Virtual Power Plants as Catalysts for Multi-Market Participation Co-optimization

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Abstract: As power systems undergo rapid decarbonization, there is a growing integration of Distributed Energy Resources (DER) at the local level, including demand response technologies, battery energy storage systems (BESS), and distributed generators (DG). Understanding the true costs and benefits of DERs is essential, particularly in light of their potential revenue from market participation. This paper introduces an optimization framework that strategically leverages DER value stacking within a Virtual Power Plant (VPP). A VPP aggregates multiple small-scale DERs—such as batteries, photovoltaic systems, and residential loads—into a cohesive entity capable of participating in wholesale energy markets and providing contingency fast raise/lower Frequency Control Ancillary Services (FCAS). The VPP, which integrates multiple small-scale DERs into a single, larger entity, brings customers value and provides flexibility to the grid. Introduce a co-optimization model that optimizes the market participation of a VPP in the wholesale spot market and FCAS markets to determine the optimal operation of BESS within a fluctuating energy market. This allows the battery to strategically store energy when prices are low and release it when prices are high, maximizing economic returns. The optimized operation is then visualized to show how the battery responds to price variations over time. Additionally, the study analyses and visualizes the revenue generated from participating in different markets, this dual visualization—of both the battery's operation and the associated revenue—provides a comprehensive understanding of the financial and operational impacts of the optimization strategy.

This study uses powerful computational tools, most notably a Jupiter notebook environment. This research shows a dynamic field of distributed energy integration and its various aspects by exploring optimization problems focused on cost reduction through DER value stacking.

Keywords: VPP, DER value stacking, co-optimization model, energy market, FCAS

Abbreviations and Acronyms

VPP	Virtual Power Plant
DER	Distributed Energy Resources
FCAS	Frequency Control Ancillary Service
VPP	Virtual Power Plant
DER	Distributed Energy Resources
FCAS	Frequency Control Ancillary Service
BESS	Battery energy storage system
SOC	State of Charge
RES	Renewable Energy Sources
NEM	National Electricity market
PV	Photovoltaics
MLIP	Mixed Integer Linear Programming
M	Arbitrarily large number
$P_{min}^{b-}/p_{max}^{b-}$	BESS min/max charge power (kWe)
$P_{min}^{b+}/p_{max}^{b+}$	BESS min/max discharge power (kWe)

Received: January 31th, 2025. Accepted: September 20th, 2025
DOI: 10.15676/ijeei.2025.17.3.3

p_i^{b-}/p_i^{b+}	BESS charge/discharge power (kWe)
u_i^b	BESS charge/discharge indicator
x_i^b	BESS energy level (kWhe)
x_{minEL} / x_{maxEL}	BESS min/max energy level (kWhe)
n^b	BESS round trip efficiency
t	Time step length (h)
P_i^p	PV electrical output power (kWe)
$p_i^{p,curt}$	PV curtailment (kWe)
$r_i^{l,p}/r_i^{r,p}$	PV lower or raise FCAS commitment (kWe/h)
$r_i^{l,b}/r_i^{r,b}$	BESS lower or raise FCAS commitment (kWe/h)
p_i^-/p_i^+	VPP import or export power (kWe)
V_i^-/V_i^+	VPP import or export electricity prices ($/kWhe)
$r_{i,\alpha}^l/r_{i,\alpha}^r$	VPP lower or raise FCAS commitment (kWe/h)
$V_{i,\alpha}^l/V_{i,\alpha}^r$	Lower or raise FCAS prices ($/kWe/h)
c^h	Flexible load curtailment costs ($/kWhe)
$p_i^{h,curt}$	Flexible load curtailment (kWe)

1. Introduction

Emerging low-carbon technologies are now starting to replace conventional large-scale synchronous generators as a result of the global move towards decarbonizing power systems. The proliferation of Distributed Energy Resources (DER) at the distributed level, which includes demand response (DR) technologies, battery energy storage systems (BESS), and distributed generations (DG) are at the forefront of this revolution. [1] These distributed energy resources (DER) present viable ways to improve the efficiency of the energy system, minimize distribution and transmission losses, and reduce the total network infrastructure footprint. [2] Nevertheless, their integration presents complex problems to the operations of conventional energy systems, particularly in the context of extensive penetration of renewables. This includes further swings in energy prices, [3] increased demand for frequency control ancillary services (FCAS), and amplified strains on distribution networks.

In light of these difficulties, the concept of Virtual Power Plants (VPPs) has emerged as a strategic solution. Early in the new millennium (2000), virtual power plants emerged as a unique way to handle DERs, which presented serious difficulties for conventional power grids [4]. By the 2010s, Europe—Denmark and Germany in particular—had taken the lead in commercializing VPPs, demonstrating their capacity to supply ancillary services, actively engage in demand response initiatives, and balance intermittent renewable energy [5-6].

A VPP represents a coordinated aggregation of DER capable of participating in energy markets and delivering grid services akin to traditional power plants. By technically and commercially integrating small-scale DER, VPPs cater to customer needs and furnish essential flexibility to the system. Initially, VPP was conceptualized as a 'virtual utility' [7-8] facilitating collaboration among independent entities to deliver energy-related services without asset ownership, VPPs have evolved to encompass distinct commercial and technical roles [5]. From a technical standpoint, VPPs prove instrumental in managing the uncertainties associated with renewable energy sources (RES) and addressing the escalating flexibility demands of power systems [9].

