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Review

The Optimal Integration of Virtual Power Plants for the South African National Grid Based on an Energy Mix as per the Integrated Resource Plan 2019: A Review †

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Abstract: The Integrated Resource Plan (IRP) 2019 outlines South Africa's goal of achieving a diverse and sustainable energy mix. To achieve this, innovative methods must be found to integrate renewable energy sources while preserving grid stability. Virtual Power Plants (VPPs), which combine dispersed energy resources like solar photovoltaic (PV), wind, and battery storage into a single, intelligent system, are one such approach. This study provides a thorough analysis of the best way to integrate VPPs into South Africa's national grid, highlighting the associated operational, regulatory, and technological challenges. In order to optimize VPP efficiency, this research looks at a number of key areas, such as enhanced renewable energy forecasting, energy management systems (EMSs), and distributed energy resource (DER) integration. Additionally, it examines how VPPs help demand-side management, reduce intermittency in renewable energy sources, and improve grid flexibility. In addition, this paper analyzes the market and regulatory structures required to permit VPP participation in energy markets and guarantee a smooth transition to a decentralized energy environment. This paper highlights the crucial role VPPs could play in reaching the nation's renewable energy targets, lowering dependency on fossil fuels, and enhancing energy access. Through this review, this paper offers insights into the technological viability and strategic benefits of VPP implementation in South Africa. The findings highlight that for VPPs to successfully integrate into South Africa's energy landscape, it will be necessary to overcome technological, regulatory, and market-related barriers.

Keywords: virtual power plant; distributed energy resources; integrated resource plan; energy management system; renewable energy sources

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1. Introduction

South Africa has been experiencing rolling blackouts or "load shedding" since 2007, as the country's capacity to produce electricity has been unable to keep up with the increase in demand [1]. This has been attributed to a number of factors including but not limited to underinvestment in infrastructure; generation plant maintenance issues; mismanagement of the state-owned enterprise, Eskom; delays in new power plant construction; and challenges associated with the coal supply for power generation. To address these issues, initiatives to diversify the energy mix, such as the Integrated Resource Plan 2019 (IRP 2019), have been implemented.

The seamless integration of Virtual Power Plants (VPPs) with the existing national grid in South Africa is a critical undertaking to realize the ambitious targets outlined in the IRP 2019. Academic research provides valuable insights into the optimal approach for this integration, taking into account the diverse technologies involved and the unique challenges presented by the South African energy landscape. This paper will delve into the optimal strategies and key considerations for VPP integration [2].

VPPs integrate decentralized, diverse, and distributed energy resources into a unified, dynamic system, providing an innovative means of resolving the intermittency challenges associated with renewable energy sources (RESs) [3].

Optimizing VPP integration requires a robust assessment of grid compatibility and stability. Studies such as the work of Morales et al. [4] highlight the significance of grid modeling and simulation techniques to evaluate the impact of VPPs on grid operations. Advanced power system simulation tools can assess voltage stability, transient stability, and frequency control under various VPP penetration scenarios. Furthermore, Zia et al. [5] emphasize the use of advanced control algorithms, such as model predictive control, to maintain grid stability while efficiently coordinating Distributed Energy Resources (DERs) within the VPP.

Effective communication and control mechanisms are critical for VPP integration. In their study, Vandoorn et al. [6] propose a hierarchical control structure for VPPs that encompasses centralized control, local control, and peer-to-peer communication. This architecture ensures real-time coordination and decision-making among DERs, enabling optimal power dispatch and grid response. Leveraging secure communication protocols, as suggested by Gunduz et al. [7], helps safeguard smart grid systems' operations against cyber threats and enhances overall system reliability.

Ultimately, the best option for a VPP in South Africa would be a well-planned and comprehensive approach that considers the unique characteristics of the region, optimizes the utilization of available resources, addresses technical and regulatory challenges, and aligns with the country's energy goals outlined in the IRP 2019. A holistic evaluation of local conditions and stakeholder engagement is crucial to ensure successful VPP implementation and integration into the South African national grid.

Through a comprehensive review of existing literature and case studies, the theoretical underpinnings, technical feasibility, and potential benefits of integrating VPPs into the South African energy landscape are explored. The measurable objectives for VPP integration are defined in Table 1 below. This paper will only focus on the technical objectives. These objectives are to be used to evaluate the success of VPP integration in South Africa.

Table 1. Measurable objectives for VPP integration.

Measurable Objective	**Explanation**	**Metrics**
Improved grid stability	Improving grid stability will reduce the duration and frequency of load shedding.	Reduced load shedding stages (GWhs avoided)
		Grid uptime (%) increase
		No. of load shedding-free days
Increased renewable energy capacity	Increase RES contribution to the energy mix as per the IRP 2019.	Renewable energy increase (%)
		Renewable energy curtailment reduction (MWhs)
		No. of DERs aggregated into VPPs
Improved energy efficiency and demand response	Use VPP-enabled demand response programs to improve demand-side management.	Reduction in peak demand (MWs shifted)
		Demand response program participation rate (% total users)
		Energy wastage reduction (kWhs saved through optimized dispatch)
Reduced costs	Reduce generation and operational costs for the grid by leveraging VPP efficiencies.	Electricity generation cost reduction (cost per kWh)
		Reduction in dependence on gas peaking plants during high demand (liters of diesel saved)
		Revenue increase due to VPP participation in the electricity market (ZAR).
Environmental benefits	Displace coal-based generation with RESs to reduce GHG emissions.	CO_2 emission reduction per annum (metric tons)
		Percentage increase in clean energy in the energy mix

Table 1. *Cont.*

Measurable Objective	Explanation	Metrics
Expansion of energy access	Provide underserved rural or remote locations with reliable electricity using VPP-enabled microgrids.	No. of households connected through VPP microgrids
		Reduction in off-grid communities that do not have reliable electricity supply
Economic development	Nurture economic growth and promote job creation by deploying renewable energy and improving VPP technologies.	No. of jobs created
		RES and smart grid technology investment growth (ZAR)
		Domestic manufacturing capacity increase in VPP components
Increased market participation and decentralization	Small-scale DERs enabling active participation in electricity markets.	No. of prosumers participating in electricity markets
		Amount of energy traded through VPP platforms (kWhs)
		Small-scale RES producers increase in revenue

There is currently limited research on the operating challenges that are unique to the South African grid infrastructure. In addition, the impact of load-shedding and subsequent transmission constraints on VPP deployment and coordination is neglected in research. There are research gaps regarding scheduling integration in the country, optimization techniques, technical and economic constraints, and how to adequately deal with uncertainties, specifically in the context of scarcity of supply. There is also a lack of detailed and practical studies on how VPPs can be optimized for the South African grid taking the country's specific concerns such as load shedding and aged infrastructure into account. More research is required on practical market integration taking the changing market (from a single-buyer model market to a multi-market structure) and demand response with extensive RES integration into account. How to practically integrate VPPs with regard to the current Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) context and how to optimize DER coordination under specific grid constraints should be considered. The REIPPPP is a competitive bidding process which is employed for major renewable energy projects [8]. The country must solve its regulatory gaps, technological difficulties in real-time data handling and the inadequacies in its infrastructure.

The paper aligns with the IRP 2019 and thus provides a tailored review of the means to achieve the country's renewable energy targets, which differs from generic VPP studies. It aims to fill the gaps in the literature by discussing how the VPP integration of wind, solar PV, and battery storage can best be managed within the country's unique energy landscape. The exploration of scheduling algorithms, grid compatibility, and energy storage integration add dimension to the technical feasibility of the undertaking. It also highlights regulatory barriers specific to South Africa, which are not prevalent in the global literature, thus promoting tailored policy frameworks. Looking at the local energy projects showcases the practical application and benefits of VPPs, providing validation to theoretical findings.

Regarding practical applications, this study emphasizes the importance of EMSs in coordinating DERs, serving as a guide for operational improvements in South Africa's grid. This study addresses load shedding, a major issue facing South Africa, by discussing how VPPs can mitigate the effect of intermittent RESs and thus enhance grid stability. Emphasis is placed on small-scale DERs and prosumers gaining access to electricity markets, which supports decentralized energy solutions. This stimulates innovation and economic participation. This paper recommends public–private partnerships, regulatory incentives like feed-in tariffs, and smart grid investments, which are practical, actionable steps for stakeholders to take to overcome the barriers to integration. Finally, this paper advocates for VPPs that are community-based so as to address energy access in remote or underserved regions. This aligns with the country's developmental and social goals.

The goal of this research is to contribute to advancing sustainable energy practices and support South Africa's path towards achieving its energy and climate goals by contributing valuable insights into the control, management, and optimization of DERs and VPPs as well as the technical and practical aspects of VPP implementation while focusing on enhancing grid stability.

This paper examines the integration of VPPs into the South African national grid as a strategic step towards realizing the envisioned energy transition outlined in the IRP 2019. It aims to provide a detailed examination of the prospects, challenges, and implications of integrating VPPs into the South African national grid, focusing on DER control and coordination, explaining the synergistic role of various RES technologies in this transformative process through an in-depth analysis of existing academic literature and empirical studies.

The remainder of the paper is structured as follows. Section 2 reviews the current literature on VPP technology and policies. The proposed methodology is formulated in Section 3. The Results and Discussion are given in Section 4. The paper is concluded in Section 5.

2. Literature Review

The implementation of VPPs can help improve grid stability, integrate renewable energy sources, and optimize the use of DERs. VPPs can also play a role in supporting grid flexibility and demand-side management. A VPP combines and manages DERs such as solar photovoltaic (PV) generators, energy storage, gas generators, and building loads.

By aggregating and intelligently managing diverse RESs, VPPs offer an opportunity to achieve sustainable energy goals, enhance grid stability, and promote equitable energy access. However, overcoming the regulatory, technological, and market-related challenges requires collaborative efforts from policymakers, energy stakeholders, and research communities.

VPPs must efficiently integrate RESs to maximize their effect on emissions reduction and energy sustainability. Research by Hong et al. [9] underscores the significance of accurate renewable energy forecasting, such as solar irradiance and wind speed prediction, for VPP planning and operational strategies. Furthermore, Nosratabadi et al. [10] propose hybrid VPP configurations that combine various RES technologies, such as solar PV and wind turbines, to ensure a balanced and reliable energy supply.

Energy storage plays a crucial role in mitigating the intermittency of renewable energy resources within VPPs. The uncertainty of the generation of these RESs can lead to economic losses [11]. Studies, such as that by Zarate-Perez et al. [12], emphasize the importance of optimal energy storage sizing and placement within the VPP network to enhance grid stability and accommodate varying load demands. Implementing advanced battery management systems, as explored by Dai et al. [13], improves the lifespan and performance of energy storage systems, rendering them more effective assets within the VPP.

Davuluri [14] highlights the significance of a supportive regulatory framework and appropriate market structures to incentivize VPP integration. Well-designed feed-in tariff (FiT) mechanisms, energy trading platforms, and demand response programs encourage VPP operators and DER owners to participate actively in grid services, ensuring a smooth transition towards a more decentralized energy ecosystem.

Optimal integration of VPPs with the South African national grid is a multifaceted endeavor that demands a careful understanding of grid compatibility, efficient communication and control mechanisms, integration of RESs, strategic energy storage deployment, and supportive regulatory measures. By drawing from academic research, policymakers and energy stakeholders can foster a cohesive roadmap for VPP integration, thereby accelerating South Africa's journey towards a greener, sustainable energy future.

