Journal of Physics: Conference Series

Value stacking flexibility services in neighborhoods participating in fast frequency reserve markets

To cite this article: Peter Stai *et al* 2023 *J. Phys.: Conf. Ser.* **2600** 052001

CISBAT 2023
Journal of Physics: Conference Series
IOP Publishing
2600 (2023) 052001
doi:10.1088/1742-6596/2600/5/052001

Value stacking flexibility services in neighborhoods participating in fast frequency reserve markets

Peter Stai[a], **Sigurd Bjarghov**[b], **Kasper E. Thorvaldsen**[b], **Stian Backe**[a,b]
[a]Dept. of Industrial Economy and Technology Management, NTNU - Trondheim, Norway
[b]SINTEF Energy Research - Trondheim, Norway

E-mail: `stian.backe@ntnu.no`

Abstract. Neighborhoods are responsible for considerable amounts of the total energy demand in Europe, and increased shares of variable renewable energy sources will require energy balancing services. Local flexibility resources in neighborhoods can help provide this. However, there is a lack of insight into the economic incentives and operational consequences for property owners to adopt prosumer qualities. Using a linear program that minimizes total electricity costs, this paper evaluates annual cost savings for a Norwegian university campus when value stacking the following flexibility services: responding to electricity spot prices, grid tariffs, and provision of fast frequency reserve (FFR). Several flexibility resources are addressed in this study, including a stationary battery, electric vehicle charging stations, and a vehicle-to-grid charging station. The results found an average 6.8% yearly cost decrease by FFR participation, supporting the notion that there is a significant economic potential in applying flexible resources from prosumers in fast frequency reserve markets, without significant conflicts with other flexibility services.

1. Introduction

Substantial shares of variable renewable energy sources (VRES) in future power systems creates opportunities for neighborhoods to provide frequency restoration flexibility [1]. Historically, sources of flexibility have been provided by the supply side of the energy system by controlling energy production to meet a varying demand and synchronize the grid frequency. In recent years, demand-side flexibility and distributed flexibility resources (DFR) have become increasingly common and esteemed in regard to providing balancing services [1].

The Fast Frequency Reserve (FFR) market emerged in Norway and the Nordics in 2022 due to the general decline in power systems' inherent synchronous inertia. The FFR reserves are the fastest measure to decelerate frequency drops in the power system and have been implemented in a variety of countries worldwide [2]. FFR markets present prosumers a new market opportunity to prosumers with DFRs. FFR capacity can be sold by either reserving curtailable capacity through non-essential loads or by discharging flexible energy to the grid.

For a neighborhood, demand-side flexibility can be provided by energy storage systems [3] and electric vehicles (EVs) [4]. Economic incentives for demand-side flexibility include short-term variability of electricity prices, dynamic grid tariff designs, and net exports. In addition, DFRs can also participate in reserve markets. Yet, there are still market barriers related to the participation of neighborhood flexibility in reserve markets [5]. The Norwegian FFR market currently requests participants capable of delivering at least 1 MW [6], acting as a barrier for modest resources to enter the market. However, Statnett does not object to aggregated loads partaking as as singular bidder, enabling aggregators for participation in FFR. The aggregator approach has been proven feasible for both participation in frequency containment reserve markets (FCR) [7], and in the frequency restoration markets (aFRR and mFRR) [8], but requires advanced bidding models [9]. Although the potential gain of DFR utilization might be significant in multiple aspects and markets, there also exist costs of providing demand-side flexibility, e.g., battery wear and tear as well as purchase and integration costs [10].

Contributions from DFR in the FFR market can be an important enabler for the sustainable energy transition. Batteries have proven to be more valuable when providing FFR in addition to FCR services due to value stacking [11]. Kushwaha et al. [12] assess aggregated scheduling of EVs potential for FFR support through both Grid-to-vehicle (G2V) and Vehicle-to-grid (V2G) charging stations, showing significant capacity for FFR support and reduction in system costs. The limited research on provision of reserves from neighborhoods show that the participation in frequency restoration markets lower neighborhood costs [13]. However, there has been little research conducted on the FFR provision capabilities from a neighborhood with flexibility from batteries and EV charging, while also responding to spot price and grid tariff price signals.

This paper assesses the cost-optimal flexibility responses from a Norwegian prosumer participating in an FFR market. To the authors knowledge, no study has explored how costs and operations of demand-side flexibility are impacted by the opportunity to participate in FFR. This paper presents a case study of a Norwegian university campus with several flexibility resources. Using metered data for three historical years, we provide an optimization model that minimizes neighborhood costs by optimizing operation of the DFRs with and without the opportunity to participate in FFR. The research questions are the following:

- How are costs and operations of demand-side flexibility impacted by participation in FFR?
- How do economic characteristics of different years impact FFR participation?