In the context of Virtual Power Plants (VPPs) and DERs, value stacking has several facets and is essential to optimizing these decentralized energy assets. Value stacking improves asset utilization, creates new revenue streams, [1] and supports grid stability by allowing distributed energy resources to engage in numerous energy markets and services at the same time. [10] It pushes innovation and investment in DER technology and market involvement tactics, speeds up the energy transition, and facilitates the integration of renewable energy supplies into the grid. Value stacking is a technique that VPPs use to coordinate the combined value of DERs, maximizing their effectiveness and contribution to a more resilient, efficient, and sustainable energy system. [11] FCAS balances demand and generation to maintain system frequency in all conditions, including continuous response.

Imbalances in the supply and demand ("regulation" FCAS) and significant occurrences like the failure of a generator, load block, etc. (FCAS "contingency") The FCAS services in the NEM have a five-minute settlement time, just like the energy market. Additionally, by raising generation or lowering demand, "raise" FCAS seek to correct frequency fall occurrences, and "lower" FCAS seek to correct frequency rise events by lowering generation or raising demand levels [12-13]. FCAS contingency is further divided into quick, slow, and delayed FCAS based on the reaction time and length of service.

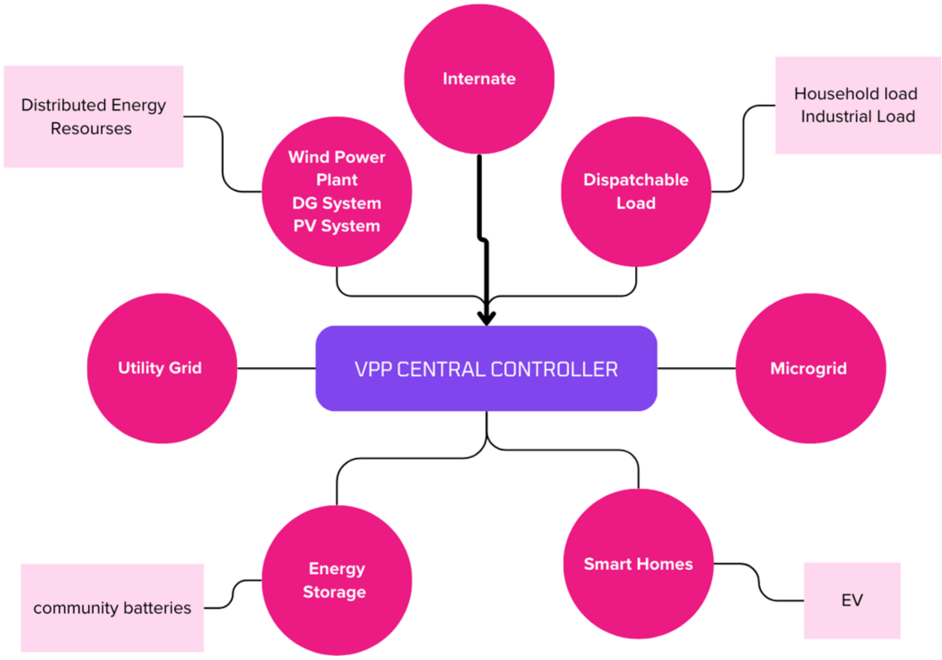


Fig. 1. Typical Architecture of virtual power plant.

Figure 1 shows a typical architecture of VPP which is an advance energy management system. Which is a bunch of different DER and optimize their operation. These assets are integrated and controlled by a cloud-based platform using software and smart communication technology. A VPP has a lot of advantages. For example, VPP can help make DERs more visible to all energy players because of on-site metering installations and enable DER remote control because of a robust communication network—something the power system now lacks. VPP can assist load dispatch centers with automating network monitoring, accurately accounting for transported power, and scheduling RE plants. Additionally, it can use aggregated DERs to deliver auxiliary services. For transmission firms, VPP can assist in reducing transmission congestion and deferring transmission upgrades. For distribution businesses, VPP may assist with precise net load predictions, enabling effective power purchase planning. A VPP's aggregated and transparent DER can also assist discoms in lowering the amount of electricity they buy. For clients with DERs, VPP may assist in increasing their supply capacity to the grid and give them market awareness. The aggregation of DER in a VPP can assist off-grid users in the future when they conduct peer-to-peer transactions.[20]

A. *Contributions of the paper*

As per the literature review mentioned above and to the best of the authors' knowledge, modeling approaches and studies that consider the opportunities presented by VPP's simultaneous participation in multiple markets and provision of various power system services thereby accessing multiple revenue streams—are fundamentally lacking. As a result, a VPP's business case potential and economic performance could be understated. Furthermore, it is crucial to comprehend the technological viability and adaptability of VPP operation in tandem with the financial analysis to increase DER's visibility to system operators and give them a greater grasp of the full potential of VPPs. This paper shows how to use DER value stacking to optimize economic results (minimize expenses) by implementing an optimization problem.