The integration of RESs into the energy mix has become a global goal to combat climate change and achieve energy sustainability. South Africa, with its abundant renewable resources and ambitious sustainability targets, has set forth a roadmap in the form of the IRP 2019 to realize its vision of a greener energy future [15].

Central to the realization of the IRP 2019's objectives is the concept of VPPs, an innovative paradigm that transcends conventional centralized power generation models. VPPs represent a revolutionary approach to energy aggregation and management by intelligently integrating DERs and coordinating their collective operations. These DERs encompass a diverse array of technologies, including energy storage systems (ESSs), wind turbines, solar photovoltaic (PV) systems, demand-side management (DSM) technologies, electric vehicles (EVs), and so on.

2.1. Virtual Power Plants: Concept and Technologies

2.1.1. Definition and Architecture

A VPP is a cloud-based platform that leverages advanced algorithms and communication technologies to coordinate and optimize the operation of diverse DERs in real time. By pooling together multiple distributed energy assets, a VPP creates a virtual, aggregated power plant capable of responding to the demands of the grid and electricity markets as a unified entity. The VPP architecture typically comprises a central control system, remote monitoring units, and a robust communication infrastructure that facilitates seamless data exchange and control actions [16]. The concept of a VPP is illustrated in Figure 1 [17]. VPPs are effective in balancing the fluctuations associated with RESs, such as wind and solar power. Various VPP demonstration projects, including the FENIX project, have been implemented in the European Union, the Netherlands, and France [18].

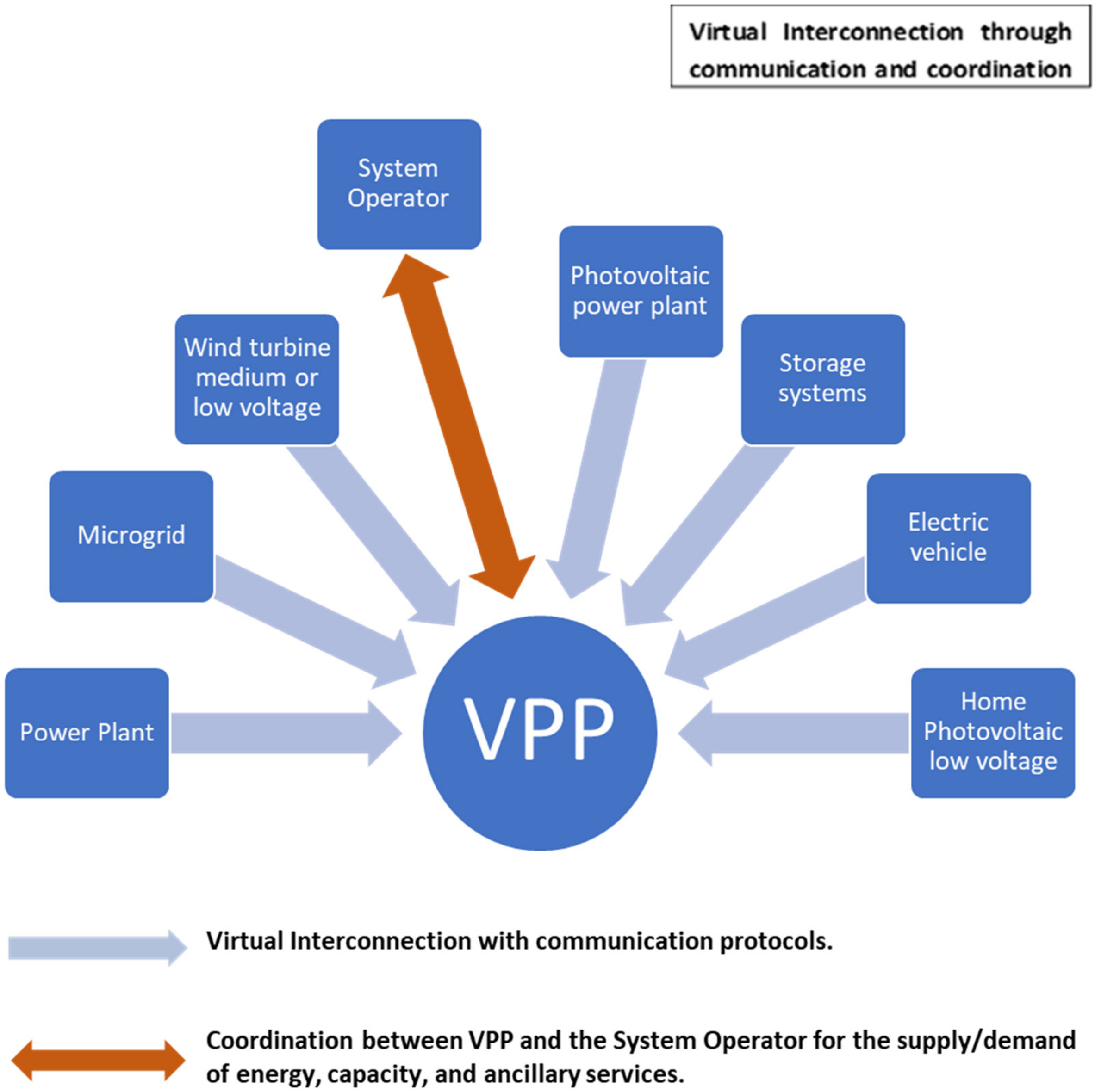

Figure 1. VPP structure.

2.1.2. Integration of RESs into VPPs

Integrating RES technologies into VPPs is essential for harnessing the potential of renewable resources and addressing their inherent variability. Solar PV systems offer a scalable and widespread distributed energy solution, while wind turbines contribute a substantial share of electricity generation. Effective utilization of these resources in a VPP framework requires sophisticated forecasting models, monitoring and optimal dispatch algorithms, and coordination mechanisms to ensure reliable and predictable energy delivery [19]. Notably, a study [20] examined the integration of renewable energy resources onto the South African national grid, albeit without incorporating VPPs as part of the plan.

2.1.3. Introduction of ESSs and VPPs

Energy storage plays a pivotal role in VPPs by mitigating the intermittency of RESs and providing grid ancillary services. The various ESS technologies include but are not limited to pumped hydro storage and battery energy storage systems (BESSs). Energy storage improves VPPs reliability, flexibility, and performance by ensuring continuous supply of energy during unexpected events such as outages or spikes in demand. ESSs provide voltage and frequency regulation, which contributes to maintaining grid stability. ESSs also allow excess energy to be stored or discharged during periods of low or peak demand, respectively. Integrating ESSs into VPPs ensures that the VPP is able to increase its profits because it is able to increase its ancillary services offering [21].

2.1.4. DSM and Smart Grid Integration

Demand-side management techniques are vital components of VPPs as they enable demand response capabilities, enhancing grid flexibility and load balancing. Integrating smart grid technologies, such as home energy management systems (HEMSs) and smart meters, empowers consumers to actively participate in energy conservation and load-shifting practices, thus optimizing VPP performance [22]. Furthermore, one study [23] focused on the technical and economic aspects and the limitations of the scheduling problem associated with VPPs, suggesting the use of deep reinforcement learning (DRL) to address these challenges.

2.2. Expected Role of Virtual Power Plants in the South African Grids

The IRP 2019 outlines a roadmap for diversifying South Africa's energy mix, including increasing the share of renewable energy to 24.7% by 2030. South Africa has a total electricity generation capacity of 54.6 GW as of the end of 2022, according to its Council for Scientific and Industrial Research (CSIR). The aim is to increase the share of renewable energy, that is, solar PV, wind, and concentrated solar power (CSP), from 11.4% (6.2 GW) to 24.7% of the energy mix. VPPs offer an enabling platform to achieve these targets by facilitating the integration and efficiently utilizing distributed renewable resources while ensuring grid stability and security. Table 2 [24] provides a breakdown of South Africa's electricity generation capacity by technology.

Table 2. Breakdown of wholesale nominal capacity per generation source (2022).

Technology	Capacity (GW)	Percentage Capacity
Coal	39.8	72.9%
Nuclear	1.9	3.5%
Diesel	3.4	6.2%
Hydro	0.6	1.1%
Pumped storage	2.7	4.9%
Wind	3.4	6.2%
Solar PV	2.3	4.2%
CSP	0.5	0.9%
Total capacity	54.6	100%

2.2.1. Renewable Energy Sources Integration

There is a chance to create distributed generation, offer off-grid electricity, and diversify the South African electricity mix with solar PV, wind, and CSP with storage. Additionally, there is a great deal of promise for localization along the value chain, the development of new industries, and the creation of jobs via renewable technology [15].

Beyond the predominance of wind around coastal locations, South Africa's Wind Atlas offers a foundation for quantifying the potential of wind energy for producing electricity in other parts of the country [15]. Thus far, the majority of wind projects have been created in the Eastern and Western Cape. These projects range in size from kWs to MWs and can be distributed across industrial centers.

South Africa has enormous potential for producing power and heat from biogas and biomass (for industry) [15]. Even in cogeneration plants, biomass from the sugar, paper, and pulp industries might be used to generate power at a price that is competitive while requiring minimal changes to the transmission and distribution infrastructure. Moreover, run-off river hydro projects from South African rivers show promise. These have been demonstrated to be practical through various projects that farming communities have put into practice.

The overall system demand in 2022 was 2.2% (or 5.2 TWh) less than the levels prior to the (COVID-19) shutdown in 2019. The energy mix in South Africa is still dominated by coal, which makes up 80% of the system load [25]. With 6.2 GW of installed capacity, renewable energy technologies—namely, wind, CSP, and solar PV—contributed 7.3% to the demand in 2022. Table 3 above demonstrates the IRP 2019 [15], that is, the capacity that is planned to be installed per generation of technology per year up until 2030. It also shows the total planned capacity for the year 2030, its respective percentage of the energy mix, and its annual energy contribution in percentage. Table 4 shows the latest statistical data from the CSIR [24], that is the capacity of each generation technology actually installed during 2022 and the actual total generation capacity at the end of 2022. It was the first year when the production of solar power (PV and CSP) generation fell. South Africa had 54,000 MW of nominal wholesale capacity at the end of 2022 (refer to Table 2).

South Africa aims to increase its share of (its PV, wind, and CSP) renewable sources to 24.7% of its energy mix. This excludes hydro power, biomass, and biogas. VPPs are necessary to integrate renewables into existing power systems as they can help alleviate the difficulties posed by the intermittent nature of renewable energy sources [23].

Table 3. The Integrated Resource Plan (IRP 2019): planned capacity (MW) to be added per year.

