implementing the respective reservation and activation variables, $p_{m,t}^{\mathrm{mFRR}}$ and $p_{m,t,s}^{\mathrm{mFRR}\uparrow}$. For the first time, the shiftable prosumer constraints must also be changed. The changes made for mFRR market bidding is shown in (5d) - (5f). (5d) ensures that any activation bid into the mFRR market is also considered in the power balance of the shiftable community members. Meanwhile (5e) and (5f) set the limit for the mFRR capacity available base on if the prosumers f is in their shiftable load period or not.

$$p_{f,t,s} + p_{f,t,s}^{\mathrm{mFRR}\uparrow} + \mathrm{PV}_{f,t,s} - d_{f,t,s} = 0$$

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[2] The bid price is calculated based on the investment cost of a battery, desired payback time, cost of participation, and desired profit.

$$\forall f \in F, t \in T, s \in S \quad (5d)$$

$$p^{\text{mFRR}}_{f,t} \leq \mathrm{D}_{f,t,s} \qquad \forall f \in F, t \in T^{\text{flex}}, s \in S \quad (5e)$$

$$p^{\text{mFRR}}_{f,t} = 0 \qquad \forall f \in F, t \in T \backslash T^{\text{flex}} \quad (5f)$$

F. Multi-market model

The multi market model is created by combining the modelling techniques formulated in this section. Rather than listing the constraints separately, the different terms are combined into an objective function with all revenue terms, a single power balance equation, one set of battery constraints and so on. Therefore the power balance constraint of the battery prosumer is formulated as shown in (6).

$$\begin{aligned} &p_{e,t,s} + \mathrm{PV}_{e,t,s} - \mathrm{D}_{e,t,s} - (b^{\text{ch}}_{e,t,s} + p^{\text{FCRN}\downarrow}_{e,t,s}) \\ &+ (b^{\text{dis}}_{e,t,s} + p^{\text{FFR}\uparrow}_{e,t,s} + p^{\text{FCRD}\uparrow}_{e,t,s} + p^{\text{FCRN}\uparrow}_{e,t,s} + p^{\text{mFRR}\uparrow}_{e,t,s}) = 0 \\ &\qquad\qquad\qquad\qquad \forall e \in E, t \in T, s \in S \quad (6) \end{aligned}$$

Here all possible activations are considered in the same balance equation to ensure that the community can be activated for whatever market necessary when called upon. All other equations are formulated in a similar manner, but not listed here.

IV. NUMERICAL CASE STUDY

A. Scenario Generation

Scenarios are generated by combining a set of prosumer baseline consumption scenarios with historical spot and ancillary market price and activation data. Each prosumer scenario consists of a pair of ten daily consumption profiles (one for each prosumer in the community), $\mathrm{D}_{e,t,s}$, and ten daily PV production curves, $\mathrm{PV}_{e,t,s}$, generated according to the methodology described in [16]. The daily spot market, ancillary service market, and ancillary service activation scenarios are taken from historical data of the Nordic synchronous grid. As this paper focuses on the eastern Danish bidding area (DK2), only historical prices for this area are used. A vital part of the scenario generation is the processing of the activation scenarios to obtain the activation factors, $y^{act}_{t,s}$, for all ancillary markets. This is done by taking the system frequency data for the Nordic synchronous grid and calculating the needed activation in a normalized fashion (0 being no activation, 1 being full activation) in each market, as was proposed in [14]. An example of such a calculation is given in (7) for FCR-D.

$$y^{\text{act,FCRD}}_{t,s} = \begin{cases} 1, & \text{if } f_{t,s} < 49.5 \text{ Hz} \\ 0, & \text{if } f_{t,s} > 49.9 \text{ Hz} \\ \frac{49.9 \text{ Hz} - f_{t,s}}{0.4 \text{ Hz}}, & \text{else} \end{cases} \quad (7)$$

These activation factors are averaged for all seconds in a given hour, to get an hourly activation factor. These market scenarios are then combined with the prosumer scenarios to create 3660 scenarios that can be used in the in-sample and out-of-sample analysis.

B. In Sample Results

The first thing investigated is which markets the energy community has decided to bid into. The bidding decisions can be seen in Fig. 1.