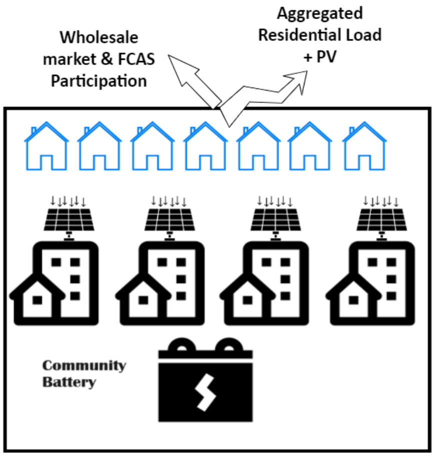
Key novelty and contribution aspects of this paper are as follows:

1. Describe the costs of various services, the available renewable energy sources, and the need for a VPP.
2. Model DER execution: FCAS and energy market.
3. Discover how to create optimization problems using JuMP and model in the Julia programming language.
4. Complete the optimization and use the optimization horizon to see how the battery operates as the price changes.
5. Optimize the process and show the earnings from every market.

This paper integrates community battery, aggregated residential load, and certain levels of PV penetration as VPP which participate in the wholesale market and FCAS (Frequency Control Ancillary Service) markets. try to optimize the cost of this DER in multi-market participation and visualize the revenue for each market using MILP [11].

2. Proposed Methodology

This case considers an aggregation of customers with inflexible demand and a certain level of penetration of PV and community battery (BESS). They participate in the energy market (Wholesale market & FCAS), aiming to minimize the costs by DER value-stack to calculate the value of these aggregations of VPP without considering network constraints. Also, the community battery impact on value stacking is analyzed. Figure 2. represents the block diagram of the proposed system.



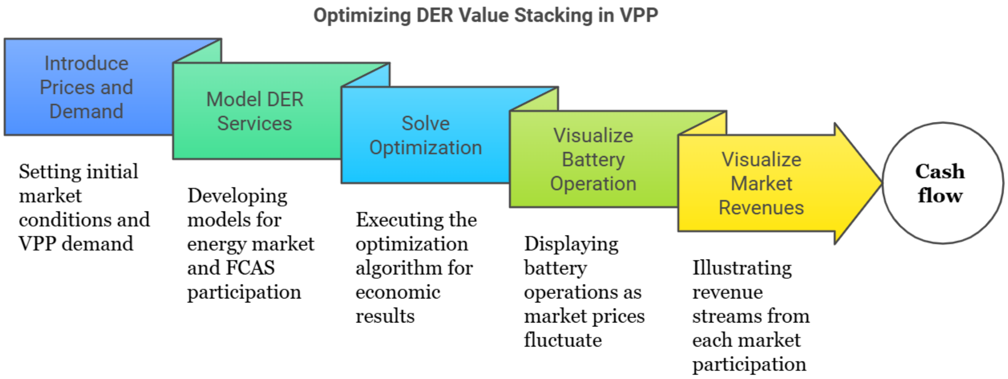


Fig.2. Block diagram of proposed system and process flow

Figure 2 represents an aggregated residential energy system where several households are connected, each having its own electrical demand and some equipped with rooftop solar PV systems. The combined electricity demand of these houses is referred to as the residential load, which typically includes appliances such as lighting, fans, refrigerators, air conditioners, washing machines, and other household devices. To provide support for this network, a community battery is installed, which stores excess solar power generated during the day and supplies it back when demand is high or solar generation is low. This united setup not only balances supply and demand at the community level but also allows participation in both the wholesale electricity market and the FCAS market, where the community battery can provide fast-response services to stabilize grid frequency. In short, this network has residential loads, rooftop PV generation, and a shared community battery working together as a small-scale VPP.

A. Potential Revenue Streams

Understanding market dynamics and the possible commercial regimes for the VPP is necessary to accurately extract and estimate the potential income streams that flexibility from the VPP may provide. These include marketplaces for the generation and consumption of energy as well as a range of technical services that VPP may offer. Within the framework of the National Electricity Market (NEM), there are two primary potential revenue streams for VPPs, the energy market and the FCAS market. These marketplaces and the ideals they represent are reviewed in this section.

Wholesale Market: The Australian Energy Market Operator (AEMO) runs the real-time, five-minute dispatch interval NEM wholesale spot market. Although there isn't a formal day-ahead market, market players must submit their schedules on that day in order for the system operator to do the so-called "pre-dispatch" study, which is mostly done for reliability reasons. In five-minute intervals, generators provide their proposals to AEMO with predetermined energy pricing [14]. The marginal cost of the power, at which all dispatched generators are compensated, establishes the spot price.

Retailers purchase electricity from the NEM at spot rates, acting as the market counterpart, and then resale it to their customers under retail tariffs that represent a variety of charges, including as energy costs, regulated network costs, retail costs, and costs associated with environmental policies [15]. There are two parts to retail tariffs: variable charges and fixed rates. It is common for fixed costs to be assessed on a daily basis. The variable fees are determined by the amount of power used by the customers. The peak demand of the customer and the time of day that power is utilized may also have an impact on the variable rates, depending on the tariff [16].

FCAS Market: The two types of FCAS defined for NEM are regulation FCAS and contingency FCAS. The FCAS market is divided into eight different markets, summarised in Table 1. Regulation AEMO controls FCAS therefore, the generators providing regulation FCAS should have a frequency of between 49.85 Hz and 50.15 Hz, while contingency FCASs are locally controlled and AEMO simply monitors availability and activation. The measures to correct the frequency in contingency events include generator governor response, load shedding, rapid generation, and rapid unit unloading.[21]

In response to ongoing supply/demand imbalances (also known as "regulation" FCAS) and significant occurrences like the loss of a generator or load block, among other things, FCAS are used to maintain the balance between generation and demand and keep the system's frequency within the NEM standards. (FCAS, "contingency"). The FCAS services in the NEM have a 5-minute settlement interval, just like the energy market. Additionally, by raising generation or lowering demand, "raise" FCAS seek to correct frequency drop occurrences, while "lower" FCAS seek to correct frequency rise events by lowering generation or raising demand [17]. Contingency FCAS are further divided into quick, slow, and delayed FCAS based on the reaction time and length of service.