	Coal	**Coal (Decommissioning)**	**Nuclear**	**Hydro**	**Storage**	**PV**	**Wind**	**CSP**	**Gas and Diesel**	**Other**
2018 Base	37,149		1860	2100	2912	1474	1980	300	3830	499
2019	711	−2373					244	300		Allocation to the extent of the short-term capacity and energy group.
2020	1433	−557				114	300			
2021	1433	−1403				300	818			
2022	711	−844			513	400 1000	1600			
2023	750	−555				1000	1600			500
2024			1860				1600		1000	500
2025						1000	1600			500
2026		−1219					1600			500
2027	750	−847					1600		2000	500
2028		−475				1000	1600			500
2029		−1694			1575	1000	1600			500
2030		−1050		2500		1000	1600			500
Total installed capacity by 2030 (MW)	33,364		1860	4600	5000	8288	17,742	600	6380	

Table 3. *Cont.*

	Coal	**Coal (Decommissioning)**	**Nuclear**	**Hydro**	**Storage**	**PV**	**Wind**	**CSP**	**Gas and Diesel**	**Other**
% Total Installed Capacity by 2030 (% of MW)	43		2.36	5.84	6.35	10.52	22.53	0.76	8.1	
Annual Energy Contribution % by 2030 (% MWh)	58.8		4.5	8.4	1.2	6.3	17.8	0.6	1.3	

[Legend]

⬜	Installed Capacity
🟨	Already Contracted Capacity
🟥	Decommissioned
🟩	New Capacity
🟦	Extension of Koeberg Plant Design Life
🟧	Distributed Generation Capacity for Own Use Included

Table 4. Actual added and installed capacity for 2022.

	Coal	**Coal (Decommissioning)**	**Nuclear**	**Hydro**	**Storage**	**PV**	**Wind**	**CSP**	**Gas and Diesel**	**Other**
2022 (Added Capacity Actual, i.e., became operational. CSIR [22])	720					75	419			
Actual installed capacity (2022, CSIR [24]) (MW)	39,800		1900	600 (hydro) and 2700 (pumped storage)		2300	3400	500	3400	

[Legend]

🟧	2022 Actual Data According to CSIR [24]

2.2.2. Leveraging Energy Storage Systems

Energy storage, renewable energy systems that are not dispatchable, and smart grid systems work in tandem. Technological advancements in energy storage are upending the conventional power distribution model, and more renewable energy may be captured even though its production may occur during times of low demand [15].

Innovations in energy storage technologies, like compressed air energy storage, hydrogen fuel cells, and battery systems, can help address the intermittent nature of RESs. This is particularly true in South Africa, where the addition of over 6 GW of renewable energy has resulted in a power system that lacks flexibility and has insufficient storage capacity [15].

2.2.3. Enhanced Grid Flexibility and Stability

The dynamic nature of VPPs enables effective load management and grid stability, reducing the risk of blackouts and grid instability. Properly orchestrated DERs can provide rapid response capabilities, reactive power support, and voltage regulation, reinforcing the resilience of the South African national grid [26]. Additionally, a study [27] explored the technical viability of pairing nuclear energy from Small Modular Reactors (SMRs) with wind power in a VPP, demonstrating reduced power variability but with insufficient economic viability insights.

2.2.4. Facilitating Energy Access and Decentralization

VPPs present an opportunity to extend electricity access to remote and underserved regions in South Africa. By deploying small-scale renewable energy systems and microgrids, VPPs can enable energy independence and local economic development, aligning with the country's commitment to energy decentralization [28].

2.3. Impact of Grid Constraints and Regulatory Frameworks

2.3.1. Grid Constraints

Load shedding occurred for more than 3700 h during 2022, resulting in 8301 GWh of actual energy shed. Because of this low energy availability coupled with transmission infrastructure issues, the energy availability factor (EAF) for the utility was 58.1% for 2022. This was lower than the four preceding years and a significant decline from the 2018 EAF of 71.8%. This was attributed to unplanned outages and the aging infrastructure [25]. These constraints result in the curtailment of solar projects and thus limit the ability of the grid to accommodate intermittent RESs. The CSIR Wind and Solar Resource Aggregation Study shows that by geographically dispersing wind and solar PV projects across the country, the variability of the output can be reduced and the short-term fluctuations alleviated. Inadequate grid planning and capacity bottlenecks, however, still hinder integration [29].

2.3.2. Regulatory Frameworks

The Renewable Energy Development Zones (REDZs) initiative was established to streamline the approval process and address spatial planning and environmental challenges associated with wind and solar PV projects in line with IRP 2019 requirements [30]. The initiative, however, needs to be implemented at a faster pace to support the addition of the required 6 GW of solar capacity (mentioned above) by 2030.

Project deployment is slowed down as a result of licensing regulatory delays and a lack of clear guidelines for Independent Power Producers (IPPs). Coordination between government entities such as NERSA and Eskom is thus critical to overcome these obstacles.

2.4. Global and Local VPP Implementation

2.4.1. VPP Implementation Around the World

VPPs are becoming increasingly popular around the world as a way to improve the adaptability, durability, and efficiency of power systems. VPPs are a key component of many European nations' energy transition plans, such as those of Germany and the United Kingdom, where they make it easier to integrate dispersed RESs into the grid. These RESs include solar and wind power. In order to collect and manage DERs like solar panels, wind turbines, batteries, and flexible loads, modern technologies such as machine learning, artificial intelligence (AI), and the Internet of Things (IoT) are used by VPPs. VPPs are able to ensure grid stability, offer ancillary services, and take part in energy markets thanks to the coordinated management of these resources.

The necessity to satisfy strict renewable energy objectives and update outdated grid infrastructure has prompted the introduction of VPPs in the United States. Enterprises like Tesla and Sunrun [31] are presently engaged in the development of VPPs that integrate grid services with household solar and battery storage.

In a similar vein, VPPs have proven especially beneficial in isolated and rural regions of Australia, where they improve energy security and lessen dependency on centralized fossil fuel generation. Supportive legislative frameworks, monetary rewards, and cutting-edge grid management technologies—which make it easier to integrate DERs and maximize their performance inside the electricity system—are the cornerstones of the global success of VPPs.

2.4.2. VPP Implementation in South Africa

VPPs are being acknowledged more and more as a potential answer to South Africa's energy problems, which include recurrent load shedding, an aging fleet of coal-based generators, and the requirement for a resilient and diversified energy mix. Over 80% of South Africa's electric power is generated using coal, which is a major contributor to the country's energy landscape. However, due to the nation's plentiful solar and wind resources as well as its promises to lower greenhouse gas emissions, there is a growing movement towards the integration of RESs. Despite this promise, South Africa is still in the early phases of VPP adoption due to a lack of investment in smart grid technology, insufficient grid infrastructure, and regulatory concerns. However, recent legislative changes, including the unbundling of South Africa's state-owned utility, Eskom, and the implementation of the IRP 2019, point to a positive trend towards more adaptable and decentralized energy solutions. Pilot programs, like the City of Cape Town's efforts to purchase electricity from small-scale embedded generators [32], show that there is increasing interest in VPPs as a way to improve energy security and take advantage of dispersed renewable resources. Overcoming legislative obstacles, making investments in grid upgrading, and fostering favorable market circumstances that promote the participation of various energy actors, from independent power producers to home prosumers, are crucial for South Africa's VPP integration to be effective.

2.5. Challenges to VPP Integration in South Africa

2.5.1. General

The integration of VPPs in South Africa's power grid necessitates comprehensive regulatory reforms and market structures to accommodate the evolving energy ecosystem. Ensuring fair compensation mechanisms, clear grid connection protocols, and equitable market participation opportunities for VPP operators are essential to fostering a conducive environment for VPP development [23]. Moreover, the varied nature of distributed energy assets poses challenges in terms of technological compatibility and interoperability within VPP architectures. Standardized communication protocols and interoperability frameworks must be established to facilitate seamless data exchange and efficient coordination among different DERs [33]. A study by the authors of [11] discusses the management, control, and optimization strategies of DERs, prosumers, and VPPs, highlighting limitations in considering holistic reliability, stability, and uncertainty.

2.5.2. The Integration of Renewable Energy Sources

As stated above, South Africa aims to increase its share of its PV, wind, and CSP renewable sources. As can be seen in Table 2 above, the PV installed capacity was 2300 MW at the end of 2022, which is less than 30% of the total planned installed capacity, as stated in the IRP 2019. Wind energy, on the other hand, just had under 20% (2300 MW) installed capacity at the end of 2022 as compared to the IRP 2019 planned capacity for 2030 (17,742 MW). This implies that a substantial amount of intermittent DERs are going to be added to the national grid over the next few years, and the integration of VPPs would be required to ensure grid stability when it does happen. The IRP 2019 lays out a comprehensive strategy to diversify the energy mix, reduce greenhouse gas emissions, and foster energy security, aiming to ensure a sustainable and resilient energy sector by 2030 [15].

3. Research Methodology and Review of Integration Strategies

3.1. Methodology

The theoretical underpinnings, technological viability, and possible advantages of integrating VPPs into the South African electricity grid are investigated through an extensive analysis of existing literature and case studies. Only studies that were published in the last twelve years that dealt with virtual power plants, microgrids, energy management, scheduling algorithms, and the South African energy mix were considered for this review. Journal papers that were peer-reviewed, conference papers, and thesis studies were included in the review. Publications that were not in English and articles not based on empirical research were excluded. Technical reports and official websites of the relevant technology and companies were also used to acquire certain information.

AI-assisted searches were combined with expert recommendations to find the study publications. Important sources were supplied by a subject matter expert, and questions to ChatGPT added context-specific details, especially regarding studies related to the

South African energy sector. While it is customary to conduct a thorough search through databases like ScienceDirect, Web of Science, and Scopus, this review used carefully chosen sources to concentrate on the most pertinent studies related to "microgrid", "virtual power plant", "scheduling strategy", "demand response", and "South African energy mix". Using this approach guaranteed a focused and pertinent selection of the literature for the review.

Potential study titles and abstracts were filtered for relevancy using predetermined inclusion and exclusion criteria. The most relevant studies were then thoroughly examined. Important information was taken out of each publication, including variables, approaches, and results. A systematic review framework was subsequently employed to assess these data points. With this technique, the literature was rigorously and consistently assessed to determine the most relevant conclusions regarding the best possible integration of virtual power plants in South Africa.

The data were created by categorizing the specific findings into thematic areas and comparing the results of the different studies. Some discrepancies in the findings were also noted. GHG emission reductions, peak demand shifts, and renewable energy integration rates were metrics used to assess the impact of VPP integration strategies. This process is illustrated in Figure 2.