The remaining paper is structured as follows: Section 2 presents the linear programming model used to simulate cost-optimal prosumer responses to price signals, including the FFR market. Section 3 presents input data and the case study setup, while Section 4 presents and discusses the results. Concluding remarks can be found in Section 5.

2. Methodology

In this section, we present the mathematical modelling framework for the prosumer cost minimization problem. The model is a deterministic linear program that computes the cost optimal responses to spot-price variation, FFR market contracts, different tariff factors and varying loads over the duration of a year. Decisions include operation of flexible assets, determination of FFR capacity participation and net consumption between the prosumer and the grid. All decision variables are non-negative.

The objective function quantifies the total electricity costs given a certain schedule for the flexible assets. This objective function is minimized:

$$\min \quad z = \sum_{m \in \mathscr{M}} c_m^{peak} p_m + \sum_{t \in T} \big((c_t^{energy} + c_t^{\mathrm{retail}}) y_t^{\mathrm{load}} - (c_t^{\mathrm{exp}} x_t^{\mathrm{load}}) \big) - c^{\mathrm{FFR}} z^{\mathrm{FFR}} \tag{1}$$

where p_m are variables for the peak load during month m. The electricity import from the grid to cover the loads are identified by variable y_t^{load}, while variable x_t^{load} represent electricity export to the grid. The total FFR capacity during $t \in \mathscr{T}^{\mathrm{FFR}}$ is represented by variable z^{FFR}. The objective contains a time-varying load-dependent retail cost for import (c_t^{retail}) and for export (c_t^{exp}), a monthly peak load cost (c_m^{peak}), and the FFR market price (c^{FFR}) which is constant with regard to the pertinent FFR contract.

The resulting import from the grid to the prosumer is defined by constraint (2). The resulting load at each time-step must be equal to the initial demand plus potential export to the grid as well as charged and discharged energy from the flexible assets:

$$y_t^{\text{load}} = \quad \xi_t^{\text{load}} + x_t^{\text{load}} + \sum_{f \in \mathscr{F}} (w_{f,t}^{\text{charge}} - \varepsilon_f^{\text{discharge}} w_{f,t,}^{\text{discharge}}) \qquad \forall \quad t \in \mathscr{T} \tag{2}$$

where ξ_t^{load} is the inflexible load, y_t^{load} and x_t^{load} are import and export of electricity, while $\omega_{f,t}^{\text{charge}}$ and $\omega_{f,t}^{\text{discharge}}$ are charging and discharging of flexible assets type f, respectively. Energy losses are only considered for discharging, represented by $\varepsilon_f^{\text{discharge}}$.

Constraint (3) ensures that the flexible asset type f has an energy level stored equal to the previous period subject to diffusion losses plus charging subject to losses minus discharging. This constraint has an initial condition version ($t = 1$) with an initial storage value k_f.

$$\varepsilon_f^{\text{diff}} w_{f,t-1}^{\text{storage}} + \varepsilon_f^{\text{charge}} w_{f,t}^{\text{charge}} - w_{f,t}^{\text{discharge}} = w_{f,t}^{\text{storage}} \qquad \forall \quad f \in \mathscr{F}, t \in \mathscr{T} \tag{3}$$

The losses with respect to charging ($\varepsilon_f^{\text{charge}}$), discharging ($\varepsilon_f^{\text{diff}}$) and diffusion ($\varepsilon_f^{\text{discharge}}$) are dependent on the characteristics of the flexible asset f. There are no losses related to discharging in constraint (3) as it is accounted for in constraint (2).

The maximum capacity for charging ($\eta_{f,t}^{\text{charge}}$), storage ($\eta_{f,t}^{\text{storage}}$) and discharging ($\eta_{f,t}^{\text{discharge}}$) of flexible asset f are defined as upper bounds for operational decisions in all time periods in constraints (4), (5) and (6). Constraint (6) makes sure that the energy level of of flexible asset f is within the required boundaries of ($\gamma_{f,t}^{\text{req}}$) and ($\gamma_{f,t}^{\text{max}}$) for all time periods t. The time-dependency of ($\eta_{f,t}^{\text{charge}}$) and ($\eta_{f,t}^{\text{discharge}}$) are necessary to consider flexible assets where availability fluctuates, such as for EV charging.