In this paper, VPP co-optimization across energy and FCAS markets using MILP results in FCAS participation being more profitable, primarily because the co-optimization model maximizes revenue by strategically allocating Distributed Energy Resources (such as batteries) to high-value FCAS capacity markets while simultaneously participating in energy arbitrage. This method shows a number of significant revenue streams: 1) "Availability payments" for FCAS (paid just for being ready, requiring minimal energy cycling and incurring near-zero marginal cost for batteries), which offer high-margin, predictable income unaffected by energy volume risk; 2) Exploitation of extreme FCAS scarcity pricing during grid stress events, where prices can spike orders of magnitude above energy prices; and 3) Revenue stacking, where the same battery MW capacity earns from multiple FCAS services (e.g., Raise/Lower Regulation) concurrently with energy buy/sell activities, significantly increasing $/MW utilization. The MILP model finds the best balance between these opportunities by weighing FCAS commitment against energy market bids, battery degradation, and state-of-charge limits. It shows mathematically that including FCAS leads to higher marginal revenue than energy-only strategies for flexible assets, like community batteries, in a VPP.

Table 1 shows the categorization of various FCAS products. For FCAS markets, the FCAS clearing price is decided every five minutes. The market-clearing price and the quantity of reserve active power supplied determine how much the FCAS suppliers are compensated [18-19]. Therefore, FCAS providers receive payment for the capability they enable in the FCAS market, whether or not they receive a request for a response.

Table 1. FCAS classification in NEM

FCAS services	Response time (seconds)	Market Type
Regulation	Continuous	Raise/lower
Contingency	Within 6 seconds	Fast raise/lower
	Within 60 seconds	Slow raise/lower
	Within 300 seconds (5 minutes)	Delayed raise/lower Until notified by central dispatch (presumably within 10 minutes)

B. Problem formulation

To perform the operation 24 hrs time series data are considered [10] which contain PV generation kw, electricity imports price $/kwh, electricity export price $/kwh, FCAS prices for 6 second lower and 6 second rise in $/kw/h and electricity demand in kwh.

From data we can visualize the available PV generation and demand. all the price data in $ per kwh which include cost of import, revenue of export, revenues from 6 second raise FCAS, revenues from 6 second lower FCAS.

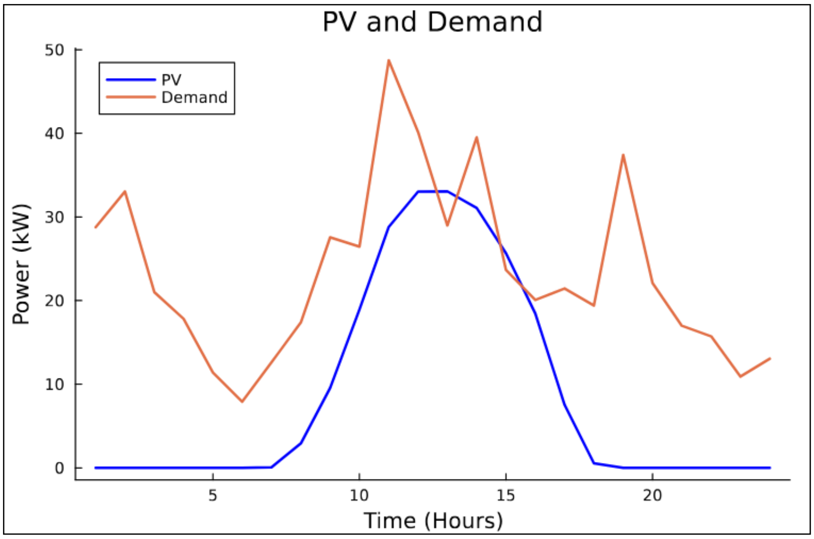


Fig.3. Plot of PV and electricity demand

Figure 3 is the graph of the PV and Demand data shown. The plot is likely to indicate how PV generation fluctuates with the amount of sunshine available, peaking during the afternoon, whereas the demand for power is comparatively high throughout the day, with only little decreases during periods of high PV generation. This shows that although PV provides a supplemental energy source, it is insufficient to curtail the overall demand for power in the time frame given.

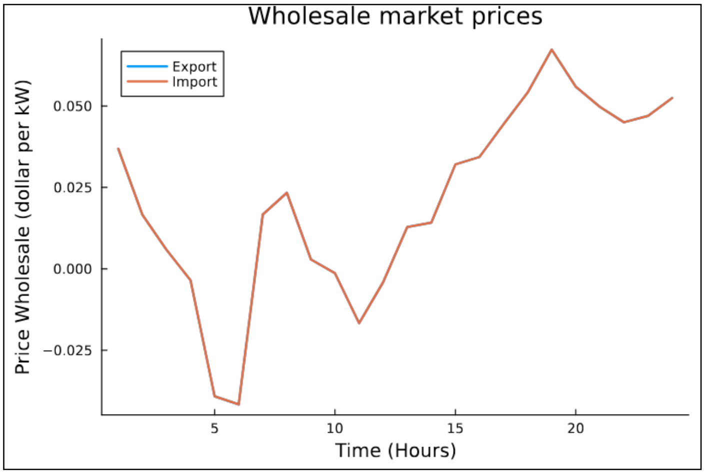


Fig. 4. Plot of wholesale market price

Figure 4 visualizes the wholesale market export and import prices. This is an interesting case, as wholesale prices go negative. This means that customers are incentivized to consume at that time and the battery can charge in anticipation of higher prices

Negative wholesale prices introduce opportunities and incentives for consumers and energy storage systems to play an active role in stabilizing the electricity grid and optimizing energy costs.