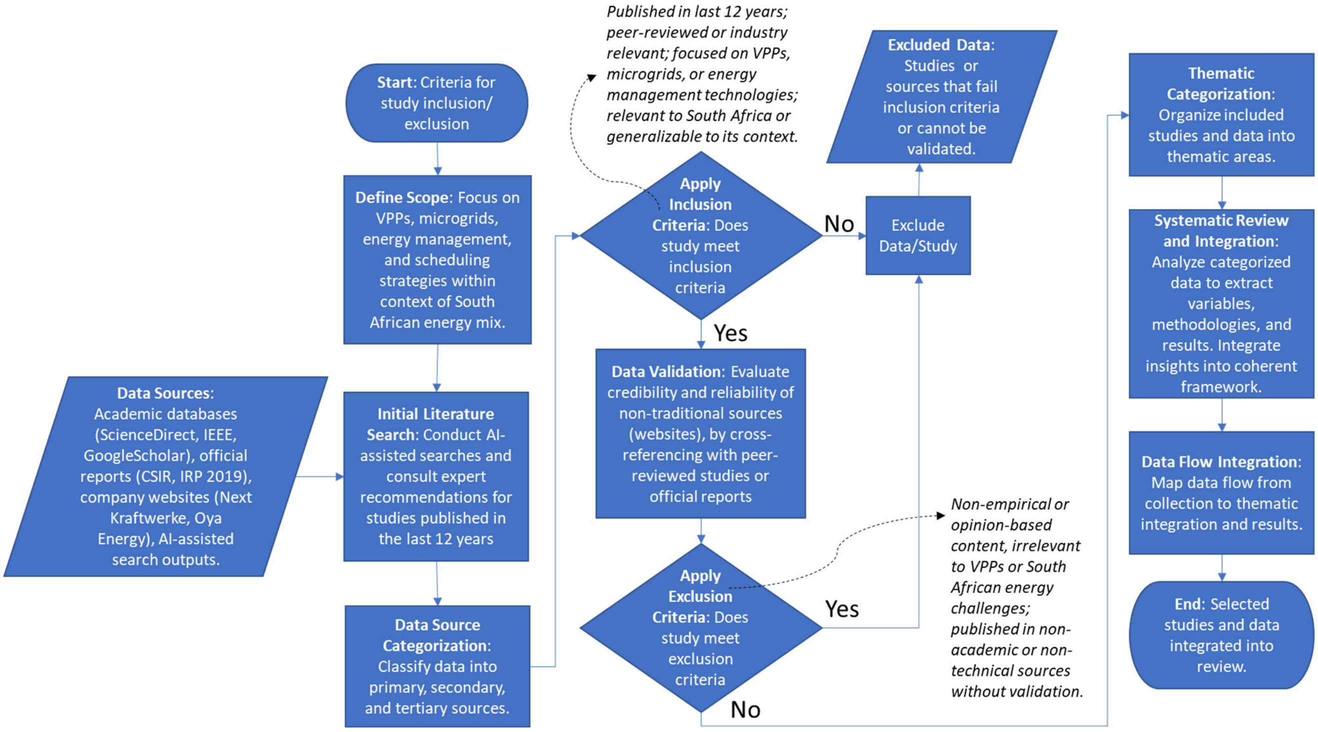

Figure 2. Methodology flowchart.

Despite the comprehensive review, the potential for publication bias still exists. The systematic methodology, however, intends to provide a thorough, unbiased overview of the current research on virtual power plants, specifically as it relates to the integration into the South African energy mix. This process is illustrated in the flowchart below.

This research focuses on addressing the following Research Questions (RQs). What security, communication, and energy management systems are best suited based on previous papers and case studies? How can communication, metering, and scheduling be optimized to successfully integrate DERs into the existing grid structure?

3.2. Optimization of VPP Configuration [34]

A VPP requires sophisticated infrastructure where various energy resources, including rooftop PV, EVs, wind farms, fuel cells, fossil fuel-based sources, and micro-hydro plants, are combined to optimize demand–supply balance, cost-effective electricity delivery, and peer-to-peer energy exchanges among prosumers. VPPs reduce reliance on conventional fossil fuel-based generation, consequently lowering power rates and diminishing the risk of oversaturated distribution lines.

VPPs can combine different RESs to increase the effectiveness of energy management and make energy trading easier, claims [23]. Energy management depends heavily on the scheduling algorithm in VPPs, which takes into account many technical, financial, and unpredictable factors that can have an impact on the scheduling program. Through the use of accurate forecasting and scheduling algorithms, VPPs may enhance energy management while boosting power system stability and dependability. Furthermore, because the scheduling algorithm maximizes prosumers' excess energy, prosumers that install any kind of small-scale RESs or storage can trade in the market through VPPs. Homeowners and businesses with grid-connected solar systems can sell extra electricity back to the grid through the City of Cape Town's "Cash for Power program" [34,35]. Customers without RES or storage, on the other hand, can still contribute by changing or cutting back on their consumption. Therefore, by offering a complete management solution, VPPs can aid in the integration of renewables into the current power networks.

3.2.1. VPP Architecture

There are two types of operational architecture mentioned in [17], namely Centralized Operational Architecture and Decentralized Operational Architecture. In Centralized Operational Architecture, the aggregator offers the resources from a group of DERs that are available and directly coordinates its operation with the system operator. Like a traditional power plant, the VPP is an active participant in the markets. Load signals are sent to, analyzed, and processed at the central control (CC). From there, the power requests are forwarded to the individual distributed generator control (DGC).

In Decentralized Operational Architecture, the distribution system operator (DSO), who oversees the distribution grid either locally or regionally, is served by the aggregator, which coordinates its operations and makes its services available to it. The DSO could engage with the system operator in active participation in markets where there is a supply and demand for services [17]. The distributed generation controller (DGC) controls the active power produced by the DGs, and each DG is controlled by its own local controller (LC). These LCs are. in turn. connected to each other, creating an amalgamated, synchronized control center.

Analysis of the proposed architectures' coordination highlights how crucial it is to have effective coordination mechanisms in place in order to satisfy the technical and commercial demands of the electricity markets. A hybrid architecture is optimal as it allows for centralized optimization with the benefits of local flexibility. This allows the individual DER within a VPP to be able to respond to local conditions while the overall system that balances supply and demand is still centrally managed.

3.2.2. Optimization Problem-Solving Methods

In order for VPPs to maximize operating profits within the different electricity markets, a mathematical problem is formulated. It is also required that different problem-solving methods be identified and analyzed in order to resolve the proposed VPP optimization model.

Scheduling and management optimization of the distributed generation facilities, optimization of energy storage solutions and demand in order to maximize profit is the main purpose of studies [36]. The studies referred to propose a problem to address several objectives in order to maximize profit and are categorized as shown in Table 5 below.

The problems are categorized according to variable type (whether it is an integer or continuous) and constraint characteristics (linear or nonlinear). The most common problem devised is of the mixed-integer linear programming variety due to its ease of implementation and the speed at which an optimal solution can be found. The problem, however, sometimes needs to accommodate nonlinear constraints, which become more complex to solve because the constraint set may not be convex. The problem may be transformed into a linear model, or different problem-solving methods can be implemented to achieve the optimal solution. These problems can be solved by either mathematical or heuristic methods. The different problem resolution methods are shown in Figure 3 below.

Table 5. Categorization of optimization problems.

Problem	Description
Linear Programming (LP)	Used for mathematical optimization when the constraints and objective function are linear. (Resource allocation problems such as profit maximization with limited resources.)
Mixed-integer linear programming (MILP)	A variation on linear programming in which the decision variables are constrained to be integers. It is used to find solutions to linearly constrained problems having both continuous and integer variables. (Scheduling problems where particular variables are integers.)
Mixed-integer nonlinear programming (MINLP)	Both continuous and integer variables can be optimized, but nonlinear constraints and/or the objective function are present. Used in complex cases when discrete decisions and nonlinear relationships are involved.
Nonlinear programming (NLP)	Optimization in which all variables are continuous, and the objective function, constraints, or both are nonlinear. It is used to solve problems where complex relationships render linear models insufficient.

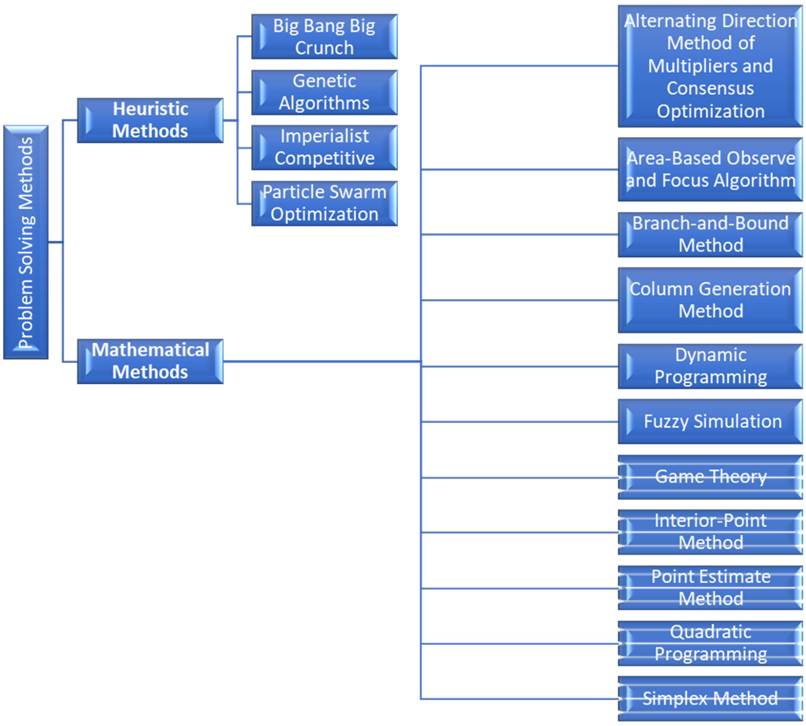

Figure 3. Resolution methods for optimization problems.

The most often employed optimization strategies in the research include genetic algorithms, particle swarm optimization, mixed-integer linear programming, and linear programming [37]. MILP and NLP can be used to optimally schedule DERs to reduce VPP operational expenses. These algorithms account for market prices, storage efficiency, renewable energy availability as well as the fluctuating energy costs associated with the various RESs. By matching energy demand as efficiently as possible, linear programming reduces billing costs. It can also reduce peak load usage by up to 38% per hour and minimizes rolling blackouts. MILP helps consumers save money on energy by optimizing household loads, storage, and generation entities [37].

To optimize profit, W.S. Sakr et al. [38] suggested consumer engagement in the VPP demand response scheme while investigating a price-based scheduling strategy for the best day-ahead scheduling of VPPs. Tested on a 33 kV, 18-bus system, a modified differential evolution algorithm (MDEA) was proposed to solve the optimal scheduling problem. Using dispatchable load as a demand response mechanism with grid and VPP limitations, the MDEA was used to solve a price-based unit commitment problem.

This method resulted in effective VPP resource scheduling, especially for reserve power, and it emphasized the crucial role that dispatchable loads play in a variety of scenarios. Dispatchable loads enhance reserve power, which decreases power outages, but it increases costs, which decreases profits. In practice, the technique boosts earnings when security conditions are suitable [38]. To optimize techno-economic benefits, dispatchable load allocation is best suited for high-load areas.

A framework for the best possible operation strategy of a VPP was presented in the E. Heydarian-Forushani et al. [39] study. It included a number of different stakeholders, including DERs with private owners, flexible loads in day-ahead and real-time energy markets, and renewable energy sources. A proactive stochastic bi-level model was created to simulate the strategic behavior of private owners within the VPP geographic area. The lower level was associated with maximizing the profits of the private owner, while the upper level was assigned to minimize the expected operation cost of the technical VPP.

The suggested bi-level model was then transformed into a mixed integer linear programming problem using strong duality theory and Karush–Kuhn–Tucker optimality assumptions.

According to K. Mahmud et al. [37], the tertiary control layer for day-ahead energy management uses a variety of forecasting algorithms in order to support real-time operations when connecting dispersed energy resources to the VPP. These forecasting algorithms include Fuzzy Logic Algorithm, Stochastic Hybrid Intelligent Algorithm, Artificial Neural Network (ANN), Empirical Mode and ANN Decomposition, Monte Carlo Simulation Method, Wavelet Neural network, Support Vector Machine (SVM), Auto-Regressive Moving Average, and SVM-ANN.