$$\begin{aligned} w_{f,t}^{\text{charge}} &\leq \eta_{f,t}^{\text{charge}} && \forall \quad f \in \mathscr{F}, t \in \mathscr{T} && (4) \\ w_{f,t}^{\text{discharge}} &\leq \eta_{f,t}^{\text{discharge}} && \forall \quad f \in \mathscr{F}, t \in \mathscr{T} && (5) \\ \gamma_{f,t}^{\text{req}} \leq w_{f,t}^{\text{storage}} &\leq \gamma_{f,t}^{\text{max}} \leq \eta_{f,t}^{\text{storage}} && \forall \quad f \in \mathscr{F}, t \in \mathscr{T} && (6) \end{aligned}$$

The constraints associated with FFR are given in (7), (8) and (9). FFR capacity can be acquired based on the curtailable charged quantity in (7), and by the remaining discharge capacity in (8), for each flexible asset f at time t. The sum of the available FFR capacity from each flexible asset $f \in \mathscr{F}$ for each time step of the year sets the upper limit of how much FFR we can offer over the whole year in (9). Energy use associated with FFR activation is disregarded in this formulation.

$$\begin{aligned} w_{f,t}^{\text{charge}} &\geq r_{f,t}^{\text{charge}} && \forall \quad f \in \mathscr{F}, t \in \mathscr{T} && (7) \\ w_{f,t}^{\text{discharge}} + r_{f,t}^{\text{discharge}} &\leq \eta_f^{\text{discharge}} && \forall \quad \in \mathscr{F}, t \in \mathscr{T} && (8) \\ \sum_{f \in \mathscr{F}^{FFR}} r_{f,t}^{\text{charge}} + r_{f,t}^{\text{discharge}} &\geq z^{\text{FFR}} && \forall \quad t \in \mathscr{T}^{\text{FFR}} && (9) \end{aligned}$$

Constraint (10) determines the highest monthly peaks of import. The highest import quantity during each month $p_m^{monthly}$ sets the threshold for the monthly demand charge grid tariff.

$$y_t^{\text{load}} \leq p_m \qquad \forall \quad t \in \mathscr{T}(m), m \in \mathscr{M} \tag{10}$$

3. Case study

Campus Evenstad is a Norwegian university campus located in Innlandet county, and it is participating as one of the FME ZEN[1] pilots[14]. From 2015 to 2021, Campus Evenstad consumed between 650MWh to 1,100MWh electricity per year. We use historical hourly load profiles from Campus Evenstad. Characteristics of the flexible assets at Campus Evenstad are provided via the FME ZEN Research Center and summarized in Table 1.

Based on historical charging trends at campus Evenstad, we have assumed a consistent cumulative daily demand of 66.3kWh for G2V charging and 26.5kWh for V2G charging. This is mainly due to lack of hourly data for EV demand. EV connective availability is assumed to be from 9am–3pm for one-directional chargers ensuring that demand is met by the end of a typical Norwegian working day. V2G is mainly utilized by campus employees and assumed to be connected from 3pm–9am. EV battery storage level is allowed to operate between 30–60%, and initial storage level for V2G is assumed to be 35%. No costs or losses are considered for any flexible asset in this case study.

Day-ahead hourly prices are gathered from the ENTSO-E Transparency Platform for price zone NO1 (South-East) in Norway. The Elvia grid tariff includes a seasonal volumetric cost, at 0.085 NOK/kWh during winter and 0.065 NOK/kWh during summer. In addition, there is a monthly demand charge cost of 90 NOK/kWh/h for the highest hourly import during a month in winter, and 40 NOK/kWh/h for summer [15]. Export of electricity is priced as the spot price minus 0.02 NOK/kWh. Fixed costs are disregarded in this analysis.

For the FFR market, Statnett requests two different contracts for reserve capacity: "Profil" and "Flex". All FFR data is collected from 2023. For Profil, capacity is sold on weekends and from 10pm until 7am on weekdays during the period of 27.May–3.Sep. For Flex, capacity is sold for 400 hours according to weekly orders during the period 29.Apr–30.Oct. According to correspondence with Statnett, the Flex orders are usually fairly scattered throughout the period, so we assume FFR orders every 13th hour. The FFR market price is assumed to be equal to the 2023 price of 150 NOK/MW-hour for Profil and 450 NOK/MW-hour for Flex. According to Statnett, FFR is generally only activated 0-3 times each season, and due to the short response time, the cost and logistics of FFR activation is not considered in this case study. Any fee associated with the aggregator is disregarded in this study.

Table 1: Operational characteristics of the flexible assets at Campus Evenstad.