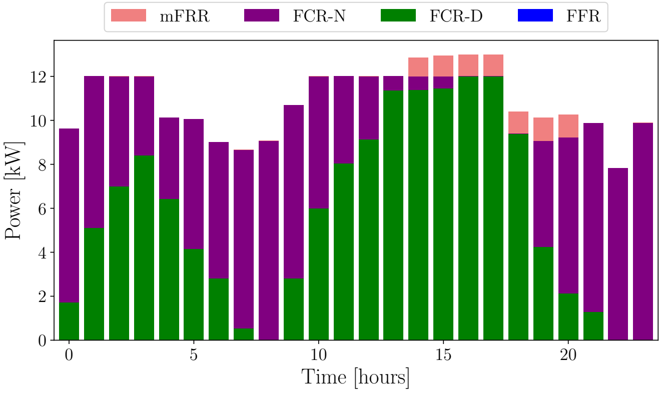

Fig. 1. Total capacity and share of available capacity bid into the different ancillary markets using a sample size of 100

From this figure it is clear that the focus of the community is to bid into the FCR-N and FCR-D markets. This is interesting, as these are the two markets in-which acceptance is not guaranteed. This means the community prefers the risk of not being accepted in a pay-as-bid market, over the guaranteed acceptance and revenue from the FFR and mFRR markets. This is due to the fact that the prices per kW of reserved capacity are much lower, and therefore the community is better off risking not being accepted for the higher per kW profit. A more detailed analysis of prices on the ancillary service markets can be found in [12]. This is confirmed by the observation that there is some mFRR bidding, but this only comes from shiftable prosumers. These community members cannot bid in the primary reserve markets, but are still able to gain some benefit by bidding into the mFRR market. This shows that there is value in mFRR bidding, but it is simply not as profitable as the FCR markets. The total amount that shiftable prosumers are able to bid pales in comparison to that of battery owners. This is due to the time limitations of when they can submit bids, and the limited capacity when the time window is indeed appropriate. In terms of total bidding shares, the FCR-N and FCR-D markets are almost equal at around 50% and 47%, with FFR receiving absolutely no bids, and mFRR only receiving just over 2% of available flexible capacity. Exact capacity numbers can be seen in table III.

TABLE III
SHARE OF ANCILLARY MARKET BIDS FOR ALL MARKETS

Market	Total Bid Capacity [kW]	% of Bid Volume
FFR	0.0	0.00
FCR-D	327.56	50.27
FCR-N	309.74	47.54
mFRR	14.24	2.19
All	651.5	-

C. Out of Sample Results

An out-of-sample analysis is performed on 2000 scenarios. Varying amounts of in-sample scenarios are used to assess

TABLE II

Different number of in-sample (IS) scenarios tested on 2000 out-of-sample (OOS) scenarios for feasibility performance

IS Size	IS Objective [DKK]	# Feasible	# Market infeasible	# Physical Infeasible	% Full feasibility	% Physical feasibility
5	-17.53	437	48	1515	21.85	24.25
10	-46.13	652	192	1156	32.60	42.20
50	-54.84	1515	183	302	75.75	84.90
100	-52.60	1750	186	64	87.50	96.80
500	-51.74	1970	30	0	98.50	100.00
1000	-50.91	2000	0	0	100.00	100.00

how many scenarios are needed to be confident about the model's ability to deliver the promised services in an unforeseen scenario. In table II, the performance of the different amounts of in-sample scenarios is evaluated using the same 2000 out-of-sample scenarios. The results from each scenario are classified as either feasible or infeasible. In this table, two different types of infeasibility are considered: market infeasibility and physical infeasibility. Physical infeasibility means that the physical constraints of the battery system or the shiftable demand curve are broken. Market infeasibility means that one of the promised bids cannot be delivered.

Looking at table II, it is clear that with a larger number of samples, the out-of-sample performance improves. At 5 in-sample scenarios, only 21.85% of scenarios are feasible out-of-sample. However, when increasing the amount of in-sample scenarios to 500 or 1000, greater than 98% feasibility is achieved, and 100% physical feasibility is achieved in both cases. Also, the achieved in-sample performance is very poor when using only 5 samples. This is due to the extreme overfitting of the optimization and the high dependence on what samples happen to be in the sample over which the model optimizes. The in-sample performance improves as the sample size increases, but only until a sample size of about 50. From this point onwards, a decrease in in-sample objective value is observed in exchange for better feasibility. One must weigh which of these two factors is more important when deciding how many in-sample scenarios one would like to run the model on.

V. Conclusion

In conclusion, the results show that the model splits the ancillary market bids almost equally between the FCR-N market at 47.54% and FCR-D market at 50.27%. In fact, prosumers who own batteries do not bid into other markets at all. Furthermore, shiftable prosumers who do not own a battery can benefit from the provision of mFRR, showing that people without a battery can also contribute to ancillary service provision. Concerning the out-of-sample performance of the model, a clear trend of improving feasibility with more in-sample scenarios is observed. Running the model with less than 10 samples results in out-of-sample feasibility being below 33%. To achieve greater than 90% out-of-sample feasibility between 100 and 500 scenarios must be used.