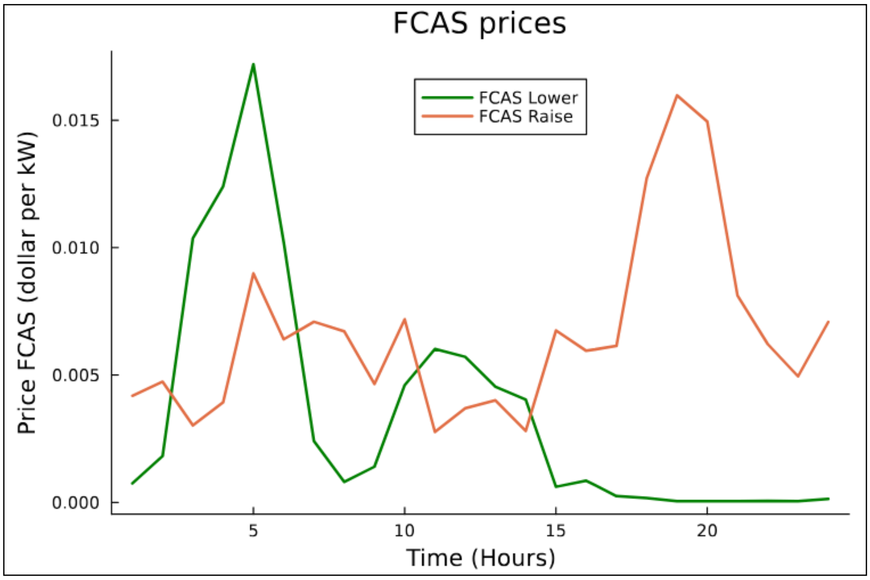


Fig.5. Plot of FCAS price for 6second lower and raise

Figure 5. represents the FCAS prices seen in Both FCAS raise and lower show high prices. This is a case with a high opportunity for the VPP to have revenues even if the demand is most time higher than renewable generation, thanks to the flexibility of the battery.

3. Optimisation Model

This section represents a mathematical optimization model that was created with the Gurobi solver acting as the optimizer in Julia utilizing the JuMP modeling language. The Model () function is used to initialize the model, and it includes specific solver parameters that are configured using the optimizer () function. These choices include disabling presolve and setting a relative MIP gap tolerance of 0.01, Moreover mention possible further customization options, such as setting a time limit for the optimization process. By integrating with strong solvers like Gurobi, this approach provides flexibility and scalability as a framework for handling complicated optimization issues. This allows for effective and efficient problem-solving in various domains.

A. Objective Function

The goal of the model is to reduce the net cost, which may be described as: [10] The cost from importing electricity from the grid subtracts the revenue from exporting electricity to the grid (calculated in the energy balance constraints) The revenues from participating in FCAS market.

objective = minimize

$$\{ \sum_{i=1}^{Ni}[(p_i^- . t. V_i^- - p_i^+ . t. V_i^+) + \sum_{h=1}^{Nh} p_i^{h,curt} . t. c^h - \sum_{\alpha}^{n\alpha}(r_{i,\alpha}^r . V_{i,\alpha}^r + r_{i,\alpha}^l . V_{i,\alpha}^l)]\} \quad (1)$$

B. Model variable and constraints

Model variables are electricity price of export and import, power of PV generation and PV curtailed power, FCAS price for lower and raise, moreover battery variables are storage level of battery, charging and discharging power of battery.

C. BESS operation constraints

The battery operating constraint is the first set of constraints. The battery's maximum and minimum power outputs should be the limits of its charge/discharge power. To ensure that the battery doesn't charge and discharge simultaneously, a binary variable is added.

$$P_{min}^{b+/-} \leq p_i^{b+/-} \leq p_{max}^{b+/-} \quad (2)$$

$$p_i^{b+} \leq \mathrm{Mu_i^b} \quad (3)$$

$$p_i^{b-} \leq \mathrm{M}(1 - \mathrm{u_i^b}) \quad (4)$$

The battery state of charge (SOC) is modeled using intertemporal constraint, which equals to the battery SOC at the previous time step, and the battery charge and discharge at the previous time step. The battery SOC is also limited within its maximum and minimum energy levels. [10]

$$x_{i+1}^b = x_i^b + \left(p_i^{b+} - \frac{p_i^{b-}}{n^b}\right) t \quad (5)$$

$$x_{minEL} \leq x_i^b \leq x_{maxEL} \quad (6)$$

D. PV operation constraint

The PV operation constraints make up the second set of constraints. The maximum output power of the PV is constrained by a time-varying parameter.