In order to lower the energy cost in demand participation for the economic dispatch problem while taking energy management uncertainties into account, particle swarm optimization is utilized. To further reduce operating expenses, a multi-objective Fuzzy Self Adaptive Particle Swarm Optimization (FSAPSO) was studied.

The reliability issues for several DERs are resolved by using the Genetic Algorithm.

For VPPs, the GRACO (Geographical Routine Algorithm Based on Ant Colony Optimization) technique offers scalability and self-healing capabilities. It stands out due to its dispersed, localized, and straightforward functioning, which can help lower end-to-end delays as VPP size increases [37].

In a study by X. Liu [40], carbon capture units, power-to-gas, manure treatment systems, combined heat and power units, and waste incineration power plants were included in the proposed multiple-region VPP framework. By coordinating the dispatch of the multiple energy systems, an optimization model was created to optimize the VPP's operational revenue. The high-dimensional, nonlinear optimization issue was solved using an enhanced compound differential evolution algorithm. The suggested method raised carbon trading revenue by 75%, lowered wind and solar power curtailment costs by 82%, and boosted overall VPP operation income by 9%. The integration of systems for the production and consumption of natural gas improved the use of renewable energy by efficiently using the power curtailment from solar and wind to produce natural gas.

Coordination of the energy systems, like waste incineration and carbon capture, assisted in moderating the variations in renewable energy output and gave the VPP operational flexibility. The complex, high-dimensional problem related to the VPP dispatch optimization was successfully resolved using an enhanced optimization algorithm [40].

A two-stage optimization methodology for systems with VPPs comprising DGs and EV charging demand was presented by Li et al. [18]. Using the aggregated parameters supplied by the VPP aggregator, the system operator optimized each VPP's overall output levels in the first stage. Each VPP aggregator then divided the overall output level among the local entities in the second stage. Both of the aforementioned framework's optimization stages were expressed as linear programming and were resolved with the aid of pre-existing software tools. Numerical results showed that the approach significantly reduced system operating costs and the levels of unmet EV charging demand as compared to standard centralized dispatch.

3.2.3. Infrastructure of VPP

The Energy Management System (EMS) serves as the core of VPP operations. Sub-EMS units within the VPP communicate bidirectionally with the central EMS, relaying information on the aggregated energy resources, generation capacity, and energy consumption. Passive consumers were forced to become prosumers by the bidirectional peer-to-peer (P–P) energy transfers. All kinds of prosumers will be able to coordinate to create VPPs with the help of the internet of energy (IoE) or the future smart grid [37].

The central EMS, through data analysis, optimizes VPP performance, while sub-EMS units oversee component behavior and may be configured to balance costs and user preferences. The EMS relies on precise data from power generators to consumption points and requires resilient communication networks and scalability, even under network failures.

Sarmiento-Vintimilla et al. [17] suggests a general architecture in which the VPP is a key component for managing net zero or fundamentally zero energy grids. Coordination between operators—the transmission system operator (TSO) and the DSO—and the electricity production system (EPS) participants are assessed based on how well they participate in the market. By using coordination tactics, aggregators can engage in both traditional energy and reserve markets in addition to ancillary service markets by coordinating their operations with TSOs and DSOs.

3.2.4. Classification of VPP

VPPs, orchestrated by the Internet of Energy (IoE), are flexible organizations categorized into two primary classes: Commercial VPPs (CVPPs) and Technical VPPs (TVPPs). CVPPs emphasize economic optimization, including electricity market participation and profit maximization. TVPPs focus on ensuring the technical performance of power systems, emphasizing real-time RES monitoring and safe, dependable, secure, and controllable operations [23]. VPPs furnish data to network regulators, specifically the Independent System Operator (ISO), for pricing, while CVPPs contribute economic and financial reports. The difference is illustrated in Figure 4 below.

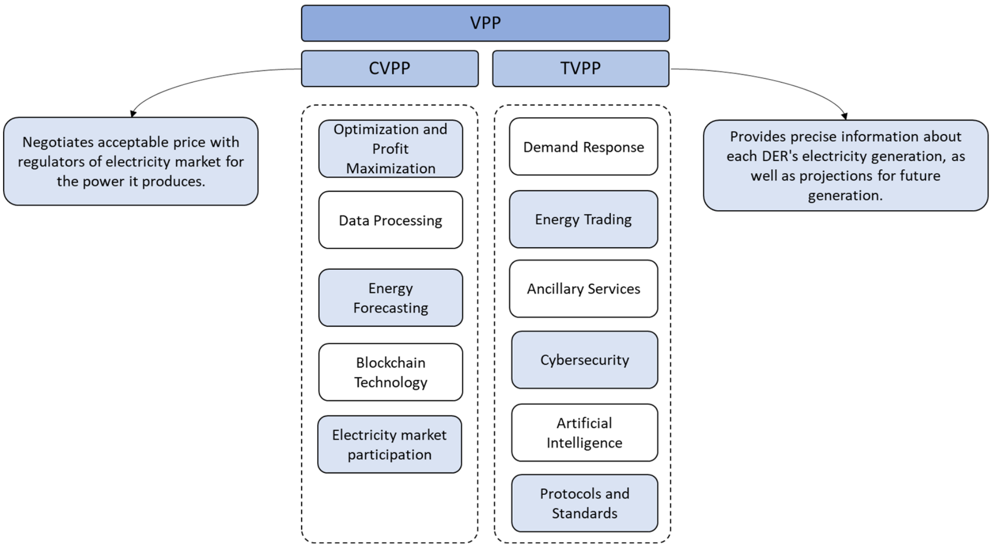

Figure 4. CVPP and TVPP components.

3.2.5. Energy Markets

The function of the CVPP is to enable VPP participation in the different electricity markets, refer to Figure 5, including power purchase agreements (PPAs), balancing services, and the day-ahead market [36]. Therefore, it is important to carefully consider the types of electricity markets in which a VPP will participate and design the VPP accordingly [36]. In the past, a short-term wholesale market dictated most of the electricity markets. An extensive number of sellers and buyers attended these auctions in order to buy or sell electricity. Current electricity markets make use of forward and futures markets as well as day-ahead markets. This ensures that the price risk associated with the sale and purchase of electricity in the respective markets is diversified. The introduction of renewable energy into the energy mix requires balancing mechanisms to be used more often due to the intermittent nature of certain RESs. The usefulness of VPPs is that they allow the sale of energy from different DERs (on behalf of the respective owners), giving small enterprises access to the wholesale markets and increasing the profit of the amalgamated enterprises [36]. A brief explanation of the different markets is described in Table 6.

Table 6. Description of different electricity markets.

Electricity Markets	Brief Description
Futures and forward market	The futures market comprises purchase and sale contracts that are established at an agreed-upon price for a predetermined time period. This prevents price uncertainty in the electricity market [20].
Bilateral contracts (PPA)	Bilateral contracts are direct agreements between two parties about the sale of electricity. The two parties are the seller (electricity generator) and the buyer of the power. This agreement prevents price uncertainty which leads to the profitability of the generation plant and consumer.
Day-ahead market	Conduct electricity transactions by having market agents offer bids for the purchase and sale of power for each hour of the next day. This can maximize VPP profits and allow for electrical system flexibility.
Ancillary services market	Ensuring the reliability and security of the energy generation and transmission system is the primary purpose of the auxiliary services market. This market must always maintain the balance between demand and generation.
Reserve market	The reserve market is a tool to ensure the security of energy supply and demand coverage by the extra generation reserves.
Intraday market	Since there is more information available during the intraday market, it is used to accurately modify the energy exchanged during the day-ahead market. Thus, a smaller amount of energy is sold during these exchanges.
Real-time balancing market	The real-time balancing market is the final market in which consumption and production can be balanced. This market closes between five to thirty minutes prior to the energy being delivered.

In [39], it was investigated how VPP's market trading strategy and interactions with private owners were affected by the implementation of three different pricing schemes: fixed pricing, time of use (TOU), and real-time pricing (RTP). The findings indicated that by employing the recommended optimal operating method, both private owners and VPP aggregators might be able to profit from the market circumstances. The use of different pricing methods may affect the behavior of private owners, particularly those who have the capacity to store electricity; in the case of the RTP mechanism, the VPP chooses to supply its power from electrical markets rather than private owners.

Implementing the DR strategy may alter the load profile's form and reduce the VPP's cost, while the TOU program may boost the utilization of private owners' assets and reduce the VPP's reliance on the market through peak shaving. It is clear that, in contrast to TOU, RTP may increase the risks associated with VPPs even while it may reduce their anticipated cost as compared to a fixed pricing plan [39].

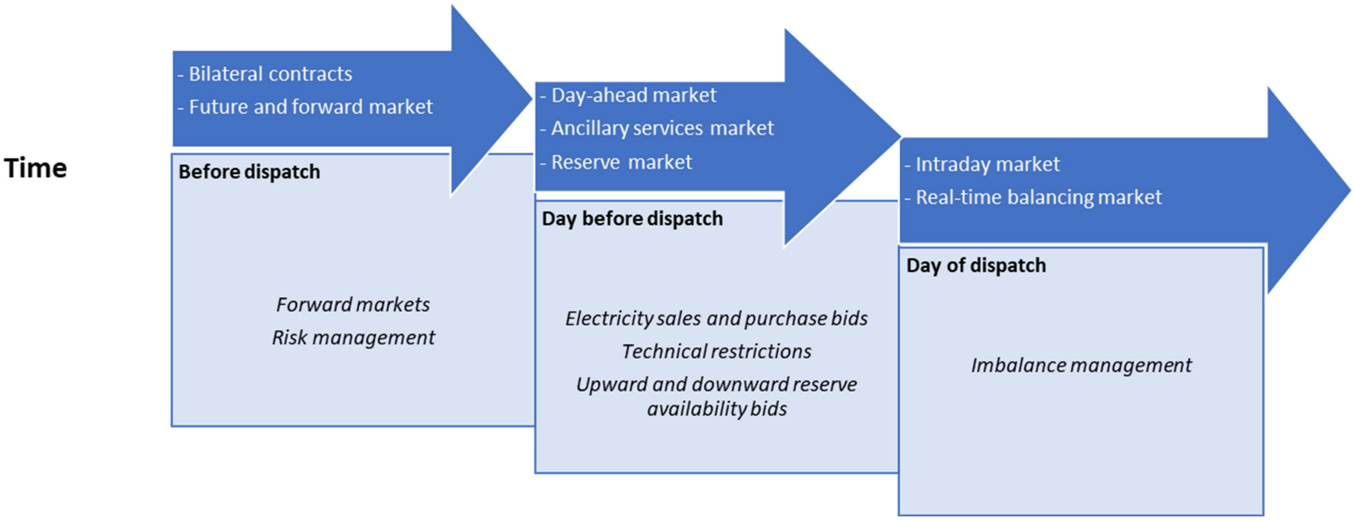

Figure 5. Electricity market types and sequence.

Energy acquisition of VPPs from/to the market is made possible via the Monte Carlo Decision Tree approach. Every distributed generation and storage device's cost function is provided. To address the stochastic behavior of distributed generating, a number of profitability levels are taken into consideration [37].

VPP models, according to the literature reviewed, buy and sell energy in the day-ahead market to ensure the maximum operating profit. VPPs are beneficial to DERs as they allow them to partake in the electricity markets which would otherwise not be possible due to their small capacity.

