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Enhancing Virtual Power Plant Profitability via Coordinated Resources and Demand Response

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ABSTRACT

Today, the limitations associated with fossil fuel consumption and the growing concerns over environmental pollution have led to an increased reliance on distributed generation resources. At the same time, the role of responsive loads in enhancing network management has gained significant importance. The integration of these elements, alongside energy storage systems, forms what is known as a Virtual Power Plant (VPP). A VPP aggregates distributed generation units, responsive loads, and storage facilities, all coordinated and managed through a central energy management system. The primary objective of this thesis is to develop an effective management framework for the operation of a VPP within the electricity market environment, with the goal of maximizing the profitability of all participating components. In this study, the uncertainties associated with wind turbine output power and fluctuations in energy and reserve market prices were explicitly considered as stochastic variables .The simulation results demonstrate that the proposed probabilistic optimization model enables the VPP to effectively manage these uncertainties. In such a way, the model assures the variability of wind power and the instability of market prices is minimally deficient, and thus there occurs a dramatic hinge in the general profitability of the aggregated system as preferred by the factors of the model.

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1 INTRODUCTION

Virtual Power Plant (VPP) concept now received enormous appeal because of its potential to embrace the distributed energy resources (DERs) in contemporary electricity markets. A VPP will combine decentralized assets e.g. wind turbines, photovoltaics, battery storage and demand response programs into a large central system capable of effectively taking part in the actions of the market [1]. With this aggregation, the DERs can drastically address their respective deficiencies and jointly offer useful services to the grid (such as energy generation, spinning reserve, and grid stability). As renewable energy penetration continues to grow exponentially and the needs of the power system becomes more flexible and responsive, VPPs have become one fundamental need to not only guarantee the efficiency of operations but the reliability of the system [2]. In addition to the technical advantage, VPPs also play the role of economic optimization since they allow small-scale producers and consumers to be fully engaged in competitive electricity systems. The purpose of this study is to maximize the profitability of the VPPs in a competitive market, where special attention to the uncertainty related to wind power generation is paid [3]. A probabilistic optimization framework is built to respond to such challenges and allows stronger scheduling of the available resources and participation in both energy and ancillary service markets [4]. Through its integration of uncertainty into decision-making, the proposed scheme has the opportunity to drive VPPs to even better economic performance in addition to reinforcing their status as an essential provider of renewable energy integration. Although the use of Virtual Power Plants (VPPs) is on the rise, a couple of challenges still exist in making them profitable amid uncertain circumstances. The hardest problems can be explained as follows:

- **Uncertainty in wind power generation**, which reduces the reliability and predictability of energy supply.
- **Volatility in electricity market prices**, which directly impacts revenues from energy sales and reserve services.
- **Operational constraints of distributed energy resources (DERs)**, including generation units, energy storage systems, and demand-side management programs.
- **Security and stability requirements**, which must be satisfied to maintain grid reliability and meet technical standards.

The conventional deterministic optimization models find it difficult to sufficiently deal with these issues, because they do not appreciate the stochastic and dynamic nature of the system. Such a restriction usually leads to improper or hazardous decision-making. Therefore, the development of a **robust probabilistic optimization framework** is essential to enable VPPs to operate effectively, mitigate uncertainties, and maximize economic returns in competitive electricity markets. The main objectives of this research can be outlined as follows:

1. **Developing a probabilistic optimization model** to maximize the profitability of a Virtual Power Plant (VPP) in both day-ahead energy and spinning reserve markets.
2. **Incorporating uncertainties** in wind power generation and market price fluctuations through scenario-based modeling techniques.
3. **Addressing technical constraints**, including generator operating limits, ramping capabilities, battery storage characteristics, and load flexibility.
4. **Ensuring grid security and reliability** while simultaneously optimizing the economic performance of the VPP.
5. **Establishing a comprehensive optimization framework** that integrates all VPP components—distributed generation, energy storage, and demand response—into a unified model.

The contributions and innovations of this study include:

- **Holistic integration of VPP components**: Unlike many prior studies that analyze generation, storage, or demand-side response in isolation, this research develops a unified optimization framework that simultaneously incorporates all components.
- **Probabilistic scenario-based modeling**: By applying scenario generation and reduction techniques, the proposed model effectively captures uncertainties in renewable output and market dynamics, leading to more reliable decision-making.
- **Application of intelligent optimization algorithms**: A genetic algorithm is employed to efficiently solve the complex optimization problem, ensuring convergence toward high-quality solutions within reasonable computational time.

