ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering
Tome XXIV [2026] | Fascicule 1 [February]

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BALANCING THE POWER SYSTEM WITH AN EMPHASIS ON VIRTUAL POWER PLANTS AND THE MARKET

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Abstract: This paper examines how virtual power plants (VPPs) contribute to power system balancing and market operation in the context of the energy transition. It first defines VPPs as digitally coordinated portfolios of heterogeneous distributed energy resources—controllable and stochastic generation, storage, and flexible demand—that together behave as a single market actor capable of providing energy, balancing, and ancillary services. The historical development of VPPs is traced from early "virtual utility" concepts and local pilot projects to today's large-scale, cloud-based platforms that leverage IoT, artificial intelligence, and blockchain to integrate thousands of units across multiple markets and regions. Particular attention is given to European and global market trends, where VPPs support decarbonization goals, enable high shares of renewables, and create new flexibility products in day-ahead, intraday, reserve, and balancing markets. The thesis reviews real-world implementations such as Next Kraftwerke, Tiko, Power Ledger, and major utility-led programs in Europe, North America, Asia-Pacific, and Japan, highlighting both technical and regulatory challenges as well as emerging business models. On the technical side, the work analyzes balancing mechanisms across different time scales and demonstrates how multi-service VPP operation, supported by advanced forecasting and optimization, can significantly increase revenues while improving grid stability. Methodologically, it surveys internal VPP control architectures (centralized, distributed, and hybrid) and a broad range of optimization techniques—from linear and mixed-integer programming to stochastic, robust, and multi-objective formulations, complemented by heuristic and AI-based methods for forecasting, scheduling, and risk management. By combining literature review, market analysis, and model-based insights, the thesis positions VPPs as a cornerstone of future decentralized, digitalized, and decarbonized power systems and outlines best practices and strategies for their further deployment in support of reliable, efficient, and sustainable power system balancing.

Keywords: Virtual power plants; Power system balancing; Distributed energy resources; Ancillary services markets; Optimization and control

1. INTRODUCTION TO VIRTUAL POWER PLANTS (VPP)

A virtual power plant (VPP) is a coordinated network of small, distributed energy resources that are controlled to act like a single power plant, providing energy and grid support services. A virtual power plant is composed of several key elements: controllable generation units, such as biomass and biogas plants that can be dispatched as needed; non-controllable (stochastic) sources, including solar and wind power plants; storage systems like battery energy storage systems (BESS) and electric vehicles; and active consumers, such as industrial facilities or households capable of adjusting their consumption in real time through demand response. The primary purpose of this configuration is to enable small producers, who are individually too small to participate directly in the market, to pool their energy and services, thereby enhancing the overall stability of the power system. The figure 1 represent a schematic representation of a virtual power plant (VPP) as a central "cloud" that digitally connects various energy resources and consumers. KOER's first Croatian virtual power plant began operating in February 2022.

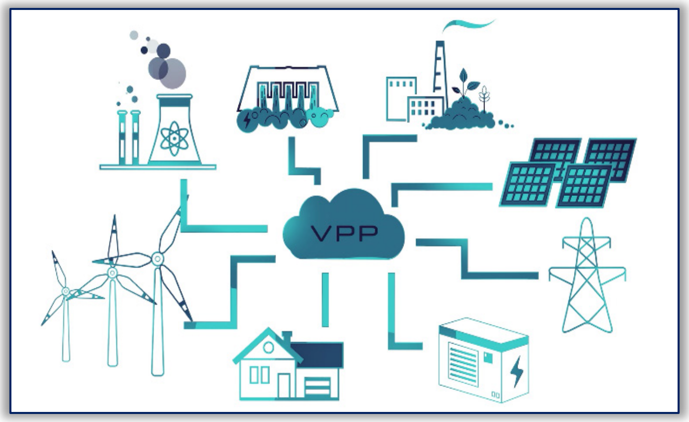

Figure 1. KOER Virtual Power Plant and enables users to share part of their electricity production and consumption capacities in a sustainable and efficient way, [1]

Balancing the power system is one of the key challenges in modern electricity networks, particularly due to the growing share of distributed energy resources (DER) such as solar and wind power, whose variable and less predictable output undermines traditional, centrally controlled balancing schemes based on dispatchable fossil-fuel units. This growing complexity is further amplified by the increasing number of small producers and consumers participating in energy markets, which creates the need for new, more flexible and decentralized approaches to system balancing. In this context, virtual power plants (VPPs) have emerged as an innovative solution that economically and technically integrates heterogeneous DERs—solar and wind plants, battery storage systems, and controllable loads—into a single coordinated entity that can act on the market as if it were a conventional power plant, thereby providing balancing services, grid support, and resource optimization while enhancing overall system flexibility and reliability. The development and implementation of VPPs is particularly important in the ongoing energy transition toward a more sustainable and greener power system, especially in Europe, where ambitious climate targets require high shares of renewables and effective mechanisms for their integration. By enabling more efficient use of renewable generation, lowering balancing costs, and supporting prosumer-based participation models in which end users become both consumers and producers, VPPs contribute not only to technical stability but also to market innovation and greater consumer engagement. Prominent initiatives such as the Next Pool operated by Next Kraftwerke, one of the largest VPPs in Europe, illustrate how advanced optimization algorithms can coordinate thousands of decentralized units to deliver balancing energy and ancillary services, while projects like Tiko in Switzerland and Power Ledger in Australia demonstrate the potential of household- and commercial-scale aggregation to support decentralized generation, reduce reliance on fossil fuels, and provide innovative services on electricity markets.