For renewable generation and demand patterns, the VPP should employ day-ahead forecasting together with real-time modifications depending on updated conditions. Planning can be improved by using advanced forecasting approaches that use machine learning to estimate solar and wind output more accurately. To maintain grid stability, the EMS should modify demand response, batteries, and generator dispatch in real time.

3.3. Security, Communication, and Energy Management

3.3.1. Data Flow and Monitoring

VPPs are founded on real-time wide-area situational awareness (WASA) facilitated by Advanced Metering Infrastructures (AMIs). High-speed communication is pivotal due to the multitude of EVs, storage units, transmission-distribution devices, smart meters, RES facilities, and home appliances that share extensive information within VPPs. Advanced communication infrastructure, including the IoE, enables bidirectional data sharing and energy trading among all participants.

Mathematical formulation and solving methods used in VPP models can have a significant impact on their performance and accuracy. Therefore, it is important to carefully select and evaluate the mathematical formulation and solving methods used in VPP models.

3.3.2. Communication Technology

The communication layer in VPPs is responsible for data exchange among different layers of VPP, including generation, consumption, state of charge, and transmission information. Communication protocols such as Modbus, DNP3, IEC 61850, and OPC UA are commonly used in VPPs to enable data exchange between different devices and systems. Modbus is a widely used protocol for communication between electronic devices, while DNP3 is a protocol used for communication between different types of data acquisition and control equipment. IEC 61850 is a standard for communication in substations, and OPC UA is a protocol for secure and reliable data exchange between different systems [23].

There are two types of communication technologies used in VPP: wired and wireless. Wired communication technologies include Power Line Communication, Twisted Pair, and Optical Fiber. Wireless communication technologies include Satellite Communication, Cellular Communication, ZigBee, Wireless Local Area Networks (WLANs), and Wireless Mesh e Z-Wave [41].

Srivastava [41] also discusses the communication delay that exists in any kind of communication technology and how it can cause instability in the VPP.

The communication time delay (Tc) in the VPP model is made up of two components, namely the time taken to gather and guide the power profile data of each VPP portion towards the EMS. When the VPP components start responding to the generation dispatch instruction after the EMS issues a generation control instruction, the second component of the communication time delay happens [23].

Regarding cybersecurity, ref. [17] emphasizes the need for robust technology of information and communications systems to provide data security and privacy through reliable cybersecurity platforms and to coordinate requirements and decision-making. Additionally, it talks about protecting smart grid cybersecurity from concept drift-related data integrity assaults. One obstacle that needs to be overcome before smart grids can be widely used is cybersecurity.

The communication layer in VPPs should be designed to ensure secure and reliable data exchange, as security and privacy are crucial constraints in every financial environment [23].

3.3.3. Scheduling of Supply and Demand

VPPs can help to integrate RESs into an existing power system by employing precise forecasting and scheduling algorithms [23]. Due to improved energy management on the parts of both customers and providers, optimal scheduling lowers the costs associated with generation, transmission, and maintenance while also increasing the power system's dependability and stability. Furthermore, as optimum scheduling moves some loads to off-peak hours and lowers their consumption, users are able to exchange excess electrical energy in the market.

The scheduling problem in VPPs is a multi-objective optimization problem that involves various technical and economic constraints, such as load balancing, peak shaving, and energy trading. The scheduling problem in VPPs is challenging due to the intermittent nature of RESs, the uncertainty of energy demand, and the complexity of the power system. Therefore, the scheduling algorithm in VPPs should consider these constraints and uncertainties to optimize energy management and improve reliability and stability in the power system.

There are several types of scheduling algorithms for VPPs, namely, the Genetic Algorithm (GA), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), Reinforcement Learning (RL), and Mixed-Integer Linear Programming (MILP).

A GA-based scheduling algorithm for VPPs was proposed in [42], a PSO-based scheduling algorithm for VPPs was proposed in [43], and an ACO-based scheduling algorithm for VPPs was proposed in [44]. These algorithms aim to minimize the total cost of energy generation, transmission, and distribution while satisfying technical and operational constraints.

The unit commitment problem can be resolved by applying optimization techniques such as MILP, which guarantees the best scheduling of nuclear, renewable, and other dispatchable sources. In the South African setting, unit commitment plays a crucial role in preserving balance during periods of unpredictable renewable output.

An RL-based scheduling algorithm for VPPs was proposed in [23]. This algorithm aims to learn the optimal scheduling policy by interacting with the environment and maximizing the expected cumulative reward.

It is also suggested that learning-based approaches, such as Deep Reinforcement Learning (DRL), be utilized to solve the difficulties posed by the scheduling issue in VPPs [23]. DRL utilizes deep neural networks to extract features from the environment and learn the optimal policy by maximizing the expected cumulative reward. DRL is capable of modeling complex and nonlinear relationships between the state, action, and reward, which makes it suitable for solving the scheduling problem in VPPs. DRL can also handle uncertainties and variations in the environment by learning from experience and adjusting the policy accordingly [23].

The proposed control strategy in [41] is an active power control strategy on an interconnected microgrid, which aims to maintain a balance between generation and demand, regardless of random power generation by renewable energy sources. The control strategy uses a two-stage PI-(1+PD) controller to regulate the frequency of the VPP model.

MATLAB is used to build the proposed VPP model, which includes various components such as wind turbines, photovoltaic panels, and battery energy storage systems. The model is designed to meet the demand for reliable and effective energy management systems. In addition, objective function formulation is used to optimize the control strategy.

Additionally, VPPs can enable prosumers who install any small-scale RESs or storage to trade in the market since the scheduling algorithm maximizes their surplus energy [45]. Customers can participate by shifting or reducing their consumption despite not having storage or any RES. Therefore, VPPs can help to integrate renewables into existing power systems by providing a comprehensive management solution that overcomes the obstacles posed by RESs' sporadic nature and makes energy trading and management more effective.

3.3.4. Energy Management

Energy management within VPPs demands dynamic control of energy exchange between consumers, conventional and renewable DGs, storages, and EVs. This entails navigating various factors, including time of day, pricing restrictions, and RES uncertainty. VPPs are compared to other energy management techniques, such as Micro Grids (MGs), Active Distribution Networks (ADNs), and Load Aggregators (LAs), with the unique ability to encompass participants' economic, technological, and security needs. VPPs offer solutions for real-time monitoring, energy flow control, and operational scheduling, contributing to reducing GHG emissions and lowering reliance on fossil fuels.

The authors of [36] discuss various ways in which VPPs can interact with different types of electricity markets, including day-ahead, intraday, balancing, and reserve markets. These interactions can be optimized using different techniques, such as stochastic programming, mixed-integer programming, and game theory. Additionally, VPPs can provide ancillary services to the grid as well as participate in demand response programs.

Naval et al. [36] proposes a two-stage optimization strategy for VPPs that incorporates energy complementation and demand response. Challenges associated with integrating VPPs into a country's existing infrastructure, such as the uncertainty of wind power, photovoltaics, and load, and the increase in computation time with the extension of the scheduling period. The first stage of the proposed strategy is day-ahead scheduling, which uses a scenario-based approach to form a preliminary dispatch plan. The second stage is real-time scheduling that uses rolling optimization on a shorter time scale to rectify the day-ahead plan. The authors also introduce an improved DR program that takes into account both the penalty mechanism and compensation in the form of a bilateral contract between the energy users and VPP for a reasonable result [46].

Programs for demand response can be enhanced by an EMS. In South Africa, where load shedding and spikes in demand are frequent occurrences, demand response can be used to minimize demand peaks and prevent grid stress by optimizing the involvement of commercial, industrial, and residential users.

Integrating VPPs into existing infrastructure poses several challenges. One of the main challenges is the technical feasibility of integrating DERs into the grid, including issues related to voltage regulation, power quality, and protection coordination [4]. Another challenge is the economic viability of VPPs, which depends on factors such as the cost of DERs, the price of electricity, and the regulatory framework [5]. To overcome these challenges, researchers have proposed various solutions. Including the use of advanced control techniques, such as model predictive control and distributed control, to manage the operation of VPPs and ensure grid stability [6,7]. Other studies have proposed using market-based mechanisms, such as energy storage systems and demand response programs, in order to enhance the economic performance of VPPs [9,10]. Overall, the integration of VPPs into existing infrastructure requires a multidisciplinary approach that considers technical, economic, and regulatory aspects. Further research is needed to develop comprehensive models that can capture the complex interactions between VPPs and energy markets and to evaluate the performance of these models in real-world scenarios.

3.4. Optimal Integration Strategy (Plan)

The best VPP integration plan for South Africa necessitates a comprehensive strategy that includes market development, grid modernization, regulatory reform, and community involvement. South Africa can utilize VPPs to improve energy security, facilitate the integration of renewable energy sources, and construct a more robust power grid by attending to the technical, economic, and social aspects of VPP implementation. To effectively enhance and grow VPP integration, the approach must be flexible, with ongoing learning from pilot projects and international best practices.

3.4.1. Enhancement of Regulatory and Policy Framework

In order to maximize the integration of VPPs in South Africa, a strong framework of laws and policies is necessary. To specify the functioning of VPPs, including aggregation rules, market involvement, and grid interactions, a specific regulatory framework should be created. Technical standards for integrating DERs, including solar PV systems, wind turbines, and battery storage, should be included in this framework, as well as licensing requirements for VPP operators. To further promote investment in VPP technologies, specific incentives such as feed-in tariffs based on renewable energy sources and performance-based tariffs for grid services should be implemented. It is imperative to streamline the permitting and grid access procedures, particularly the transparent interconnection procedures, to mitigate the bureaucratic obstacles that impede the current deployment of VPPs.

The idea of VPPs enhanced by feed-in tariffs (FiTs) encourages the production of electricity by these small-scale energy producers, and VPPs can manage their output to guarantee a more dependable and efficient energy supply to the grid.

To encourage private investment in renewable energy and diversify its energy mix, which is primarily based on coal, South Africa adopted FiTs under the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) [8,47].

3.4.2. Digital Infrastructure Investment and Grid Modernization

The best VPP integration plan also includes investments in digital infrastructure and grid modernization. In order to accommodate the bidirectional flow of electricity from VPPs and manage RES's fluctuating nature, South Africa's old grid infrastructure needs to be upgraded. Improvements should concentrate on boosting the distribution network's capacity and reliability, especially in areas with significant potential for renewable energy. The implementation of smart grid technology, including advanced distribution management systems (ADMSs) and real-time monitoring, along with AMI, will allow VPPs to accurately settle for grid services and improve energy dispatch. To safeguard against potential cyber-attacks and maintain the integrity and stability of grid operations, cybersecurity measures specifically designed for virtual private network operations must be put into place.

3.4.3. Financial Model and Flexible Market Development

It is imperative to create adaptable finance models and market structures to facilitate VPP involvement in South Africa's energy markets. It is necessary to provide a framework for VPP participation so that these companies can participate in the markets for ancillary services, capacity auctions, and energy trading. Real-time pricing and time-of-use (TOU) are two types of dynamic pricing models that should be implemented to represent the current cost of electricity and encourage users to modify their demand in response to grid conditions. Financial tools like government-backed guarantees or creative insurance products should be created to support VPP projects that offer grid services or guard against income swings brought on by variable renewable energy generation in order to further reduce investment risks.