4. 2. Related work

This section will present a description of literature that has been developed on the issue of the Virtual Power Plants (VPPs), describing different methods of their modeling and management in competitive electricity markets. Performance in both energy and ancillary service markets, the use of effective strategies in their participation, and optimization of VPP schedule and dispatch enhancement are the primary areas of consideration that relate to VPP evolution. Besides, a number of papers have shown case-based and simulation-based analysis of hypothetical and real-world configuration of VPP, which provide useful insights into their feasibility in practice [10], [11]. The review reveals the need to combine the integration of all key VPP elements generation, storage, and demand-side, management into a single system to increase profitability, efficiency and ensure reliability of the modern power system.VPPs are the main key to active systems of distribution and competitive electricity markets. In active distribution systems, VPPs allow decentralized energy resources to be managed in a coordinated manner, supporting grid resilience, and helping to limit technical losses. In power markets VPPs make prices by competing in the day-ahead market and in reserve markets, which impact the price formation and improve system balancing. Combining distributed energy resources (DERs), VPPs can empower smaller generating resources to surmount their drawbacks and thereby compete in large markets effectively [12]. The commercial dynamics between entities in a virtual power plant (VPP) include revenue as well as cost settlement. A VPP will get its revenues mostly through the sale of electricity, reserve services and the ability to engage in demand response programs. On the other hand, fuel consumption, equipment maintenance cost, degradation of the batteries, and possible fines due to misconducts during market bidding will affect its cost structure. Alongside that, contractual arrangements with distributed generators, consumers as well as storage operators will be central to determining the profitability and the overall risk portfolio of the VPP [13].

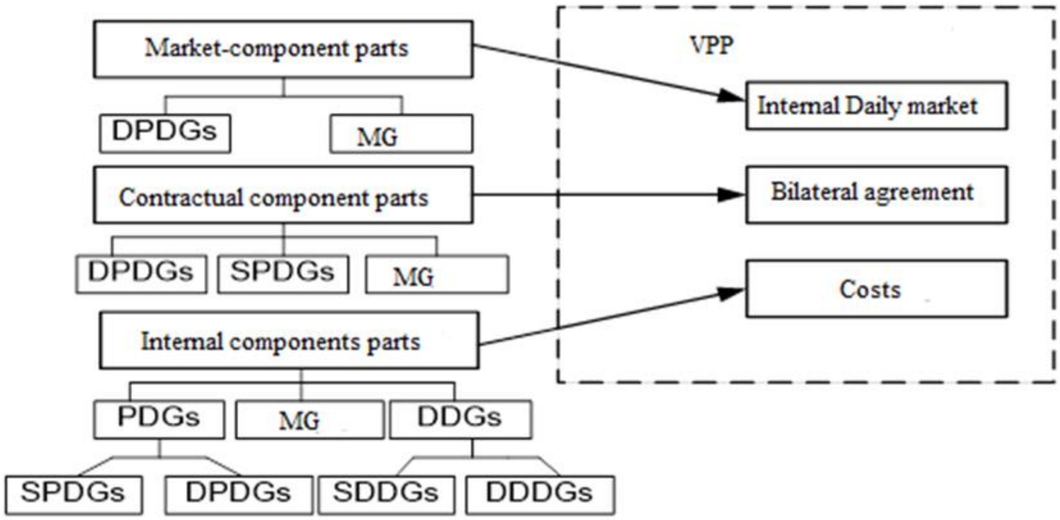

Figure 1 : VPP's economic relationship with its sectors

A more in-depth comprehension of these sources of economy is obviously necessary when considering the implementation of efficient bidding strategies and failure to take these into consideration can lead to the inability to maximize profits when operating as a Virtual Power Plant. The active control of distribution networks is a critical need when designing successful integration of Virtual Power Plants (VPPs). This involves:

• Keeping the power quality within acceptable tolerance with regard to voltage and frequency stability.
• Reducing loss of energy in transmission as well as distribution by increasing the efficiency of the entire system.
• Quality assurance in terms of adherence to technical and safety benchmark which is critical towards secure stable operations.

Significant coordination between distribution system operators (DSOs) and VPPs is thus required to ensure that stability, reliability, and efficiency or supply systems are maintained in present day decentralised power supply networks [14].

5. **The interaction of Virtual Power Plants (VPPs) with electricity markets highlights the fact that market-oriented strategies must be implemented so that these systems can be optimized with respect to the economic performance. The following outline is provided of these interactions:**

• **Day-Ahead Energy Market:** VPPs bid in the energy market and therefore they should have the correct estimation of energy production as well as demand so that they can maximize their place in the market.

• **Spinning Reserve Market:** VPPs are dispatched to add reserve capacity to the system and provide quick responses to unanticipated supply and demand swings to increase overall system reliability as a spinning reserve.

• **Demand Response Programs:** VPPs adjust consumer loads, in real-time, so that supply and demand can be maintained at equilibrium and remain stable on the grid.

For maximum profitability and where they need to be compliant to contractual obligations, VPPs have to take bold biddings and dynamic operational shifts that will be responsive to market uncertainties [15].

2 Methods

6. **The given section provides a probabilistic optimization model to turn a profit of the Virtual Power Plants (VPPs) in the competitive electricity markets. The model is characterized by explicitly covering uncertainties that include uncertainties in wind power generation and the change in market prices, which happen to have significant influence on economic performance of VPPs. Unlike the deterministic methodologies, the probabilistic framework can increase the performance of risk management and allows making more consistent decisions in the environment of uncertainties during operations.**

the proposed model integrates all major elements of VPP-distributed generators (DGs), series of wind turbines, energy storage systems, and demand response systems-into one optimization framework. This integration ensures optimal participation in both day-ahead energy markets and spinning reserve markets, thereby maximizing profitability while maintaining system reliability [16].