$$p_i^p + p_i^{p,curt} \leq P_i^p \quad (7)$$

E. Service provision: Raise FCAS

Batteries and PV systems can raise FCAS by utilizing their operational headroom. This can be accomplished for the PV by running it in curtail mode, which limits the raise FCAS commitment from the PV. Reducing the battery's charge power or boosting its discharge power can also raise FCAS. Additionally, it must be ensured that the battery has sufficient energy to provide services in the event of an emergency.

$$r_i^{r,p} \leq p_i^{p,curt} \quad (8)$$

$$r_i^{r,b} \leq P_{rFCAS}^{b-} - p_i^{b-} + p_i^{b+} \quad (9)$$

$$r_i^{r,p} call \leq x_i^b \quad (10)$$

F. Service provision: Lower FCAS

Batteries and PV systems can reduce FCAS by utilizing their operational margin. This is restricted by PV's power output. For a battery, lower FCAS can be provided by increasing its charge power or decreasing its discharge power. Additionally, it is ensured that there is sufficient headroom in the battery energy level to support service delivery in the event of an emergency.

$$r_i^{l,p} \leq p_i^p \quad (11)$$

$$r_i^{l,b} \leq P_{lFCAS}^{b+} + p_i^{b-} - p_i^{b+} \quad (12)$$

$$r_i^{l,b} call \leq X_{max} - x_i^b \quad (13)$$

G. Energy balance constraint

At the grid connection point (GCP), the energy balance is computed. In other words, demand, battery charge and discharge, and PV generation all affect the import and export of power. The VPP is ensured not to import and export at the same time. The network limit affects import and export at the GCP.

$$p_i^+ - p_i^- = P_i^d + p_i^{b+} - p_i^{b-} - p_i^p \quad (14)$$

$$0 \leq p_i^- \leq M u_i^p \quad (15)$$

$$0 \leq p_i^+ \leq M(1 - u_i^p) \quad (16)$$

4. Results Analysis & Discussion

To maximize overall profit from the wholesale and Frequency Control Ancillary Services (FCAS) markets, solve the model using Gurobi optimizer with an academic license for non-commercial use. The model is built with a time horizon of 24 hours. Calculate total VPP profit for the day, revenue from wholesale market participation and revenue form FCAS market participation. visualize all the results in data frame. The objective function's goal is to maximize market participation revenue while abiding by restrictions on efficiency, power limitations, and storage capacity. battery operation depending on different services and prices. The community batteries system under consideration in the model has a maximum power output of 40 kW, a storage capacity of 100 kWh, and a round trip efficiency of 90%.

Table 1. VPP cash flow data

Cash flow Parameter	Result (dollars)
Total VPP Profits for day	10.023257450677644
Revenue from wholesale market participation	1.5605849010838773
revenue from FCAS market participation	8.462672549593762

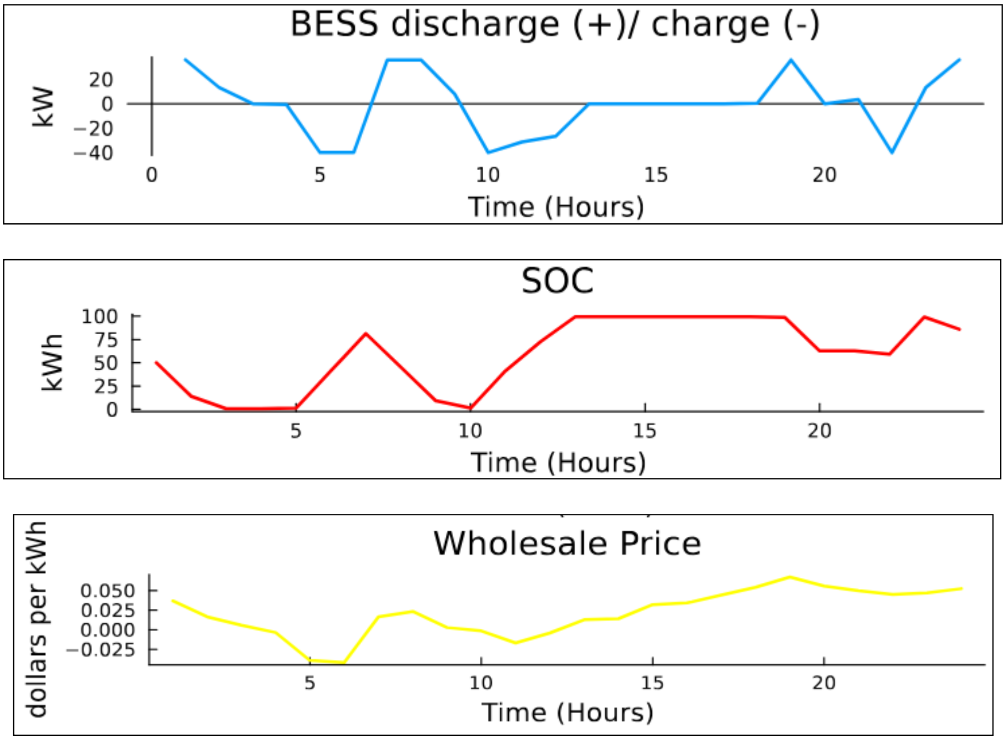


Fig. 6. Plot of BESS charging and discharge with storage level and wholesale price

Combined with the BESS storage level and wholesale power pricing, this plot displays the BESS's charging and discharging operations. The storage level of the BESS shows the proportion of energy capacity filled, and the BESS power indicates positive values for discharging and negative values for charging. An investigation of the relationship between storage activities and market price signals is made possible by plotting the wholesale price of electricity. The system uses price arbitrage behavior to optimize revenue when prices change, selectively charging during low-priced times and discharging during higher-priced periods.