Table 1 VPP market share, source [2].

Region	Market Share (%)	Key Drivers
Europe	41% - 43%	Renewable integration, decarbonization
North America	35% - 37%	Demand response programs
Asia-Pacific	~18%	Rapid urbanization, smart grids (China, Australia)
Rest of World	~5%	Infrastructure development

Beyond technical design, the economic and regulatory framework is crucial: regulations that promote decentralization, open market access for small producers and aggregators, and offer fair remuneration for flexibility are essential for the successful deployment of VPPs and the creation of new revenue streams across different market segments, including balancing, reserves, and demand-side management. At the same time, VPPs help address operational challenges associated with integrating high shares of variable renewables by using advanced energy management systems and optimization methods to minimize losses, reduce the need for expensive backup capacity, and maintain grid stability, while digital technologies such as blockchain and the Internet of Things further enhance transparency, security, and efficiency in VPP operation through automated, near real-time transactions and control. As a result, VPPs are increasingly recognized as a core component of future energy systems that will be decentralized, digitalized, and decarbonized, supporting technological innovation, economic growth, and environmental sustainability. In this context, the task of the present work is to investigate and analyze the role of VPPs in power system balancing, with a particular focus on optimization models such as linear, stochastic, and multi-criteria optimization, examining DER characteristics, integration challenges and opportunities, and their impact on grid stability and efficiency, and, through case studies and simulations, identifying best practices and strategies to guide further development and the energy transition toward more sustainable and resilient power systems.

A Virtual Power Plant (VPP), figure 2, is a system that aggregates diverse distributed energy resources (such as solar panels, wind turbines, battery systems, and flexible loads) to function as a single, controllable entity on the electricity market. The term "Virtual Power Plant" originates from Dr. Shimon Awerbuch's book “The Virtual Utility: Accounting, Technology & Competitive Aspects of the Emerging Industry. Key components”. The literature distinguishes two types of VPPs [3]:

- Commercial (CVPP): Focused on profit optimization and participation in wholesale markets.
- Technical (TVPP): Provide ancillary services to transmission system operators for grid stabilization (e.g., voltage and frequency regulation).

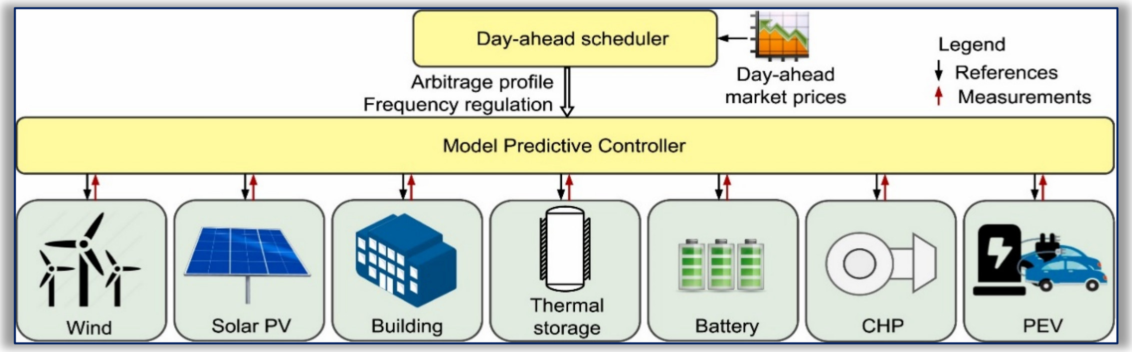

Figure 2. Model predictive control of virtual power plants, [3].

2. VIRTUAL POWER PLANTS: DEFINITION, CONCEPT AND DEVELOPMENT

The rapid growth of distributed energy resources (DER), driven by the push for more sustainable, diversified and efficient energy systems, together with the liberalization of electricity markets, makes coordinated management of numerous small, weather-dependent units under market conditions unavoidable and increasingly complex, especially given their current barriers to market access, variable and often penalized output, and fragmented, stand-alone operation. Figure 3 shows the participation of the reviewed VPP models in different markets (day-ahead, intraday, futures, ancillary services, reserve, real-time balancing, and bilateral contracts). The most recent models show greater diversity in the types of electricity markets in which VPPs participate.