7. Structure and Components of the VPP

The structure of the Virtual Power Plant (VPP) in this study consists of the following key elements:

- **Conventional distributed generators:** These units deliver stable and controllable power output, ensuring baseline reliability within the VPP framework.
- **Wind turbines:** As renewable sources, wind turbines introduce variability and uncertainty into the system, reflecting the challenges of integrating intermittent energy resources.
- **Energy storage systems:** These assets enhance flexibility by storing excess electricity during periods of low demand and releasing it during peak or high-price intervals, thereby stabilizing operations.
- **Demand response loads:** These enable adaptive load shifting or reduction based on market price signals or grid requirements, further supporting system balance and cost-effectiveness.

Together, these components interact dynamically with the main grid, collectively shaping both the technical reliability and the overall economic efficiency of the VPP [17].

8. Assumptions Considered for the VPP

The modeling of the proposed model relies on a number of assumptions:

Stochastic representation of uncertainty: wind power production and market price are considered as stochastic representations which are represented using the appropriate probability distributions in order to capture the variability involved.

• Integration of technical constraints: There are specifically included limits of operation, like defined bounds on output of generators, ramping rates, battery storage efficiency, defining realistic behavior of the system.

• Market participation structure: The VPP is even presumed to get involved in the day-ahead energy markets, as well as in spinning reserve markets, as it operates on two fronts of energy supply and system reliability.

• A scenario- based modeling approach: Uncertainties are modeled as a scenario-generation process, and methods of uncertainty reduction can be used to avoid the exponential growth of computational complexity of such models without sacrificing accuracy.

The assumptions form a basis of developing a feasible and sound optimization structure that would respond to that which is actually experienced in the market and in the operations themselves. [18].

9. Probabilistic Scheduling of the VPP

To effectively manage uncertainties, the study employs a stochastic programming framework that follows these steps:

- Scenario generation: A diverse set of possible scenarios is created using historical data and appropriate statistical distributions, capturing the variability of wind power output and market prices.
- Scenario reduction: Advanced reduction algorithms are applied to minimize computational burden while retaining the essential variability and probabilistic characteristics of the system.
- Optimization across scenarios: The formulated optimization problem is solved across all remaining representative scenarios, producing an expected optimal solution that balances profitability and risk.

This stochastic approach ensures that the Virtual Power Plant can operate under realistic market and technical conditions while maintaining computational efficiency [19].

3.1 Modeling of Uncertainties

Uncertainties in wind power generation and market prices are captured through the use of probability distributions:

- **Wind power forecast errors:** These are represented using the Beta distribution, which effectively models the bounded and asymmetric nature of wind variability.
- **Day-ahead market prices:** These are modeled either through Normal distributions or by employing historical market data to reflect realistic price fluctuations.

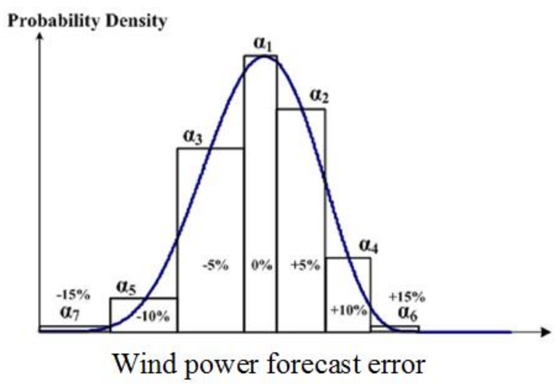

Figure 2: An example of the beta probability distribution function for the output prediction error of a wind unit and its discretization method [5]

By incorporating these probabilistic distributions, the model can simulate a wide range of potential outcomes, enabling more informed and resilient decision-making under uncertainty [20].

10. Formulation of the Stochastic Optimization Problem

3.2Objective Function

The optimization model proposed is to best fit the main aim, that is: the maximization of the expected profit of the Virtual Power Plant (VPP). The profit formula includes the incomes and expenses connected with the entering of the market and managing the system:

Sources of revenues

o Day-ahead electricity market revenue generated by the sale of energy.

o Compensations when delivering spinning reserve capacity.

o Incentive compliance with renewable energy production.

Elements of cost

o Costs involved in running the generators such as cost of fuel as well as maintenance costs.

o The battery degradation losses and inefficiency of the battery storage system.

o Punishments occasioned under demand reduction.

o Fines because of scheduled and actual market participation imbalances.

Mathematically the objective function can be written as the weighted sum of potential profits under all possible scenarios with each weight being the probability of that scenario. Such probabilistic formulation will guarantee balanced profitability and risk management trade-off to improve the economic robustness of VPP operations [21].

3.3Constraints in the Base Scenario

The optimization framework builds in a set of operational constraints that must be satisfied all the time across all scenarios so as to ensure technical feasibility and system reliability:

- Power balance constraint: Ensures that the total power generation and the total power stored match that of the total system demand, which ensures grid stability at each given time step.
- Limits on transmission lines: Impose constraints on power flows so that there is no overloading of the transmission lines that couple the VPP and the main grid and hence safe and secure operation.
- Battery capacity and efficiency: Specify operating limits of the energy storage including state of charge limits, limits to charging and discharging voltages / currents, and round trip efficiency parameters.

Since the model imposes these limits, the scheduling and operation of the VPP becomes technical feasible and economically desirable at different market and generation scenarios [22].

3.4 Constraints in Each Individual Scenario

Such limitations are only scenario-specific and represent the operating constraints applied to VPP components:

- Generator output limits: Specifies the lower limit and the upper limit of distributed generation units.