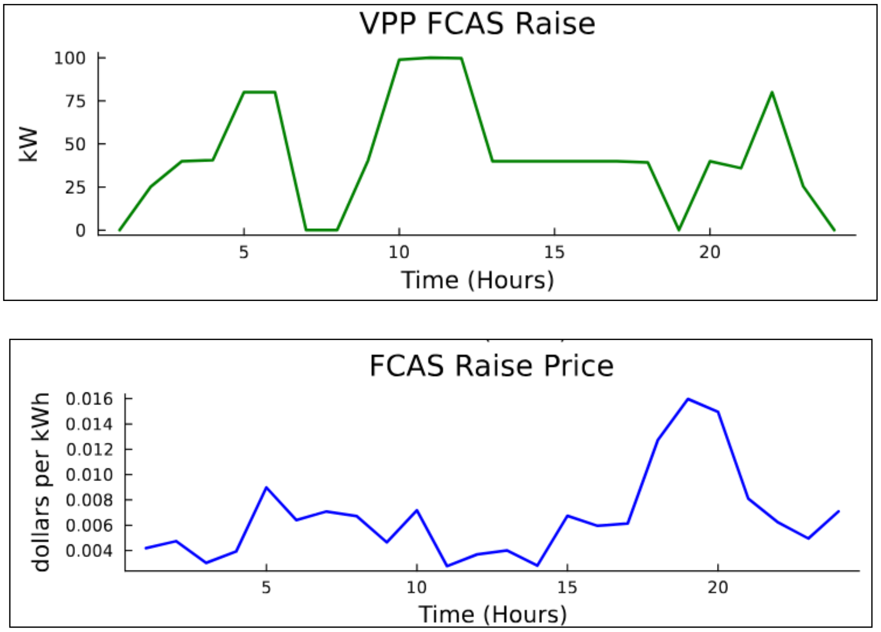


Fig. 7. Plot of VPP for FCAS raise and its price

This plot (Fig.7) depicts the VPP's involvement in the "Raise" service's FCAS market along with the associated costs. Peaks in FCAS participation correspond with larger FCAS price increases, which reflects the VPP's policy of increasing capacity as prices rise in order to maximize ancillary service income. This graphic illustrates how VPPs profit from advantageous market situations while still promoting grid stability.

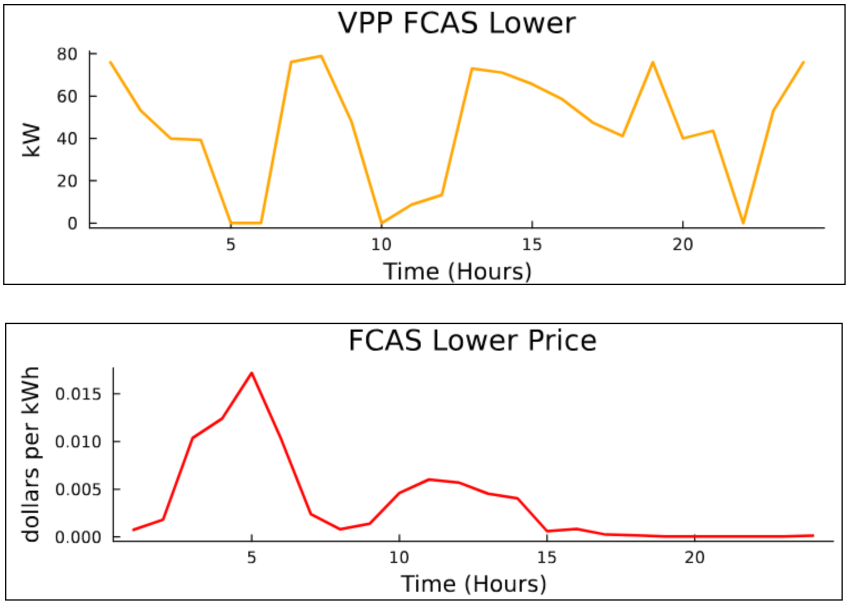


Fig.8. Plot of VPP for FCAS lower and its price

The VPP's participation in the FCAS Lower service is plotted against the FCAS lower pricing over time. Price spikes are clearly correlated with times of higher FCAS and Lower participation. It is clear that the VPP responds to market conditions in an adaptable manner, expanding its service offerings when prices are raised to increase profitability. The function of VPPs in responding to market price signals and controlling lower-frequency grid disruptions is shown in Figure 8.