3.4.4. Public–Private Partnerships and Investment

Scaling VPPs in South Africa requires both investor recruitment and public–private partnerships (PPPs). By providing co-funding possibilities, sharing risks, and utilizing public monies to draw in private capital, the government should support PPPs. In underserved communities, where public funding can cover the initial infrastructure expenses for VPP initiatives, this strategy may be especially helpful. Furthermore, encouraging domestic production of VPP components—like smart inverters and battery storage units—through tax breaks and R&D funding will contribute to the development of a domestic economy centered around these technologies. Creating a national VPP plan with precise goals, deadlines, and completion dates will promote consistent investment in VPP development and offer additional strategic direction.

3.4.5. Decentralized Energy Solutions and Community Engagement

Decentralized energy solutions and community involvement are critical to VPP success in South Africa. To improve energy access, especially in rural or low-income areas, community-based VPPs—which combine local DERs such as rooftop solar panels, small wind turbines, and battery storage—should be encouraged. This decentralized approach will be supported by standardizing interconnection agreements to facilitate the integration of small-scale DERs and by offering incentives for participating in demand response programs. To increase confidence in and adoption of VPP technologies, public education campaigns, and community involvement programs should be started. These should emphasize the technologies' ability to lessen load shedding and provide energy bill savings.

3.4.6. Consistent Innovation and Pilot Projects

In order to improve VPP integration techniques within the context of South Africa, pilot projects and ongoing innovation are essential. To evaluate different VPP designs and commercial models, targeted pilot projects should be undertaken in strategic places, such as areas with great potential for renewable energy or areas with regular grid instability. Innovations like AI-driven energy management and improved battery storage solutions will be the focus of R&D in VPP technologies, which will be driven by collaboration with academic institutions, research organizations, and industry stakeholders. The creation of a national VPP innovation hub can offer a cooperative environment for creating and evaluating novel VPP solutions customized to regional requirements.

3.4.7. Social Requirements

In South Africa, ensuring social acceptance, equity, and access is a fundamental component of VPP integration. Underserved communities should be given priority when it comes to energy access through VPP efforts, which should use VPP profits to fund energy access programs or use cross-subsidization models. In order to address social and environmental concerns, it is imperative that local communities be involved early in the planning stages of VPP projects. This will ensure that the projects are in line with local goals and follow best practices for sustainability and community benefit.

3.5. Case Studies and Comparative Analysis

At least five utility-scale VPPs are either active or in the development stage as of 2024 in South Africa. These VPPs are improving energy management, boosting grid stability, and setting the standard for how renewable energy sources are integrated into the national grid [48]. The Umoyilanga and Oya Energy projects are among the VPPs that are covered in this paper, along with information on the other three projects that are influencing South Africa's energy future.

3.5.1. Local Case Studies

Umoyilanga Project

The first integrated wind, solar, and battery storage VPP in South Africa is the Umoyilanga project. Together with Electricite de France (EDF) Renewables, Sungrow has launched this ground-breaking project to ease the nation's power problem by offering a dispatchable and dependable energy source [49]. Sungrow is required to deliver 264 MWh of liquid-cooled energy storage devices for this plant in accordance with the terms of the supply agreement. The project comprises two plants that are 900 km from each other. The first plant is a wind-plus-storage plant, and the second one is a solar-plus-storage plant. Eskom can draw upon the 75 MW of dispatchable electricity that the VPP is scheduled to offer to the national grid at relatively short notice, which is expected to play a critical role in stabilizing the power supply.

Oya Energy Project

Another notable VPP in South Africa is the Oya Energy project, which uses artificial intelligence to maximize the performance of renewable energy resources [50]. Important parties like the global energy and services conglomerate Engie, Meadows Energy, Perpetua Investments Holdings, and G7 Renewable Energies [51] are participating in this collaborative project. The VPP is a component of a larger initiative to combine battery ESSs along with other RESs, such as solar and wind, to build a unified and adaptable power generation network.

Other VPP initiatives

Engie has played a pivotal role in propelling VPPs forward in South Africa. Engie's VPPs incorporate a range of decentralized RESs, such as solar photovoltaic systems and wind turbines, that are controlled as a single unit yet are individually owned. This method strengthens the power supply's flexibility and dependability, making it a pillar of South Africa's renewable energy policy.

The development of VPPs that supply dispatchable power to the national grid has been made easier by the government's Risk Mitigation IPP Programme (RMIPPPP) [50,52]. The RMIPPPP uses VPPs to guarantee a consistent supply of electricity even in situations where individual renewable energy sources are sporadic or unpredictable, thereby reducing the risks connected with independent power production.

3.5.2. Comparative Analysis of Local Case Studies

To improve energy management and grid stability, Section 3.2 highlights the significance of integrating various energy sources using sophisticated scheduling algorithms. This strategy is demonstrated by the Umoyilanga Project, which combines energy storage with wind and solar power plants to produce a hybrid VPP. Its quick power dispatch demonstrates the optimization techniques discussed, especially as it pertains to coordinating control and utilizing optimization techniques to manage intermittent energy. In line with the control and communication tactics covered in Section 3.3, Oya Energy also uses AI to make real-time performance modifications. In order to enhance the dispatch and coordination of DERs, AI is used, which exhibits the application of cutting-edge energy management technologies, which, in turn, improves the supply stability of the South African grid.

The necessity of trustworthy and secure data sharing in VPP operations is emphasized in Section 3.3. The integration of AI-powered technologies improves the data flow, monitoring, and control necessary to manage large-scale energy systems in the Oya Energy Project. In a similar vein, both initiatives support the tactics of maximizing communication technology and guaranteeing cybersecurity via cutting-edge infrastructure. This reflects the theoretical debates about the significance of data security, real-time system control, and communication protocols in Section 3.3.

Finally, the technical, financial, and regulatory frameworks required to support VPPs in South Africa are highlighted in Section 3.4. The Umoyilanga and Oya Energy Projects are supported by the RMIPPPP, which serves as an example of how public–private partnerships and government policy may offer the funding and legal assistance required for the effective implementation of VPP. This is in line with the strategic suggestions made in Section 3.4 about improving policies, investing in digital infrastructure, and creating adaptable market mechanisms.

3.5.3. Global Case Studies

The growing significance of VPPs can be attributed to the necessity for grid flexibility and the decentralization of energy systems, and the global movement towards the integration of RESs. VPPs are a vital component of many European nations' energy transition plans, such as that of Germany (Energiewende). To manage DERs, VPPs use cutting-edge technology like AI, machine learning, and the Internet of Things (IoT). These VPPs ensure grid stability, offer ancillary services and participate in the energy market as a result of the coordinated management of the resources. The US was prompted to introduce VPPs in order to satisfy strict renewable energy objectives and update the outdated grid infrastructure. Enterprises such as Tesla and Sunrun [31] are engaged in the development of VPPs that integrate grid services with household solar and battery storage. VPPs have also proven beneficial in the isolated and rural regions of Australia, where they improve energy security and decrease dependence on centralized fossil fuel generation. Supportive regulatory frameworks, financial incentives, and sophisticated grid management technologies are the basis of VPPs' global success. The international case studies examined were from Germany, Australia, the USA and Japan because of their relevance to the South African landscape and because of their advanced VPP integration. Their varied approaches to energy constraints made it possible to determine appropriate tactics and possible obstacles relevant to South Africa's grid modernization initiatives.

Germany (Next Kraftwerke)

Germany has pioneered the implementation of VPPs [53]. Next Kraftwerke is a leading provider of VPPs and manages over 10 GW of flexible load or generation (2022), one of the largest in Europe [54]. This VPP network comprises 13,000 decentralized plants (mainly solar power). The power generators, storage units, and consumers are networked and controlled by Next Kraftwerke [55]. It can reduce its members' energy expenses by sending signals to them while making money by charging the grid operator for essential services like voltage support, auxiliary services, flexibility, and capacity. Through its own 24/7 electricity trading, the VPP trades the networked customers' power on many European exchanges (such as EPEX and EEX) and optimizes their electricity output and consumption based on price signals [55]. In Germany, the VPP offers auxiliary services, including frequency regulation in addition to grid balancing [55]. It illustrates how, with proper management, significant penetration of renewable energy sources is possible. The management of a high percentage of renewable energy in the grid, which is crucial for South Africa's renewable energy targets, can be taken from Germany's experience with VPPs.

Australia (Tesla VPP)

A massive VPP project, spearheaded by Tesla, was initiated in Australia. It unites household solar and battery systems throughout South Australia. The VPP lowers peak demand, stabilizes the system, and supplies backup power during blackouts. It supplies reliable, secure, and more affordable electricity [56]. The experiment demonstrates how distributed energy storage in VPPs may be used. By 2023, the initiative had benefited over 5500 South Australian houses, and more were being added each month. The research demonstrates the possibility of distributed energy storage in VPPs, which stores extra solar electricity and releases it when needed to lessen the intermittent nature of RESs [57]. This scenario emphasizes how important it is to integrate distributed storage systems into VPPs in order to balance supply and demand, especially in light of South Africa's potential for energy storage and the necessity to address grid instability. It charges and discharges energy from household battery systems and trades it on the National Energy Market using Wi-Fi technology and advanced software [58].

USA (Pacific Gas and Electric Company VPP)

Demand response systems, wind, and solar energy are all integrated into a VPP run by Pacific Gas and Electric (PG&E) in California in the United States. As of 2024, PG&E anticipated having 412 megawatts of VPP capacity in its portfolio. In addition to preventing grid overloads and lowering demand during peak hours, the VPP enables distributed energy resources to engage in energy markets [59]. In order to increase its VPP capabilities, PG&E has teamed with businesses such as Sunrun and Tesla. VPPs' access to wholesale energy markets can assist DER owners in optimizing their financial gains and encourage additional investments in renewable energy. For instance, participants in the Tesla VPP with PG&E receive USD 2.00 for each extra kWh that their Powerwall produces during an event [60]. Demand response technologies used by VPPs in the USA can help South Africa manage peak loads and lessen its dependency on fossil fuels during times of high demand.

Japan (TEPCO's Smart Grid and VPP)

As part of its smart grid strategy, Tokyo Electric Power Company (TEPCO) in Japan created a VPP [61,62]. To stabilize the grid and encourage the integration of more renewable energy, this VPP combines residential energy systems, EV batteries, and RESs. The integration of VPPs and smart grid technologies in Japan emphasizes the significance of sophisticated control and communication systems for DER real-time management [62]. Using smart grid technology in conjunction with VPPs may enhance the grid's ability to manage energy in real time in South Africa and facilitate the integration of storage and renewable energy sources.

3.5.4. Recommendations for South Africa Based on Lessons from Global Case Studies

The full potential of VPPs is limited by regulatory hurdles that many countries encounter. Among these include the absence of standardized grid integration frameworks and ambiguous market regulations for DER participation [63]. To effectively handle the coordination of dispersed assets, successful VPPs depend on sophisticated ICT systems. International case studies demonstrate that strong IT infrastructure and smart grid capabilities are necessary for the integration of renewable energy, storage, and demand response technologies [54,55,64,65]. In many VPPs, storage is essential, particularly in nations with high rates of renewable energy adoption. Grid dependability is increased by storing excess electricity during periods of low demand and using it during peak hours.