- Limitations on the rate of change: limit the rate at which generators are able to modify their output.
- Demand response flexibility: Define the allowable shifts or load reduction.

Spinning reserve needs: The needs of the reserve capacity must be given to meet the sudden increases or decreases in supplies or demands [23].

11. Key Features of the Model:

- **Simultaneous participation in energy and spinning reserve markets**: Ensures that the VPP maximizes its profitability by leveraging multiple revenue streams.
- **Integration of distributed generation, storage, and demand response**: Provides a holistic framework that captures the full potential of all VPP components.
- **Adoption of advanced optimization techniques such as genetic algorithms**: Facilitates the efficient solution of complex mathematical formulations associated with VPP operations.
- **Application of scenario generation and reduction methods**: Effectively manages uncertainties, reducing computational burden while preserving decision-making accuracy

4. Case Study and Simulation Results of the Probabilistic Optimization Model for VPP Profit

This section is a case study that seeks to determine the usefulness of the probabilistic optimization model that was developed in Chapter Three in optimizing the profitability of a Virtual Power Plant (VPP) when faced with uncertainty in market conditions. The case study assumes a VPP that consists of five distributed resources such as conventional generators, wind turbines, energy storage solutions, demand response loads. The key goal is to optimize the VPP incorporation in the day-ahead energy market as well as spinning reserve market. A simulation approach is used and 6000 initial scenarios are built using probability distributions of market prices and wind power output. These scenarios are then sequentially trimmed down to seven scenarios representing with the use of scenario reduction methods methods to be sure that such representations are computationally effortless and at the same time it has efficacy in expressing the innate uncertainty.

5. Input Data for Solving the Problem

4.1 Structure of the VPP

Each component of the VPP is designed to contribute to its overall operational and economic performance:

- **Distributed Generators (DGs):** Conventional generation units characterized by fixed operational costs, providing stable and controllable power output.
- **Wind Turbines:** Renewable energy sources whose variable output is represented using a Beta probability distribution to capture forecast uncertainty.
- **Demand Response Loads:** Flexible consumer loads that can be curtailed during peak demand periods to lower consumption, or increased during low-price periods to enhance market efficiency.

Table 1 : Information on DGs installed in units

unit	P^{min} $[kW]$	P^{max} $[kW]$	$OMVAR$ $[kW/h]$	HR $[kJ/kWh]$
1	10	100	0/015	13846
2	10	100	0/018	12000
3	30	300	0/013	11613
4	30	300	0/013	11613
5	100	1000	0/0096	16438

Table 2 : Electrical load of each unit in 24 hours of planning in kW

HOUR	UNIT 1	UNIT 2	UNIT 3	UNIT 4	UNIT 5
1	84	38	70	68	68
2	83	37	73	68	63
3	84	38	75	68	52
4	84	36	73	68	52
5	80	37	73	68	52
6	90	33	73	67	52
7	118	58	75	69	59
8	130	78	74	71	57
9	141	95	68	81	66
10	147	97	71	90	86
11	148	92	72	87	92
12	128	95	74	88	92
13	99	91	73	86	88
14	96	96	71	85	88
15	109	90	70	89	82
16	135	99	70	87	100
17	145	100	79	86	85
18	150	100	80	82	81
19	144	82	77	80	73
20	133	66	72	77	64
21	92	45	73	71	62
22	60	34	70	69	60
23	63	30	66	69	69
24	62	29	67	69	73

4.2Wind Power Forecast

Table 4-3 presents the forecasted wind power output (kW) for each unit across a 24-hour horizon. For instance:

Table 3 : Predicted power output for installed wind turbines in units in kW

HOUR	UNIT 1	UNIT 2	UNIT 3	UNIT 4	UNIT 5
1	0	22	12	0	12
2	0	14	4	0	4
3	2	0	8	2	8
4	0	0	2	0	2
5	12	4	0	10	8
6	12	14	0	10	8
7	0	4	0	0	8
8	4	8	0	8	8
9	4	14	2	8	2
10	12	14	0	16	0
11	8	4	2	10	2
12	26	4	0	30	0
13	12	0	2	16	2
14	18	48	0	22	6
15	26	0	0	30	6
16	18	0	0	22	4
17	4	0	6	4	6
18	48	0	0	48	0
19	48	0	12	48	12
20	8	0	12	10	12
21	8	2	26	10	26
22	12	0	48	14	48
23	4	0	34	6	34
24	2	0	26	4	26

4.3 Market Price Forecast

Table 4-4 presents the forecasted market prices (in $/kW) for both energy and spinning reserve services:

Table 4 : Forecasted Price Values in Energy and Spinning Reserve Markets

Hour	Energy Purchase Price	Energy Sale Price	Spinning Reserve Price
1–9	0.12	1.08	0.09
10–19	0.17	1.53	0.185
20–24	0.12	1.08	0.09

Specific portions of the load can be curtailed during designated hours as follows:

- **Unit 1**: 70 kW between 10:00 and 19:00
- **Unit 2**: 50 kW between 10:00 and 19:00
- **Unit 3**: 30 kW between 01:00 and 09:00
- **Unit 4**: 10 kW between 20:00 and 24:00
- **Unit 5**: 40 kW between 10:00 and 19:00

5. Results and Discussion

The objective function is formulated to **maximize the expected profit** of the VPP, taking into account the following elements:

- **Revenue from energy sales** in the electricity market.
- **Revenue from providing spinning reserves** to support grid reliability.
- **Incentives for renewable energy generation**, reflecting environmental and policy benefits.
- **Operational costs**, including fuel consumption, maintenance expenses, battery degradation, and penalty charges.