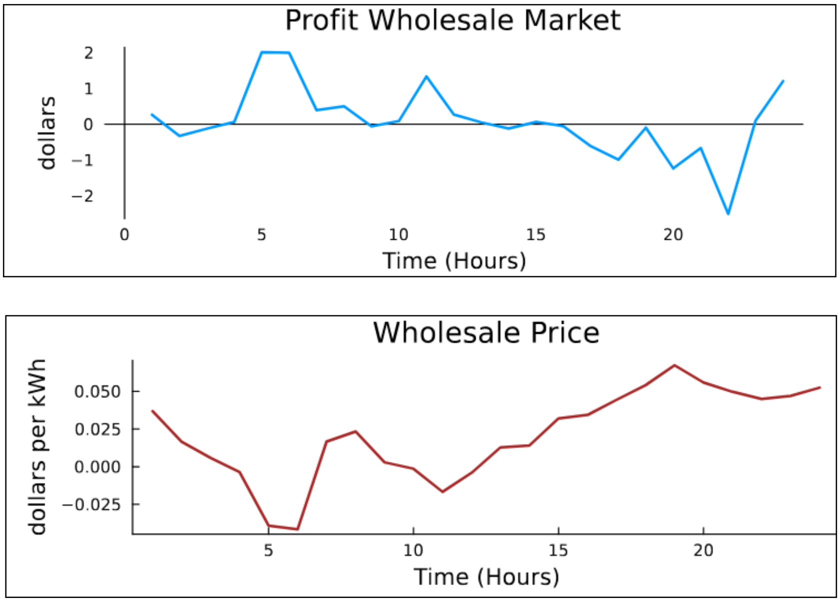


Fig.9. Plot of wholesale market profit its price

Figure 9 indicates the connection between the wholesale power price and the VPP's profitability from energy arbitrage in the wholesale market. According to the statistics, periods with high prices tend to have profit peaks, whereas times with low prices frequently have negative or negligible earnings. The graphic clearly illustrates how changes in wholesale market prices affect VPP profitability, with the system proactively taking advantage of periods of high prices to maximize profits.

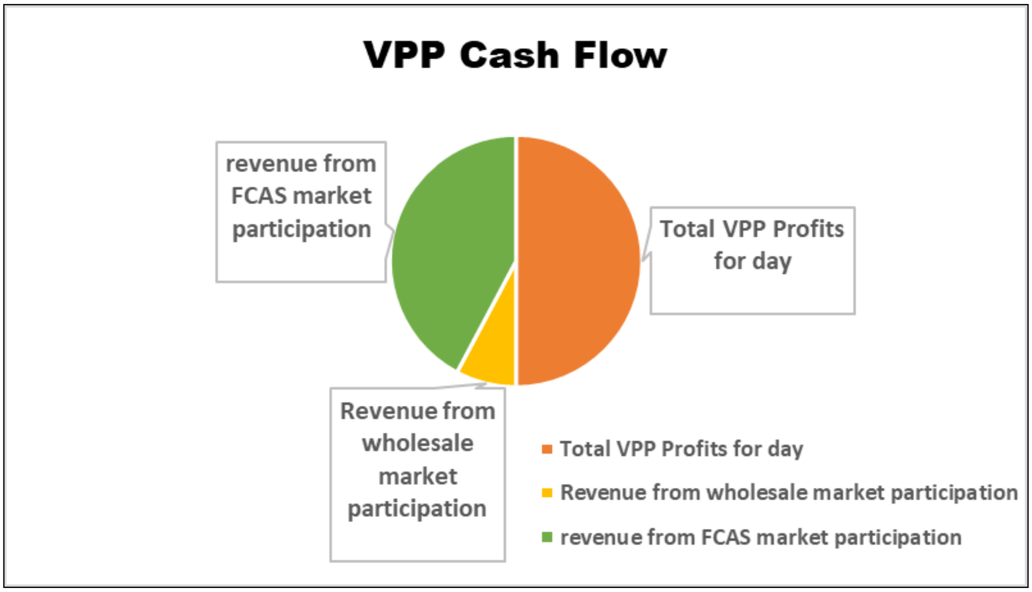


Fig.10. Plot of total cash flow in the wholesale and FCAS market

According to the result, the Virtual Power Plant profits approximately $10.02 for the whole day. The majority of this total—$8.46—comes from participation in the FCAS market, with $1.56 coming from wholesale market involvement. This breakdown shows how much the FCAS market participation contributed to the VPP operation's total profitability. The main source of revenue appears to be FCAS participation, which highlights the vital role that the VPP plays in offering services related to frequency regulation and grid stability. VPPs need to participate in the wholesale market because it offers them access to a wide range of market participants, income diversification, price arbitrage opportunities, grid balancing, and ecosystem integration. Through their participation in wholesale markets, VPPs improve their operational efficiency, bolster their financial stability, and contribute significantly to grid resilience and the shift to sustainable energy.

5. Conclusion

This research has provided an extensive integrated technical and economic evaluation of a VPP made up of conventional DER accessible, including multiple possible revenue streams that can be obtained through multi-market involvement., involving Energy and FCAS markets. the VPP's significant profits from FCAS market participation underscore the importance of grid stability services in its revenue generation strategy. Also, visualize the differences in battery operation depending on the different services and prices. best BESS performance in a volatile energy market. This maximizes financial returns by enabling the battery to strategically store energy during periods of low price and release it during periods of high price. dual visualization—of the battery's operation and the associated revenue—provides an in-depth grasp of the financial and operational impacts of the optimization strategy. The positive cash flow and profitability in both markets reflect the effectiveness of the VPP's operations and its ability to generate revenue from multiple market streams. This indicates a very good business model and operational strategy in the energy market.

For future work, add two additional markets, such as the demand response (DR) market and the hedging market. The energy and Frequency Control Ancillary Services (FCAS) markets are cleared simultaneously, and participants must submit their bids for each five-minute settlement up to one and a half days in advance. However, participants may modify their offers at any time before the start of each five-minute dispatch process, in accordance with market rules. On the other hand, participants acquire DR and hedging products through forward contracts and settle them over a three-month period. Also, addition of more DERs represent a strong real time scenario.

6. References

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