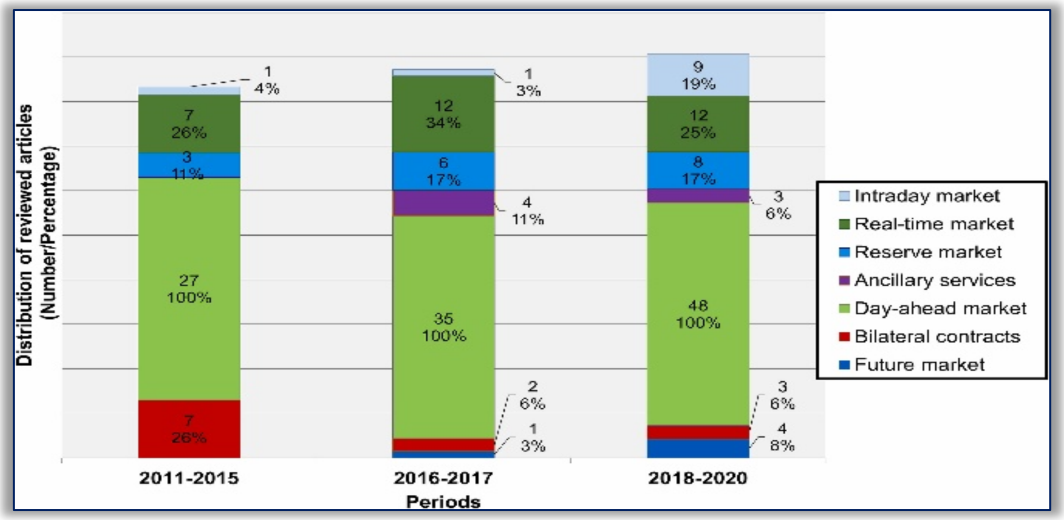

Figure 3. Distribution of the types of markets included in the VPPs (2011–2020), [4]

One of the most effective responses to these challenges is the aggregation of multiple DER units into a virtual power plant (VPP), a concept defined as a coordinated portfolio of distributed assets—such as solar and wind units, battery storage and controllable loads—managed through advanced software platforms so that, from a system and market perspective, they resemble a single conventional power plant with comparable visibility, controllability and functionality. The core idea of a VPP lies in digital aggregation, where optimization algorithms, energy management systems and modern communication technologies enable real-time coordination of geographically dispersed resources, allowing them to provide balancing and reserve services, participate in day-ahead, intraday and balancing markets, and open market access to small producers who would otherwise be excluded.

Historically, VPPs evolved from early local initiatives focused on technically optimizing DER operation within distribution networks toward more sophisticated architectures that combine technical dispatch with market strategies across multiple market segments, including flexibility and ancillary service markets. A key milestone in this evolution was the adoption of advanced ICT solutions—particularly the Internet of Things (IoT), blockchain and artificial intelligence—which together support real-time data acquisition, secure and transparent transaction processing, and predictive analytics-based optimization of production, consumption and storage to maximize efficiency and revenues while maintaining system security. Table 2 outlines the evolution of virtual power plants (VPPs) through key milestones from 1997 to 2025, structured by year with details on achievements, key players, technologies, and regions. It traces the journey from the first academic proposal to aggregate distributed energy resources (DERs) into a "virtual utility" (1997, Germany) to widespread standardization and interoperability via protocols like IEEE 2030.5 (2025, US, EU, Australia). Major trends include early research and pilots (1997-2009), commercial expansion with cloud, IoT, and smart metering (2013), AI and blockchain integration alongside regulatory frameworks (2018-2021), and global plug-and-play adoption (2025).

Table 2. The evolution of the VPP concept and technology: key milestones tracing the development of VPPs from conceptual inception to global deployment, [5].

Year	Milestone	Description	Key Players	Technologies	Regions
1997	Original concept	First academic proposal to aggregate DERs into a "virtual utility" entity	Dr. Shimon Awerbuch, European research labs	Early distributed control theory, supervisory control and data acquisition	Germany, Europe
2005	Technological exploration	Launch of pilot VPP projects testing remote monitoring and basic demand response	Siemens, Fraunhofer Institute	Supervisory control and data acquisition integration, basic demand response	Germany, Denmark
2009	First commercial-scale VPP	Deployment of the first fully operational VPP, combining wind, solar, and biogas in real time	LichtBlick, RWE	Real-time dispatch software, smart metering	Hamburg, Germany
2013	Expansion and commercialization	Rapid rollout of cloud-based VPP platforms enabling broader DER participation	Tesla, AutoGrid, Enbala	Cloud computing, Internet of Things sensors, smart meters and thermostats	United States, Australia, China
2018	Policy recognition	Formal inclusion of VPPs in energy policy frameworks and market rules	U.S. Department of Energy, European Commission	Regulatory compliance tools, market bidding	Australia, North America, European Union
2021	AI-driven growth	Integration of AI for predictive analytics, dynamic market bidding, and automated grid services	Next Kraftwerke, Sunverge, PXiSE	Machine learning, blockchain for energy trade	Global (multiregion)
2025	Interoperability and standardization	Widespread adoption of IEEE 2030.5 and other protocols to ensure plug-and-play interoperability	IEEE, Pecan Street, major DER manufacturers	IEEE 2030.5, open application programming interfaces, secure communications	United States, European Union, Australia

In modern power systems, VPPs therefore play a dual role: technically, they facilitate the integration of variable renewables by using precise forecasting models and storage systems to smooth variability and respond dynamically to imbalances; strategically, they act as an enabler of decarbonization policies, especially in the EU, where Green Deal and related strategies explicitly rely on aggregation, storage and flexibility solutions to meet 2030 and 2050 climate targets. Figure 5. presents EU VPP Market Share, [6], in which the main companies in the market are: Siemens AG, Toshiba Corporation, Shell plc, Hitachi Ltd., ABB Ltd., Tesla Inc., Robert Bosch GmbH, GE Vernova Group, Schneider Electric SE, Cisco Systems Inc.