A Genetic Algorithm (GA) was employed to address the complex stochastic optimization problem. The algorithm was configured with the following parameters:

- **Population size**: 100
- **Mutation rate**: 0.9
- **Crossover rate**: 0.1

5.1 Output Tables for DG Units

Tables 4-5 through 4-12 present the power output of the distributed generation (DG) units (measured in kW) over a 24-hour period across seven different scenarios. For example, **Table 4-5** illustrates the results for the base case, representing the main scenario:

Table 5 : Output power of DGs in the main mode in kW

HOUR	1	2	3	4	5	6	7	8	9	10	11	12
DG1	0	0	0	0	0	0	0	0	0	10	10	10
DGR1	0	0	0	0	0	0	0	0	0	0	90	90
DG2	27	30	38	36	35	26	56	74	88	10	10	10
DGR2	0	0	0	0	0	0	0	0	0	0	90	90
DG3	34	41	41	42	43	43	45	44	37	30	30	30
DGR3	0	0	0	0	0	0	0	0	0	0	270	270
DG4	68	68	67	68	63	62	69	67	77	30	30	30
DGR4	0	0	0	0	0	0	0	0	0	0	270	270
DG5	0	0	0	0	0	0	0	0	0	100	100	100
DGR5	0	0	0	0	0	0	0	0	0	0	900	900
HOUR	13	14	15	16	17	18	19	20	21	22	23	24
DG1	10	10	10	10	10	10	10	0	0	0	0	0
DGR1	90	90	90	90	90	90	90	0	0	0	0	0
DG2	10	10	10	10	10	10	10	66	44	34	30	29
DGR2	90	90	90	90	90	90	90	0	0	0	0	0
DG3	30	30	30	30	30	30	30	66	60	46	49	54
DGR3	270	270	270	270	270	270	270	0	0	0	0	0
DG4	30	30	30	30	30	30	30	62	56	52	56	57
DGR4	270	270	270	270	270	270	270	0	0	0	0	0
DG5	100	100	100	100	100	100	100	0	0	0	0	0
DGR5	900	900	900	900	900	900	900	0	0	0	0	0

Where:
- **DGx**: Refers to the base generation produced by unit *x*.
- **DGRx**: Represents the renewable generation component of unit *x*.

These tables demonstrate how the VPP dynamically adjusts its generation strategy in response to variations in wind availability and fluctuations in market prices.

Optimal Scheduling Strategy

The results reveal that:
- **During peak hours (10–19):** when market prices rise, the VPP increases its power generation and enhances its participation in the energy market.
- **During off-peak hours:** the VPP decreases generation and may utilize surplus capacity to charge batteries for future use.
- **Under high wind generation conditions:** reliance on conventional DGs is reduced, thereby lowering operational costs.

• **Through demand response programs:** the VPP can curtail loads during high-price periods, effectively improving overall profitability.

Table 6 : Output power of DGs in the first scenario in kW

HOUR	1	2	3	4	5	6	7	8	9	10	11	12
DG1	0	0	0	0	0	0	0	0	0	10	10	10
DGR1	0	0	0	0	0	0	0	0	0	90	90	90
DG2	26	30	38	36	35	26	56	74	88	10	10	10
DGR2	0	0	0	0	0	0	0	0	0	90	90	90
DG3	34	41	41	42	43	43	45	44	37	30	30	30
DGR3	0	0	0	0	0	0	0	0	0	270	270	270
DG4	68	68	67	68	63	62	69	67	77	30	30	30
DGR4	0	0	0	0	0	0	0	0	0	270	270	270
DG5	0	0	0	0	0	0	0	0	0	100	100	100
DGR5	0	0	0	0	0	0	0	0	0	900	900	900
HOUR	13	14	15	16	17	18	19	20	21	22	23	24
DG1	10	10	10	10	10	10	10	100	88	54	61	61
DGR1	90	90	90	90	90	90	90	0	0	0	0	0
DG2	10	10	10	10	10	10	10	100	100	100	100	100
DGR2	90	90	90	90	90	90	90	0	0	0	0	0
DG3	30	30	30	30	30	30	30	300	300	300	300	300
DGR3	270	270	270	270	270	270	270	0	0	0	0	0
DG4	30	30	30	30	30	30	30	300	300	300	300	300
DGR4	270	270	270	270	270	270	270	0	0	0	0	0
DG5	100	100	100	100	100	100	100	0	0	0	0	0
DGR5	900	900	900	900	900	900	900	0	0	0	0	0