Future work could include looking at how to distribute the derived benefits among the community members; how much benefit goes to the vital battery prosumers as opposed to the inflexible consumers who cannot contribute to the ancillary market bidding at all. As this is a communal optimization problem, notions could be taken from cooperative game theory like Shapley value and nucleolus, where the notion of fairness while distributing the benefits. Further future work could consider including battery degradation cost into this model and seeing if this changes the optimal bidding results.

References

[1] B. H. Jørgensen, K. Remler, and P. H. Madsen, "IEA Wind TCP Annual Report Denmark 2021," International Energy Agency, Tech. Rep., 12 2022.

[2] Energinet, "Scenarierapport 2022-2032: Forventninger til fremtidens Systemydelser," Energinet, Fredericia, Tech. Rep., 2022.

[3] Energistyrelsen, "Markedsmodel 3.0: Analyse of markedudviklingen for fleksibilitet i lokale elnet," Danish Energy Agency, Tech. Rep., 5 2021.

[4] E. Commission and D.-G. for Energy, *Clean energy for all Europeans*. Publications Office, 2019.

[5] Council of the European Union, "Directive (eu) 2019/944 of the european parliament and of the council of 5 june 2019 on common rules for the internal market for electricity and amending directive 2012/27/eu," *Official Journal of the European Union*, pp. 125–158, 2019.

[6] T. Capper, A. Gorbatcheva, M. A. Mustafa, M. Bahloul, J. M. Schwidtal, R. Chitchyan, M. Andoni, V. Robu, M. Montakhabi, I. J. Scott *et al.*, "Peer-to-peer, community self-consumption, and transactive energy: A systematic literature review of local energy market models," *Renewable and Sustainable Energy Reviews*, vol. 162, p. 112403, 2022.

[7] P. A. Gade, T. Skjøtskift, C. Ziras, H. W. Bindner, and J. Kazempour, "Load shifting versus manual frequency reserve: Which one is more appealing to thermostatically controlled loads in denmark?" *Electric Power Systems Research*, vol. 232, p. 110364, 2024.

[8] P. A. V. Gade, T. Skjøtskift, H. W. Bindner, and J. Kazempour, "Energy-intensive industries providing ancillary services: A real case of zinc galvanizing process," 2024.

[9] P. A. Gade, T. Skjøtskift, H. W. Bindner, and J. Kazempour, "Synergy among flexible demands: Forming a coalition to earn more from reserve market," in *2023 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*, 2023, pp. 1–5.

[10] Z. Hameed, S. Hashemi, H. H. Ipsen, and C. Traholt, "Placement of Battery Energy Storage for Provision of Grid Services – A Bornholm Case Study," in *2021 IEEE 9th International Conference on Smart Energy Grid Engineering (SEGE)*. IEEE, 8 2021, pp. 36–41.

[11] W. Seward, M. Qadrdan, and N. Jenkins, "Revenue stacking for behind the meter battery storage in energy and ancillary services markets," *Electric Power Systems Research*, vol. 211, p. 108292, 10 2022.

[12] Z. Hameed, C. Træholt, and S. Hashemi, "Investigating the participation of battery energy storage systems in the Nordic ancillary services markets from a business perspective," *Journal of Energy Storage*, vol. 58, p. 106464, 2 2023.

[13] L. Puglia, A. Bemporad, A. Jokic, and A. Virag, "A stochastic optimization approach to optimal bidding on dutch ancillary services markets," in *2013 10th International Conference on the European Energy Market (EEM)*. IEEE, 5 2013, pp. 1–8.

[14] A. Thingvad, C. Ziras, G. L. Ray, J. Engelhardt, R. R. Mosbak, and M. Marinelli, "Economic Value of Multi-Market Bidding in Nordic Frequency Markets," in *2022 International Conference on Renewable Energies and Smart Technologies (REST)*. IEEE, 7 2022, pp. 1–5.

[15] Energinet, "Introduktion til Systemydelser," Energinet, Fredericia, Tech. Rep., 1 2023. [Online]. Available: https://energinet.dk/el/systemydelser/introduktion-til-systemydelser/

[16] S. Pfenninger and I. Staffell, "Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data," *Energy*, vol. 114, pp. 1251–1265, 11 2016.