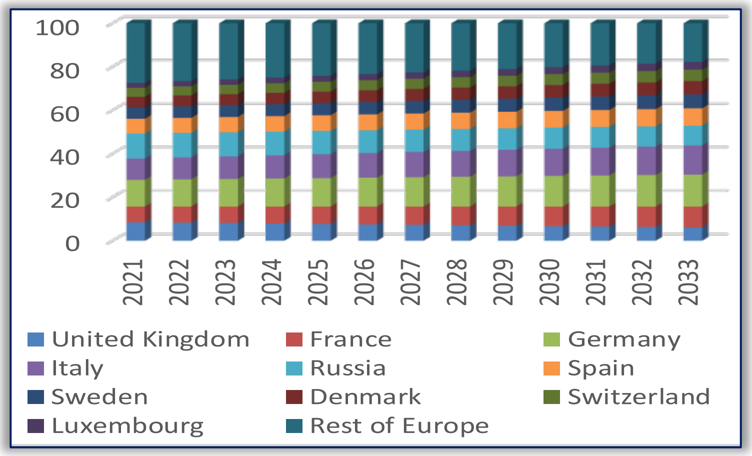

Figure 4. EU VPP Market Share, [6]

Ongoing development focuses on enhancing flexibility, scalability and autonomy of VPP control through artificial intelligence and machine learning, enabling dynamic optimization based on grid conditions, market prices and balancing needs, while simultaneously creating new revenue streams for DER owners by aggregating them into portfolios that can access wholesale, reserve and emerging flexibility markets. Beyond the technical and economic dimensions, VPPs transform end users into active "prosumers" capable of producing, storing and trading energy via digital platforms, which improves system-level flexibility, supports energy savings and emission reductions, and strengthens the social and economic foundations of the energy transition. As technologies, markets and regulation continue to mature globally, VPPs are increasingly recognized as a cornerstone of future decentralized, digitalized and decarbonized power systems, shaping energy policy and investment strategies not only in Europe but also in other advanced markets worldwide.

For example Japan is emerging as a promising market for virtual power plants (VPPs) because it has very limited domestic energy resources, covering under 10% of its primary energy needs since 2012, which forces a heavy reliance on imported LNG, coal and oil and makes the system structurally exposed to supply and price risks, while at the same time the country has set an ambitious 2030 energy mix target that combines significant shares of LNG (27%), coal (26%), renewables (22–24%), nuclear (20–22%) and oil (3%), implying a complex portfolio to manage in terms of security, cost and decarbonization.

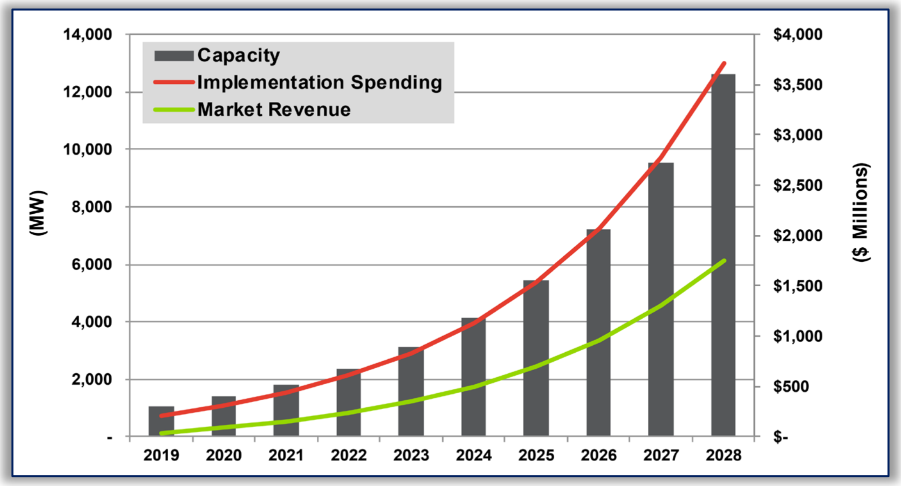

Figure 5. VPP Capacity, Implementation Spending, and Market Revenue, Asia Pacific: 2019-2028 [7]

Within this portfolio, large centralized assets such as hydropower, utility-scale wind farms and solar parks will certainly play an important role, but some of the biggest operational and market challenges are expected to arise from consumer-owned resources, especially rooftop PV, whose fragmented and weather-dependent production will require advanced coordination and aggregation, a role for which VPPs are particularly well suited. Japan's traditionally risk-averse utilities and system operators will therefore be pushed to adopt more innovative, data-driven approaches to system operation and market design, a process additionally complicated by the still-strong social and political impact of the 2011 Fukushima nuclear accident, which continues to influence public acceptance of nuclear power and long-term investment choices. In parallel, VPPs face the generic challenge of high price volatility on electricity markets and the need for precise forecasting, since energy prices can change sharply over short time intervals; to remain profitable and support system stability, VPP operators must deploy advanced forecasting models and optimization algorithms, drawing on machine learning and artificial intelligence to analyze large data sets and predict both market movements and renewable output, thereby deciding when to dispatch storage, curtail or shift loads, or sell energy. By doing so, VPPs can increase their own profitability while also smoothing market dynamics and contributing to more stable prices. Another crucial function of VPPs lies in their role as digital intermediaries that connect consumers to energy markets via user-friendly platforms, giving households and businesses visibility into their consumption and production, enabling them to participate in incentive schemes and demand-response programs, and thus turning them into active participants in the energy transition rather than passive bill payers. This heightened consumer participation enhances overall system flexibility and efficiency, encourages energy savings and emission reductions, and supports broader societal sustainability goals. Taken together, these factors make VPPs a key component of modern electricity markets and future power systems: their ability to integrate distributed resources, manage them intelligently in real time, and participate in multiple market segments positions them as central enablers of decarbonization and energy transition. As technology, market design and regulation continue to evolve—both in Japan and globally—VPPs are expected to gain importance as market actors that support grid stability, reduce emissions and help ensure affordable, reliable and sustainable energy supply for all users.