Table 7 : Output power of DGs in the second scenario in kW

HOUR	1	2	3	4	5	6	7	8	9	10	11	12
DG1	84	83	83	84	74	84	100	100	100	10	10	10
DGR1	0	0	0	0	0	0	0	0	0	90	90	90
DG2	100	100	100	100	100	100	100	100	100	10	10	10
DGR2	0	0	0	0	0	0	0	0	0	90	90	90
DG3	300	300	300	300	300	300	300	300	300	30	30	30
DGR3	0	0	0	0	0	0	0	0	0	270	270	270
DG4	300	300	300	300	300	300	300	300	300	30	30	30

DGR4	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**270**	**270**	**270**
DG5	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**100**	**100**	**100**
DGR5	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**900**	**900**	**900**
HOUR	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
DG1	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**0**	**0**	**54**	**61**	61
DGR1	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**0**	**0**	**0**	**0**	0
DG2	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**66**	**44**	**100**	**100**	100
DGR2	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**0**	**0**	**0**	**0**	0
DG3	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**300**	**300**	**300**	**300**	300
DGR3	**270**	**270**	**270**	**270**	**270**	**270**	**270**	**0**	**0**	**0**	**0**	0
DG4	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**300**	**300**	**300**	**300**	300
DGR4	**270**	**270**	**270**	**270**	**270**	**270**	**270**	**0**	**0**	**0**	**0**	0
DG5	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**0**	**0**	**0**	**0**	0
DGR5	**900**	**900**	**900**	**900**	**900**	**900**	**900**	**0**	**0**	**0**	**0**	0

Table 8 : Output power of DGs in the third scenario in kW

HOUR	**1**	**2**	3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
DG1	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**10**	**10**	**10**
DGR1	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**		**0**	**90**	**90**
DG2	**27**	**30**	**38**	**36**	**35**	**26**	**56**	**74**	**88**	**10**	**10**	**10**
DGR2	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**		**0**	**90**	**90**
DG3	**34**	**41**	**41**	**42**	**43**	**43**	**45**	**44**	**37**	**30**	**30**	**30**
DGR3	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**		**0**	**270**	**270**
DG4	**68**	**68**	**67**	**68**	**63**	**62**	**69**	**67**	**77**	**30**	**30**	**30**
DGR4	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**		**0**	**270**	**270**
DG5	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**100**	**100**	**100**
DGR5	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**		**0**	**900**	**900**
HOUR	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
DG1	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**0**	**0**	**0**	**0**	**0**
DGR1	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**0**	**0**	**0**	**0**	**0**
DG2	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**0**	**0**	**0**	**0**	**0**
DGR2	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**0**	**0**	**0**	**0**	**0**
DG3	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**66**	**60**	**46**	**50**	**54**

DGR3	**270**	**270**	**270**	**270**	**270**	**270**	**270**	**0**	**0**	**0**	**0**	**0**
DG4	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**62**	**56**	**52**	**56**	**57**
DGR4	**270**	**270**	**270**	**270**	**270**	**270**	**270**	**0**	**0**	**0**	**0**	**0**
DG5	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**0**	**0**	**0**	**0**	**0**
DGR5	**900**	**900**	**900**	**900**	**900**	**900**	**900**	**0**	**0**	**0**	**0**	**0**

Table 9 : Output power of DGs in the fourth scenario in kW

HOUR	**1**	**2**	3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
DG1	**84**	**83**	**83**	**84**	**74**	**84**	**100**	**100**	**100**	**10**	**10**	**10**
DGR1	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**90**	**90**	**90**
DG2	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**10**	**10**	**10**
DGR2	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**90**	**90**	**90**
DG3	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**30**	**30**	**30**
DGR3	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**270**	**270**	**270**
DG4	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**30**	**30**	**30**
DGR4	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**270**	**270**	**270**
DG5	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**100**	**100**	**100**
DGR5	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**900**	**900**	**900**
HOUR	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
DG1	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**0**	**0**	**0**	**0**	**0**
DGR1	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**0**	**0**	**0**	**0**	**0**
DG2	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**66**	**44**	**34**	**30**	**29**
DGR2	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**0**	**0**	**0**	**0**	**0**
DG3	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**66**	**61**	**46**	**50**	**55**
DGR3	**270**	**270**	**270**	**270**	**270**	**270**	**270**	**0**	**0**	**0**	**0**	**0**
DG4	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**62**	**56**	**52**	**56**	**57**
DGR4	**270**	**270**	**270**	**270**	**270**	**270**	**270**	**0**	**0**	**0**	**0**	**0**
DG5	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**0**	**0**	**0**	**0**	**0**
DGR5	**900**	**900**	**900**	**900**	**900**	**900**	**900**	**0**	**0**	**0**	**0**	**0**

Table 10 : DG output power in the fifth scenario in kW

HOUR	**1**	**2**	3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
DG1	**84**	**83**	**83**	**84**	**74**	**84**	**100**	**100**	**100**	**10**	**10**	**10**
DGR1	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**90**	**90**	**90**