Flexible asset	η^{charge}[kWh/h]	$\eta^{discharge}$[kWh/h]	$\eta^{storage}$[kWh/h]	k_f[kWh]
1x li-ion battery	120	120	204	0
2x V2G	20.0	20.0	61.2	10
5x G2V	100.0	0.00	66.3	0

The objective of this case study is to assess the impact of prosumer participation in a FFR market, with regard to limiting their electricity bill, particularly by leveraging different flexible capabilities. Four cases optimizing costs, revenues and flexible asset operation will be presented for each year; 2019, 2020 and 2021. The classes of cases analysed in this paper are:

- **NoFlexNoFFR**: No flexible assets and no FFR market (no optimization).
- **FlexNoFFR**: All flexible assets available and no FFR market.
- **FlexFFR-P**: All flexible assets available and participation in FFR Profil.
- **FlexFFR-F**: All flexible assets available and participation in FFR Flex.

4. Results and discussion

Figure 1 shows resulting costs and revenues for each modelling instance, and it shows larger differences between years than between instances. Among the four instances considered within each year, FlexFFR-P is consistently the most profitable, followed by FlexFFR-F, FlexNoFFR,

---

[1] `https://fmezen.no`

and NoFlexNoFFR. Optimal operation of flexible assets led to the greatest cost savings in 2021, followed by 2019 and 2020, although the results show the opposite order in terms of relative cost savings (23.34% for 2020, 14.14% for 2019, and 11.48% for 2021).

Over the three years, implementation of FFR contracts resulted in an average reduction of total costs by 6.8% for Profil and 5.1% for Flex, compared to FlexNoFFR. The Profil contract achieved the highest total cost reduction of 12% in 2020. FFR Profil contributed with 32% of the total cost savings of flexible asset operation during the same year. FFR volume and profits for both Flex and Profil contracts peaked in 2020, with 2019 showing approximately 9% less FFR volume for both contracts. The authors attribute this to a high average spot-price of 0.40 NOK/kWh and a low standard deviation of 0.08, in relation to a high average load of 83.56 kWh for 2019, which incentivized limiting energy costs and peak capacity costs at the expense of maintaining a high FFR capacity. The Profil contract yielded the highest FFR earnings, reaching 29.1 kNOK in both 2020 and 2021. The consistent results over both years indicate that the FFR capacity has reached its limit relative to the case's flexibility. Participating in the FFR market resulted in losses in other cost components, which represented an average of 19.65% and 17.31% of the FFR profits for Profil and Flex contracts, respectively. Almost all of the indirect losses are attributed to the peak capacity cost (90%), where the monthly highest peak either increased or remained constant in every month where FFR was available. The monthly peaks increased on average with 20.41% for Profil and 14.12% for Flex. FFR seems to have little effect on the other cost elements, but interestingly, resulted in an increase in energy export profits by an average of 8.1% for Flex and 2.4% for Profil. The export profits reached a significant high in 2021 due to the remarkable spot-price standard deviation of 0.48, in contrast to 0.08 observed in 2020 and 2019. Electricity is only exported in the cases when flexibility is available.

The FFR capacity and volume distribution for each year is provided in Table 2. On a yearly average, the li-ion battery provides approximately 86% of the total FFR capacity in both Profil and Flex, whereas V2G and G2V on average contributes 13% and 2%, respectively. Profil had a higher contract quantity than Flex, mainly due to a total reduced availability of V2G and G2V participation, during periods of reserve need. Due to the flexible assets' different characteristics in capacity for charging and discharging, hourly availability and EV charging constraints, the distribution was somewhat as expected. However, when adjusting for active hours and charge/discharge capacity for each flexible asset type, V2G contributes with approximately 9% and 1% more FFR capacity than the electric battery and 42% and 40% more than G2V for Profil and Flex, respectively. The case study also revealed that discharging capabilities are highly valuable in regard to providing FFR capacity. For Profil, discharging of V2G and the li-ion battery in turn contributed, on average, with 55.6% and 22.6% more FFR capacity than curtailment of charging.