3. VIRTUAL POWER SYSTEM BALANCING

Balancing the power system is the critical process of maintaining equilibrium between electricity generation and consumption at every moment, ensuring grid stability, supply quality, and preventing major disruptions like blackouts. In traditional systems, this relies on centralized mechanisms from conventional power plants that quickly adjust output, but the rise of renewables (RES) such as wind and solar farms introduces variability tied to weather, making them less predictable and dispatchable. The core challenge is integrating large volumes of RES, which demands system flexibility via energy storage, demand response (flexible load management), and virtual power plants (VPPs)—aggregators of distributed resources that coordinate small producers, batteries, and controllable consumers for efficient balancing. Balancing operates across timescales: primary control (seconds) rapidly restores frequency after sudden deviations; secondary (minutes) stabilizes post-initial response; tertiary (hours) ensures long-term production-consumption alignment, especially with dominant variable sources. To counter RES variability, advanced technologies shine: precise forecasting algorithms for solar and wind output enable better grid operator planning; battery storage absorbs surpluses during low demand and discharges when needed; and digitalization through ICT, sensors, smart meters, and IoT delivers real-time data for swift, precise decisions and automated management, figure 6.

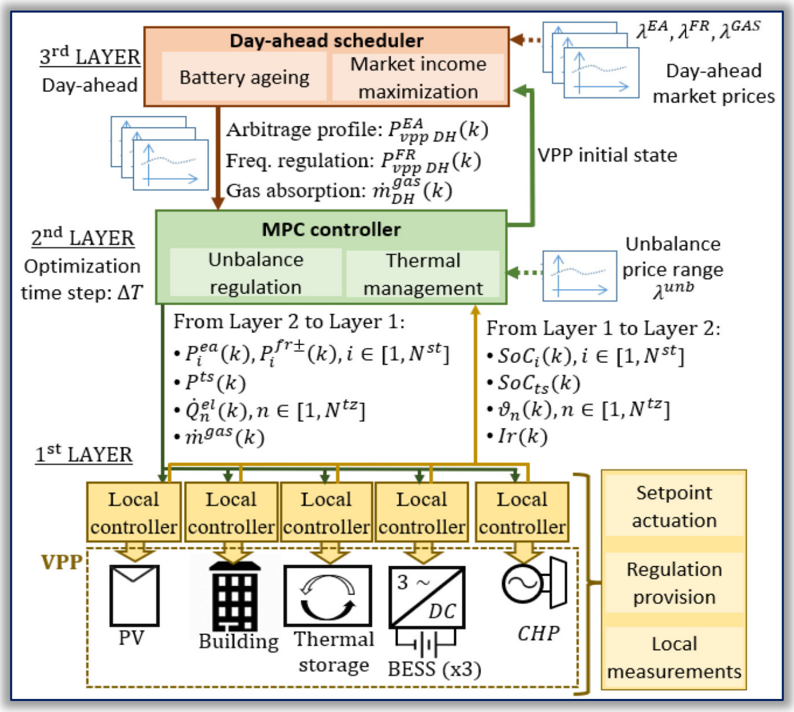

Figure 6. Optimal Virtual Power Plant Management for Multiple Grid Support Services, [8].

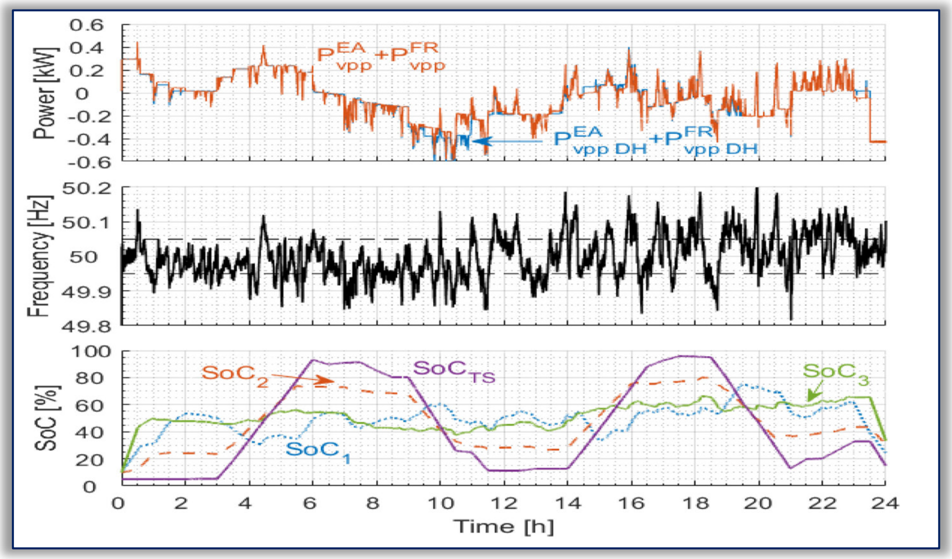

Figure 7. Day-ahead VPP profile and actual VPP power output (top), 24 hour frequency profile (middle), and VPP assets SoC (bottom), [8].