DG2	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**10**	**10**	**10**
DGR2	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**90**	**90**	**90**
DG3	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**30**	**30**	**30**
DGR3	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**270**	**270**	**270**
DG4	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**30**	**30**	**30**
DGR4	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**270**	**270**	**270**
DG5	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**100**	**100**	**100**
DGR5	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**900**	**900**	**900**
HOUR	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
DG1	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**0**	**0**	**0**	**0**	**0**
DGR1	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**0**	**0**	**0**	**0**	**0**
DG2	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**66**	**44**	**34**	**30**	**29**
DGR2	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**0**	**0**	**0**	**0**	**0**
DG3	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**300**	**300**	**300**	**300**	**300**
DGR3	**270**	**270**	**270**	**270**	**270**	**270**	**270**	**0**	**0**	**0**	**0**	**0**
DG4	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**300**	**300**	**300**	**300**	**300**
DGR4	**270**	**270**	**270**	**270**	**270**	**270**	**270**	**0**	**0**	**0**	**0**	**0**
DG5	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**0**	**0**	**0**	**0**	**0**
DGR5	**900**	**900**	**900**	**900**	**900**	**900**	**900**	**0**	**0**	**0**	**0**	**0**

Table 11 : DG output power in the sixth scenario in kW

HOUR	**1**	**2**	3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
DG1	**84**	**83**	**83**	**84**	**74**	**84**	**100**	**100**	**100**	**10**	**10**	**10**
DGR1	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**90**	**90**	**90**
DG2	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**10**	**10**	**10**
DGR2	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**90**	**90**	**90**
DG3	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**30**	**30**	**30**
DGR3	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**270**	**270**	**270**
DG4	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**30**	**30**	**30**
DGR4	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**270**	**270**	**270**
DG5	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**100**	**100**	**100**
DGR5	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**900**	**900**	**900**
HOUR	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**

DG1	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**0**	**0**	**0**	**0**	**0**
DGR1	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**0**	**0**	**0**	**0**	**0**
DG2	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**0**	**0**	**0**	**0**	**0**
DGR2	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**0**	**0**	**0**	**0**	**0**
DG3	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**66**	**60**	**45**	**48**	**55**
DGR3	**270**	**270**	**270**	**270**	**270**	**270**	**270**	**0**	**0**	**0**	**0**	**0**
DG4	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**62**	**56**	**52**	**56**	**57**
DGR4	**270**	**270**	**270**	**270**	**270**	**270**	**270**	**0**	**0**	**0**	**0**	**0**
DG5	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**0**	**0**	**0**	**0**	**0**
DGR5	**900**	**900**	**900**	**900**	**900**	**900**	**900**	**0**	**0**	**0**	**0**	**0**

Table 12 : Output power of DGs in the seventh scenario in kW

HOUR	**1**	**2**	3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
DG1	**84**	**83**	**83**	**84**	**74**	**84**	**100**	**100**	**100**	**10**	**10**	**10**
DGR1	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**90**	**90**	**90**
DG2	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**10**	**10**	**10**
DGR2	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**90**	**90**	**90**
DG3	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**30**	**30**	**30**
DGR3	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**270**	**270**	**270**
DG4	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**	**30**	**30**	**30**
DGR4	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**270**	**270**	**270**
DG5	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**100**	**100**	**100**
DGR5	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**900**	**900**	**900**
HOUR	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
DG1	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**0**	**0**	**0**	**0**	**0**
DGR1	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**0**	**0**	**0**	**0**	**0**
DG2	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**0**	**0**	**0**	**0**	**0**
DGR2	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**0**	**0**	**0**	**0**	**0**
DG3	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**66**	**60**	**45**	**48**	**55**
DGR3	**270**	**270**	**270**	**270**	**270**	**270**	**270**	**0**	**0**	**0**	**0**	**0**
DG4	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**62**	**56**	**52**	**56**	**57**
DGR4	**270**	**270**	**270**	**270**	**270**	**270**	**270**	**0**	**0**	**0**	**0**	**0**
DG5	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**0**	**0**	**0**	**0**	**0**

DGR5	**900**	**900**	**900**	**900**	**900**	**900**	**900**	**0**	**0**	**0**	**0**	**0**

When all units are centrally coordinated and managed within an integrated framework, the VPP achieves a total profit of **$455**. In contrast, if the units operate independently without coordination, the profit falls sharply to **$124**, representing a reduction of **$331**.

Under integrated management:

• From hours **1–9**, rising market prices lead DGs (except DG1 and DG5) to operate at maximum capacity, reflecting that their generation costs remain lower than the energy selling price.

• From hours **10–19** (peak hours), all DGs run at full capacity to provide both energy and spinning reserves.

• From hours **20–24**, DG2, DG3, and DG4 are active, with DG3 and DG4 operating at maximum capacity.

Under decentralized management, where units act independently:

• From hours **1–9**, all distributed generators prioritize maximizing their individual profits in the energy market, resulting in full utilization of all five units.

• From hours **10–19**, all units shift their participation exclusively toward the spinning reserve market and withdraw from energy sales.

• From hours **20–24**, only DG2 and DG3 remain fully active.

• Consequently, the overall VPP profit drops to **$124**, indicating a loss of **$331** compared to coordinated operation.

Table 13 : Load Curtailment Capacity per Unit

Unit Number	Energy Market Load Curtailment (kW)	Spinning Reserve Market Load Curtailment (kW)
1	70	0
2	50	0
3	30	0
4	10	0
5	40	0

This table presents the available load curtailment for each unit, highlighting its allocation between the energy market and the spinning reserve market. The outcomes are consistent across all scenarios, including the base case:

• **For Units 1, 2, and 4 during peak hours (10–19):** the full allowable load curtailment is directed toward spinning reserve provision, as the reserve price exceeds the energy price.