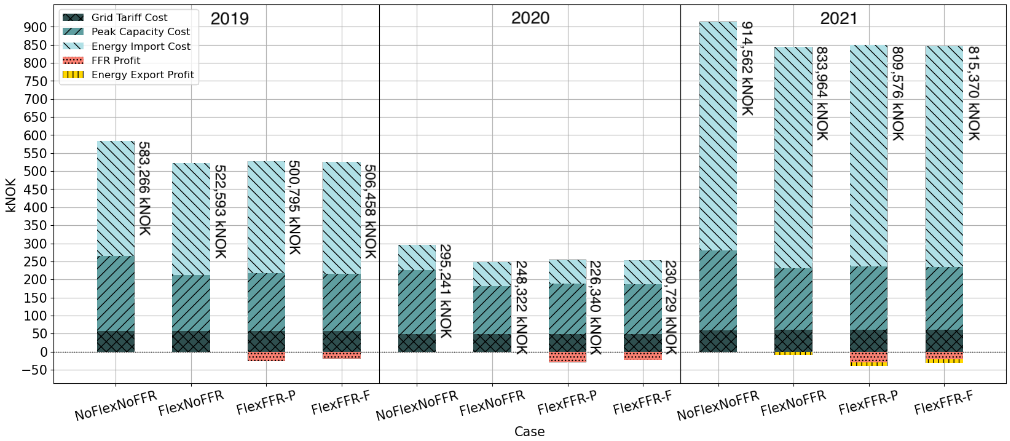

Figure 1: Overview of costs and revenues of each case for 2019, 2020 and 2021.

Table 2: FFR-volume distribution in contribution percentage for each year and asset.

Contract Year\ FFR	FFR Volume [kW]	FFR Battery charge [%]	FFR Battery discharge [%]	FFR EV charge [%]	FFR V2G discharge [%]	FFR G2V charge [%]
Flex 2019	110.74	32.22	54.69	3.80	6.90	2.39
Flex 2020	123.10	28.65	57.35	3.96	7.41	2.64
Flex 2021	117.70	32.13	54.30	3.76	6.95	2.87
Profil 2019	131.41	35.18	50.41	4.85	8.58	0.98
Profil 2020	143.61	40.74	46.63	4.75	7.01	0.86
Profil 2021	143.61	40.00	45.44	5.55	8.03	0.97

5. Conclusion

This paper provides a tangible analysis of how different flexible assets are optimally utilized when value stacking flexible qualities for a prosumer, and we contribute with a generalizable modeling framework applicable to a wide array of scenarios and data. The case study highlights the potential gain of distributed flexibility resources participation in fast frequency reserve (FFR) markets and assesses how reserved FFR capacity interacts with several market drivers across contrasting years. The case implies that the profits of FFR participation is predominant to the indirect losses of reserving security capacity, reducing the three year average total costs by 6.8% and 5.1% for Profil and Flex contracts, respectively. The study also provides key indicators that FFR market participation can effectively complement electricity exports, while simultaneously having a negative effect on limiting monthly peaks, thus providing valuable insights for energy market stakeholders. The paper provides support for the notion that the discharging capabilities of flexible assets can be highly effective in providing reserve capacity, while emphasizing the versatility and potency of vehicle-to-grid technology. Uncertainty related to EV demand profiles, loads, and energy prices would likely influence the results. Future work could explore the implementation of short-term forecasts using e.g. model predictive control to enable real-time decision-making.

Acknowledgement

We gratefully acknowledge the support through the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN) (grant no. 257660) and the PowerDig project (grant no. 320789) from the Research Council of Norway and project partners.

References

[1] Prakash V and Pandzic H 2023 *Electric Power Systems Research* **217** 109161

[2] Fernández-Muñoz D *et al.* 2020 *Renewable and Sustainable Energy Reviews* **120** 109662

[3] Stinner S, Huchtemann K and Müller D 2016 *Applied Energy* **181** 140–154

[4] Sørensen Å L, Lindberg K B, Sartori I and Andresen I 2021 *Energy and Buildings* **241**

[5] Poplavskaya K and de Vries L 2019 *Energy Policy* **126** 264–276

[6] Statnett 2023 Fast frequency reserves - FFR `https://tinyurl.com/ycxnfcm9`

[7] Astero P and Evens C 2020 *IET Generation, Transmission & Distribution* **14** 2566–2572

[8] Iria J, Soares F and Matos M 2019 *Applied Energy* **238** 1361–1372

[9] Manna C and Sanjab A 2023 *Journal of Cleaner Production* **389** 135962

[10] Han S and Han S 2013 *Energies* **6** 748–765

[11] Thingvad A *et al.* 2022 Economic Value of Multi-Market Bidding in Nordic Frequency Markets *2022 International Conference on Renewable Energies and Smart Technologies (REST)* vol 1 (IEEE) pp 1–5

[12] Kushwaha P, Prakash V, Yamujala S and Bhakar R 2023 *Journal of Energy Storage* **62**

[13] Firoozi H, Khajeh H and Laaksonen H 2020 *IEEE Access* **8** 180558–180575

[14] Backe S *et al.* 2019 Opportunities for Local Energy Supply in Norway: A Case Study of a University Campus Site *IOP Conference Series: Earth and Environmental Science* vol 352 (IOP Publishing) p 012039

[15] Elvia 2022 Næringskunder med årlig forbruk over 100 000 kWh Effekttariff – lavspent URL `https://tinyurl.com/mwkprpv6`