These tools reduce reliance on costly conventional reserves, cutting costs and greenhouse gas emissions. The analysis in the paper [8] demonstrates the superiority of multi-service operation over single grid support services. For instance, net revenue rises by 30% in winter and 7% in summer compared to frequency regulation alone, and by +99% in winter and 30% in summer versus energy arbitrage only. Similar results emerge in the multi-energy scenario across extensive price sensitivity analysis, confirming the approach's effectiveness across a wide range of operating conditions, figure 7.

VPPs boost flexibility by pooling distributed capacities for coordinated market participation, faster responses to fluctuations, and greater grid agility, diminishing the need for large centralized plants. In summary, amid the energy transition, balancing requires innovative approaches where VPPs play a pivotal role in building a stable, adaptable system ready for RES variability, modern market dynamics, and a sustainable future, [9].

4. VIRTUAL POWER PLANTS IN PRACTICE

Each VVP shows a unique approach to using VPP, from the aggregation of small distributed resources to large systems connecting thousands of resources. Projects such as Next Pool, Tiko, Power Ledger, Next Kraftwerke and GreenPowerHub illustrate different technologies and strategies that enable efficient grid management and provision of balancing services, [9]. These projects also highlight the challenges facing VPPs, including technical, regulatory and market barriers, as well as the opportunities brought by innovative business models and technologies. Base on [10] data the world's largest Virtual Power Plants (VPPs) currently include:

- Next Kraftwerke (Germany): The VPP with the largest displayed capacity at around 12.7 GW. It aggregates about 14,300 DERs (renewables, biogas, industrial plants). Focuses on reserves, trading, and system balancing across multiple European markets.
- Sunrun VPPs – CalReady, PowerOn, etc. (US, nationwide): Around 375 MW peak power from residential solar and battery systems. Over 20,000 households participate in DR and storage programs. The largest residential VPP in the US, including vehicle-to-grid pilots (e.g., Ford F-150 Lightning).
- Tesla South Australia VPP (Australia): Currently about 35 MW, aiming for 250 MW growth. Thousands of Tesla Powerwall batteries in homes, including social housing. Provides ancillary services, FCAS, and peak shaving on the Australian market.
- Agregio (EDF) – France: Around 6 GW aggregated portfolio (renewables, DR portfolios, storage). Handles flexibility, market offer shaping, and production/consumption optimization. Operates as a B2B aggregator with advanced forecasting and trading tools.
- Jiangsu VPP pilots (China): Regional pilot program at "regional scale" (hundreds of MW). Includes industrial loads and distributed generation. Focuses on DR, solar coordination, and industrial load management.
- Hawaiian Electric VPPs (US, Hawaii): About 55 MW combined residential and commercial battery storage. Used for capacity and ancillary services in an isolated island grid. Enables ~22 MW daily evening load reduction.
- Arizona Public Service – Cool Rewards (US, Arizona): ~145 MW VPP via 83,000+ smart thermostats. Designed for distributed load management and summer peak shaving. One of the larger DR-oriented VPPs in the US.
- Green Mountain Power (US, Vermont): Over 30 MW capacity from ~3,000 customer batteries. Provides grid resilience, capacity, and demand management services. Saves millions of USD annually in peak demand costs.
- Pacific Gas and Electric + Tesla Pilot (US, California): ~16 MW from customer Powerwall systems. Used for emergency dispatch during extreme events. Delivered all 16 MW in initial stress events.
- Rocky Mountain Power – Wattsmart (US, Utah): ~20 MW through ~3,200 batteries. Targets frequency response and demand optimization. Executed 61 dispatch events in 2023.
- DTE Smart Charge (US, Michigan): ~14 MW load reduction via 663 electric vehicles. Managed EV charging program. Adjusts charging based on grid conditions and prices.
- Bandera Electric Cooperative + Tesla VPPs (US, Texas): Pilot project at ~25.5 MW. Aggregates Tesla Powerwalls and co-op loads. Connected to ERCOT; the region's first community-driven VPP.
- Abundance/Sonnen/Energywell (US, Texas): Pilot phase with residential batteries in Houston and Dallas. Focuses on resilience and demand management. Designed as ERCOT-compliant VPP for hurricanes.
- Montréal Smart Grid Lab – Huawei-led testbed (Canada): Platform scaled to ~500,000 DERs. Includes prosumers, distributed BESS, and solar systems. Test environment for AI-based autotrading, digital twins, and advanced VPP capability curves.