• **For Units 3 and 4 during off-peak hours (outside peak periods):** when the energy price is higher than the reserve price, the maximum allowable load curtailment is allocated to energy trading, while no capacity is committed to spinning reserves.

5.2Cost Components

The cost structure of the VPP encompasses several key elements:

• **Fuel and maintenance expenses** associated with distributed generators (DGs).
• **Battery degradation costs**, reflecting the impact of frequent charging and discharging cycles.
• **Penalty charges** incurred for failing to meet market commitments.
• **Curtailment costs** related to demand response programs.

On the other hand, the revenue streams are derived from multiple sources:

• **Energy sales** in the electricity market.
• **Provision of spinning reserve services** to support system reliability.
• **Government incentives** granted to encourage renewable energy generation.

5.3Wind Power Uncertainty

The scenarios capture varying levels of wind power availability and their corresponding market conditions:

• **Scenario 1**: Represents low wind generation with moderate market prices.

• **Scenario 4**: Characterized by high wind generation combined with elevated market prices.

• **Scenario 7**: Reflects very high wind generation but accompanied by low market prices.

In scenarios with abundant wind resources, the VPP significantly increases renewable energy generation, thereby reducing reliance on fossil-fuel-based units and lowering operational costs. The VPP adapts its bidding strategy to market price changes:

- In high-price scenarios, it sells more energy and offers higher reserve capacity.
- In low-price scenarios, it prioritizes battery charging and load shifting.

5.3Demand Response Contribution

The flexible load serves as a key element in enhancing VPP profitability:

• **During high-price hours**, reducing consumption minimizes costly energy purchases.

• **In off-peak periods**, demand is shifted to benefit from lower electricity prices.

• **This adaptability** improves overall system efficiency while also mitigating imbalance penalties.

1. Genetic Algorithm Implementation

The optimization problem was addressed using **MATLAB's Genetic Algorithm (GA) Toolbox**. A sample implementation for **Scenario 1** is presented in **Appendix A**. The GA proved effective in managing the large set of variables and constraints, achieving reliable convergence toward near-optimal solutions.

2. Comparative Analysis Across Scenarios

The performance of the VPP was evaluated across all seven scenarios, with the following key insights:

• Profitability differs among scenarios, highlighting the influence of uncertainty.

• Scenarios with **high wind generation and elevated market prices** deliver the greatest profits.

• Scenarios with **low wind and low prices** lead to reduced revenues; however, adaptive scheduling strategies help mitigate potential losses**.**.

6.Conclusion

This paper investigated the operation of a Virtual Power Plant (VPP) whose rationale was to improve the profitability in the face of Distributed Energy Resources (DERs), and responsive loads. This analysis was done in the backdrop of a competitive electricity market where a VPP was a unifying solution that integrates decentralized generations and demands-side resources into one common operating unit. The model of VPP designed was one where the system is centrally coordinated and under the watchdog of the Central Coordination Center (CCC) to ensure that its grid is secure and stable. Price-based generation model was used in planning and scheduling which takes technical and economic constraints into consideration in the bidding strategy on both the day-ahead and spinning reserve market. The results indicated that the schedule coordinate allocation of distributed generation operation helps to achieve efficient market activities and allows profits maximization. Moreover, it was decided to use the idea of a large-scale VPP where geographically distributed units will be interconnected over various nodes of the distribution system. Renewable sources and energy storage systems were incorporated into this framework since they were combined with conventional units in order to facilitate the profit maximization issue. These findings are consistent with the literature content in recent years, which stresses the importance of options of resource aggregation through VPPs, the utility of probability programming approaches in an uncertain environment, and the import of profit-driven approaches to scheduling in competitive markets [23][24][25]. This paper also explored ideal VPP operations through adoption of demand response price based and Electrical Vehicles demand response incentive-based. Financial incentives were imposed to encourage EV owners to either drain their batteries or to travel not during peak demand. To avoid the negative effects of EV integration in power systems (especially in VPPs), it is important to introduce properly designed charging control, and scheduling procedures. A corresponding scheduling framework that integrates price-based demand response of regular loads with EV charging/discharging is coordinated with renewable generation has therefore been developed. This plan had the effect of:

• A reduction in energy supply costs.

• A decrease in greenhouse gas emissions.

The optimization was formulated as Mixed Integer Linear Programming (MILP) vessel and solved in GAMS, and the EV behavior and unknowns to its usage were simulated in MATLAB. The findings indicate that, this coordinated participation is beneficial to the VPP as an aggregator as well as to individual participants, as it leads to profitability to individual players. In addition, the proposed strategy helped in load curve flattening which in turn lowered the cost of procurement and environmental effects. Future studies must expand the uncertainty modeling further into load variability, EV behavior and price fluctuations, as these features have a significant effect on the accuracy of optimization and choice. This dissertation will add to the further development of probabilistic optimization models in the operation of VPP with specification on the variability on the wind generation and volatility on the electricity market. It makes apparent the importance of incorporating renewable energy sources, energy storage systems, and programs demand response to increase the profitability of VPP and its flexibility of operation. As future work, the built framework could be expanded to consider other sources of uncertainty and introduce more robust optimization methods that have been developed aimed at enhancing the scalability and resilience of solutions to real world applications.

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