5. OPTIMIZATION TECHNIQUES FOR VIRTUAL POWER PLANTS

Internal control methods for virtual power plants (VPPs) can be grouped into centralized, distributed, and hybrid (comprehensive) control, each balancing computation, coordination, and autonomy in a different way.

- Centralized control: In centralized control, the VPP operates a single coordination center that has full authority over all integrated distributed energy resources (DERs). A reliable communication network feeds internal and external data to this center, enabling real-time dispatch decisions and turning many small, previously uncoordinated DERs into a single, sizeable market actor. Such VPPs can often act as price makers on the electricity market due to their aggregated capacity, whereas smaller VPPs behave more like price takers. Optimization typically relies on mixed-integer linear programming (MILP) and other advanced mathematical models, sometimes combined with robust optimization to maintain performance under worst-case conditions. Heuristic methods such as particle swarm optimization and genetic algorithms are also used to coordinate DERs and provide services like frequency regulation, voltage control, and balancing. However, centralized schemes demand high computational power, substantial data storage, powerful solvers, and high-bandwidth, secure communication, making them vulnerable to communication failures and cyberattacks.
- Distributed control: Distributed control uses two relatively independent layers: a VPP coordination layer and multiple subsystem layers formed by groups of DERs. Each subsystem behaves as an agent that optimizes its local resources to maximize individual profit, while the VPP coordinates these agents via an information and communication infrastructure to avoid market dominance by any single central entity. By spreading decision variables across subsystems, distributed control reduces the computational burden at the central level. Nonetheless, the lack of a single global optimizer can cause conflicts between subsystems, reduce overall competitiveness, and complicate market behavior. Game-theoretic approaches and distributed algorithms (e.g., primal-dual subgradient methods) are employed to accelerate convergence of autonomous strategies and improve computational and communication efficiency. Practical challenges include communication delays, channel noise, and errors, which must be handled to keep DER integration efficient.
- Comprehensive (hybrid) control: Hybrid control combines centralized and distributed approaches to capture the strengths of both. At the upper level, the VPP centrally coordinates agents' bidding strategies to form a unified market participation strategy, thereby reducing the computational load associated with fully centralized optimization. At the lower level, distributed agents perform local optimization and send their operational profiles to the VPP, which then issues a globally coordinated profile for all participants. Agents subsequently align and execute their regional tasks in accordance with this coordinated plan. This structure improves flexibility and efficiency while supporting deeper integration of DERs into the wider power system.
- Programming models: Common programming models used in VPP optimization include stochastic programming, robust optimization, and hybrid robust-stochastic models. Robust models describe uncertainty through prediction intervals and seek decisions that minimize worst-case costs, while ensuring that all constraints are satisfied for any realization within the specified intervals. Stochastic programming, in contrast, represents uncertainty using a finite set of scenarios and minimizes expected costs, which requires a sufficiently large scenario set for accurate results. Hybrid robust-stochastic models blend both approaches by using intervals and scenario sets, achieving faster computation than pure stochastic optimization and better risk management than deterministic or purely robust methods. They offer good probabilistic performance with limited computation time, making them suitable for real-time decision-making in VPPs. In many studies, robust models deliver better computational performance and often higher profitability, while stochastic models can achieve slightly better economic outcomes at the cost of heavier computation. Optimization problems themselves are typically classified by variable type and constraint form into linear programming (LP), mixed-integer linear programming (MILP), nonlinear programming (NLP), and mixed-integer nonlinear programming (MINLP). Linear and MILP models are favored in VPP applications because they are easier and faster to solve, whereas nonlinear formulations are often nonconvex and may have many local optima, making global solutions difficult to guarantee.

- Selected optimization problems and methods: In day-ahead (DA) and real-time (RT) markets, adaptive robust MILP approaches are used to determine optimal energy schedules, reserve allocations, and worst-case outcomes for uncertain prices. Mixed-integer linear methods are also applied to forecast wind speed and solar irradiance, where forecasting errors are identified by comparing predicted and actual energy production. Commercial tools such as IBM's CPLEX solve MILP formulations for real-time integration of DERs, improving economic viability and ensuring reliable energy delivery. When nonlinear constraints are introduced, models become harder to solve due to nonconvexity and the presence of multiple local minima. To address this, both mathematical and heuristic solution techniques are used, including fuzzy logic algorithms, Monte Carlo simulation, artificial neural networks (ANNs), ant colony and firefly algorithms, genetic algorithms, particle swarm optimization (PSO and its quantum variant QPSO), artificial bee colonies, and other evolutionary or swarm-based heuristics. These methods support tasks such as improving wind-energy forecasting, predicting PV irradiance, diagnosing turbine faults, optimizing network flows, sizing and siting DERs, and managing uncertainties in microgrid operation. Mathematical methods like fuzzy logic and branch-and-bound provide structured ways to search for optimal solutions while pruning infeasible or suboptimal regions. Dynamic scheduling decomposes complex auction or dispatch problems into subproblems over different time horizons, improving practicality for intra-day operations by reducing redundant calculations. Heuristic methods, although not guaranteed to find the absolute optimum, often deliver sufficiently good and robust solutions with significantly lower computational effort, which is crucial for real-time or large-scale VPP applications.
- Multi-objective and distributed optimization: Multi-objective optimization algorithms are used to balance several criteria simultaneously when designing and operating VPPs. Typical objectives include maximizing VPP profit, minimizing self-consumption costs of PV plants, improving overall economic performance, and reducing the financial risks associated with market participation. Decentralized (distributed) optimization methods can be broadly categorized into three types. Iterative information-exchange methods rely on a central coordinator and several regional controllers that iteratively adjust decisions based on control signals until they converge to a consistent solution. Game-theoretic methods seek Nash equilibria in a fully distributed manner, allowing participants to pursue self-interested strategies with or without cooperation. Auction-based methods enable bidirectional energy trading under predefined rules, increasingly supported by blockchain and smart contracts to address trust issues among participants.

Most existing decentralized strategies still assume full information and fully rational decision-makers, and the link between coordinators and controlled units can remain strong even in nominally decentralized settings. This creates design and implementation challenges for VPPs, particularly in complex, real-world environments where information is incomplete and participants behave imperfectly.

6. CONCLUSION

The analysis in this thesis confirms that virtual power plants (VPPs) are becoming a cornerstone of modern power system balancing and electricity markets. By aggregating heterogeneous distributed energy resources—renewable generators, storage systems, and flexible loads—into a single controllable entity, VPPs enhance system flexibility, support the secure integration of high shares of variable renewables, and open market access to actors that were previously too small or too fragmented to participate. In doing so, they help shift the power system from a centralized, fossil-fuel-based model toward a more decentralized, digitalized, and decarbonized paradigm. From a technical perspective, the work shows that VPPs substantially improve balancing across all time scales by combining accurate forecasting, advanced control architectures (centralized, distributed, and hybrid), and sophisticated optimization methods ranging from mixed-integer and stochastic programming to robust, multi-objective, and heuristic algorithms. These tools enable VPPs to coordinate thousands of devices in real time, reduce the need for expensive backup capacity, and provide a wide portfolio of grid services such as frequency control, reserves, congestion management, and peak shaving. Case studies of multi-service operation demonstrate that such coordinated use of resources not only supports grid stability but can significantly increase revenues compared to single-service strategies. On the market and regulatory side, the thesis highlights that the full potential of VPPs depends on appropriate frameworks that reward flexibility, ensure non-discriminatory market access for aggregators, and recognize the value of distributed resources in balancing, ancillary services, and emerging flexibility markets. International examples—from large European platforms like Next Kraftwerke to residential-scale programs in Australia, North America, and Japan—illustrate that well-designed VPP schemes can lower system costs, mitigate price volatility, and empower end users to become active “prosumers” who contribute to system stability and decarbonization. Overall, the findings suggest that VPPs are not merely an incremental upgrade but a systemic innovation that links technical operation, market design, and consumer participation into a coherent whole. Future research should therefore focus on scaling hybrid control concepts, improving uncertainty modelling and multi-energy integration, and developing regulatory and business models that align incentives for all stakeholders. If these challenges are addressed, VPPs can play a pivotal role in delivering a resilient, economically efficient, and environmentally sustainable power system.

References

[1] KOER first Virtual Power Plant in Croatia, https://www.koer.com/about-us/, access 30.april 2025.

[2] Virtual Power Plant (VPP) Market Size, Share and Trends 2026 to 2035: https://www.precedenceresearch.com/virtual-power-plant-market, access 30.april 2025.

[3] Oluleke Babayomi, Zhenbin Zhang, Tomislav Dragicevic, Jiefeng Hu, Jose Rodriguez,Smart grid evolution: Predictive control of distributed energy resources—A review,International Journal of Electrical Power & Energy Systems,Volume 147,2023,108812,

[4] N. Naval and J. M. Yusta, “Virtual power plant models and electricity markets – A review,” Renewable and Sustainable Energy Reviews, vol. 149, no. 111393, Oct. 2021.

[5] IEEE Power & Energy Magazine “Virtual power plants (VPP): VPP modeling, control, coordination, and market integration,” , vol. 23, no. 6, Nov.–Dec. 2025.

[6] Kalyani Raje, Europe Virtual Power Plant VPP Market Analysis 2026, https://www.cognitivemarketresearch.com/regional-analysis/europe-virtual-power-plant-vpp-market-report, access 30.april 2025

[7] Peter Asmus: „Deregulation Drives Virtual Power Plant Expansion in Japan Expanding VPPs in the Asia Pacific Region: Part 1“, Commissioned by Enbala, Navigant Consulting, Inc. white paper, 2019

[8] A. Bolzoni, A. Parisio, R. Todd, and A. J. Forsyth, “Optimal virtual power plant management for multiple grid support services,” IEEE Transactions on Energy Conversion, vol. 36, no. 2, pp. 1479–1490, 2021

[9] Blaženka Smolčić, “Balancing of power system with an emphasis on virtual power plants and the market,” Master’s thesis, Josip Juraj Strossmayer University of Osijek, Faculty of Electrical Engineering, Computer Science and Information Technology Osijek (FERIT), 2024.

[10] IEEE Power & Energy Magazine “Virtual power plants (VPP): VPP modeling, control, coordination, and market integration”, vol. 23, no. 6, Nov.–Dec. 2025

ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665

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