Japan has a greater focus on IoT-driven real-time communication than Germany, which employs a centralized control system [54,55,66–68]. Japan's strategy uses cutting-edge IoT to enable quicker demand response, while Germany's model is excellent at effectively integrating various DERs. Given its requirement for real-time energy management in the face of frequent load shedding, this brings up the question regarding which approach would be more suitable for South Africa. Centralized control ensures that all players work together seamlessly and makes oversight easier. The German VPP manages ancillary services via a grid that is well developed [69]. This may not be feasible to be replicated in South Africa due to the shortcomings in the country's infrastructure.

Australia's decentralized, prosumer-centered VPP offers a practical example for energy management, which may be more suitable to adapt to the region but would still require adequate regulatory support [65]. A similar strategy would be beneficial for South Africa, particularly in areas with significant solar potential [29]. Making sure that these technologies are affordable and backed by a strong regulatory framework to encourage home involvement would be difficult, however.

An alternative strategy for attaining flexibility is shown by Japan's local-level resource management through smart grids, which use advanced metering infrastructure (AMI) and IoT for real-time control [66–68]. IoT-enabled residential VPPs may provide more immediate benefits for South Africa, where the grid faces real-time response and infrastructure constraints; nevertheless, this would necessitate investment in data infrastructure and smart metering.

3.6. Regulatory Changes

The REIPPPP was created by the South African government to counteract the energy supply deficiency [70]. This policy has been beneficial to the expansion of the renewable energy industry. The South African Grid Code (SAGC) does not explicitly specify requirements for VPPs [71]. The SAGC will need to be updated to accommodate VPPs. Feed-in tariff schemes are currently location-dependent and only offered by certain municipalities [8,47]. To fully benefit from this scheme, which encourages consumer participation, a nationally standardized feed-in scheme needs to be implemented. These net metering policies allow prosumers' self-generated power to offset their consumption as well as ease the burden on the grid. This is further encouraged by incentives for distributed generation, namely tax incentives for renewable energy assets [72], REIPPPP [8], local government initiatives like feed-in tariffs and carbon tax initiatives [73]. Net metering and wheeling arrangements (small-scale produces selling excess energy to other consumers) policies should be established to further expand distributed generation.

A thorough regulatory framework that outlines VPPs should be provided, including their operating guidelines and the regulations governing market participation. This ought to consist of detailed explanations of VPPs and their constituent parts, rules for VPP certification, and registration guidelines for VPP involvement in electricity markets. Mechanisms that allow VPPs to trade in wholesale electricity markets must be established.

Incentive schemes to be established should include providing tax breaks to consumers and companies making DER investments, offering VPP initiatives grants or low-interest loans, and providing net metering initiatives or feed-in tariffs for small-scale generators. Grid infrastructure investments to modernize distribution and transmission networks should be made to facilitate VPP integration.

Privacy and data management policies should be implemented. This includes the creation of procedures for grid managers and VPP operators to share data, establishing strong cybersecurity measures, and making sure that customer privacy is protected.

To enable demand response aggregators to engage in the wholesale market, the Demand Response Mechanism (DRM) was put into place in Australia. This allows for the direct sale of demand response to the National Energy Market by authorized consumers [74]. In the United States, grid operators must permit VPPs to engage in wholesale energy markets in accordance with FERC Order 2222 [75] and aggregators and demand response involvement in energy markets are covered by the EU's Clean Energy Package [76,77]. Similar policies should be adopted in South Africa to facilitate the transition to a higher percentage of RESs in the energy mix.

4. Result and Discussion

In line with the objectives of IRP 2019, the analysis identified VPPs as crucial instruments for South Africa's shift to a sustainable energy future. Through the integration of RESs and improved grid stability, VPPs decrease the country's dependence on traditional power generation sources. This emphasizes the importance of VPPs in accelerating South Africa's energy transformation by effectively coordinating the use of a wide variety of renewable resources.

Central to VPP operations is the EMS, which ensures effective energy management and coordinates DERs. Though the precise functions of agents, namely prosumers, aggregators, and system operators, within the system are still undefined, proposed architectures for net-zero energy grids emphasize VPPs as essential to both technical and commercial DER operations. This lack of transparency highlights the need for additional research on the successful coordination of these different agents. The ability of VPPs to effectively manage DERs and participate in electricity markets may be compromised in the absence of this.

The ability to balance supply and demand in real time becomes essential as South Africa's share of RESs increases. Grid stability is guaranteed by VPPs' optimization of flexible resources like demand response and battery storage through EMS. For example, demand response devices can lower consumption, but batteries must discharge to fulfill demand during times of poor solar production. One of the main benefits of using VPPs for managing intermittent renewable energy sources is their capacity to utilize flexible resources to follow load, especially in South Africa, where the renewable energy industry is expanding.

The communication layer, which facilitates real-time data sharing and energy trading between DERs and the grid, is a crucial component of VPP integration. The intricate nature of VPP operations highlights the necessity for dependable and secure communication systems. The ability to dynamically regulate energy supply and demand is made possible by bidirectional data sharing, which is essential for energy trading in financial contexts. This emphasizes how crucial it is to provide reliable communication technologies that safeguard private information and facilitate effective energy transfers within VPPs.

In order to successfully integrate VPPs into South Africa's grid, a number of intricate regulatory and market issues must be resolved. The necessity for demand response programs, well-thought-out feed-in tariff schemes, dynamic energy trading platforms, and supportive regulations and policies are some of the current obstacles. The study highlights that in order to overcome these obstacles, collaboration between the scientific community, energy stakeholders, and policymakers is crucial. Without such cooperation, VPPs may not be able to fully realize their potential in achieving the goals of IRP 2019.

For VPPs to optimize energy management, effective scheduling algorithms are essential. These algorithms take into account variables like market prices, storage efficiency, and the availability of renewable energy. Deep Reinforcement Learning is one example of an advanced learning-based approach that is being used to address the complexity and uncertainty of VPP operations, which is necessary given the variable nature of renewable resources.

Technical VPPs, which concentrate on technical performance and real-time monitoring of RES, and Commercial VPPs, which are focused on economic optimization and market involvement, are the two categories into which VPPs are divided. This distinction demonstrates the flexibility of VPPs in addressing a variety of goals, from market-driven profitability to maintaining grid reliability. Integrating VPPs will result in the following improvements in technical metrics; refer to Table 7.

Table 7. Technical metrics after VPP integration.

Metric	Current Value	Value After VPP Integration
Curtailment rate	0.24% curtailment of renewables [78,79] >10% (general curtailment rate) [80]	5% [81] (due to VPP optimization) but require 10% to double renewable generators [80]
System Average Interruption Duration Index, SAIDI (hours per year)	184.7 (2022/23 Eskom annual report) [82]	Load-shedding is reduced by providing additional power
Renewable penetration	9.5% (2022) [24]	24.7% by 2030 (IRP 2019 target) [15]
Frequency stability	±1 Hz (critical threshold) [71]	±0.5 Hz (normal range, reduction in variability) [71]
Transmission losses	8.39% [83]	6% [84] (due to enhanced distributed generation [85])
Reduction in GHG emissions	478.89 MtCO2e (2022) (of which the energy sector accounts for 78%) [86]	−10% (target of 350–420 MtCO2e by 2030) [86]

Grid curtailment increased from 4.606 GWh in the first half of 2023 to 19.9 GWh for the same period in 2024. The values have thus increased by 300%. Even though the percentage of renewable curtailment is low, there is a goal to reduce curtailment (in general) to less than 10%. In [80], it states that South Africa will benefit greatly if it can decrease its curtailment down to 10%. The general curtailment rate is due to a number of factors, such as limited capacity and the aged infrastructure. Integrating more renewables will only increase the curtailment rate. Thus, addressing curtailment using VPP optimization will improve RES utilization. The 5% is based on Germany's curtailment value [81] since it is a country with a high renewable energy capacity. The SAIDI is driven by load-shedding so VPP implementation will not only add generating capacity but enhance real-time grid balancing and thus reduce interruptions. The integration of VPPs means the addition of DERs, which supports the IRP 2019 2030 renewable energy target. Frequency deviations can occur due to sudden load changes or insufficient generation. VPPs are able to adjust loads and dispatch stored energy thus reducing deviations and keeping it within the normal range. The increased renewable energy integration and efficiency due to VPPs will result in a reduction in GHG emissions.

To achieve an increase in renewable energy integration, targeted investments in smart grid technologies and VPPs should be prioritized.

The literature review emphasizes the critical role energy storage plays in lowering renewable intermittency and enhancing grid stability, even if this study did not specifically address it. Sophisticated battery management technologies combined with appropriately scaled energy storage systems can greatly improve VPP performance by guaranteeing a constant power supply even in the face of changes in renewable energy generation. This provides more evidence that VPPs can successfully manage South Africa's energy transformation.

The results demonstrate the opportunities and difficulties associated with VPP integration in South Africa. Although Virtual Power Plants (VPPs) provide a remarkable prospect to augment grid stability, broaden access to renewable energy, and improve energy management, there exist noteworthy technological, regulatory, and market-related challenges to surmount. To enable successful adoption, future research should concentrate on real-world case studies and additional elucidation of responsibilities within the VPP ecosystem.

5. Conclusions

In conclusion, this review emphasizes the substantial potential of VPPs in advancing South Africa's energy transformation, as delineated in the 2019 IRP. Several significant challenges facing the current energy landscape, such as the over-reliance on fossil fuels, grid instability, and the intermittent nature of RESs, can be resolved with the integration of VPPs. VPPs can improve grid reliability, offer ancillary services, and optimize energy dispatch by combining DERs such as solar PV, wind turbines, and energy storage devices.

Key findings of this study indicate that VPPs can enable more efficient integration of RESs by leveraging modern control systems and predictive algorithms. By controlling renewable energy's fluctuation, these technologies help resolve the intermittency issues associated with solar and wind power while maintaining a steady supply of energy. As South Africa increases its renewable energy capacity to 24.7% by 2030, this capability is crucial. Furthermore, one of the most significant aspects of reducing the fluctuations associated with RESs is the efficient deployment and management of energy storage systems within VPPs. VPPs can further improve grid stability by balancing supply and demand by utilizing advanced battery management systems and optimal sizing methodologies.

In order to enable VPP participation in electricity markets, this review emphasizes the necessity of a supportive regulatory framework. To enable small-scale DERs to make a significant grid contribution, it will be necessary to develop clear policies and incentives, such as feed-in tariffs. Furthermore, effective cybersecurity protections and seamless communication and control mechanisms are essential for VPP operations, guaranteeing real-time DER coordination.

This paper establishes a framework whereby the success of the integration of VPPs can be measured by emphasizing the critical objectives, namely, grid reliability, renewable energy penetration, and cost reduction. It also demonstrates the benefits of VPP integration as it relates to grid stability, improved reliability and curtailment reduction. The resultant reduction in GHG emissions also contributes to the country's climate goals.

VPP integration has an influence on South Africa's grid that extends beyond increasing the use of renewable energy; it offers a mechanism with which to modernize grid infrastructure, decentralize energy production, and encourage prosumer economic engagement. In order to take a significant step towards its sustainability targets, lower its carbon footprint, and enhance energy access in underserved areas, South Africa would need to successfully deploy VPPs. But in order to overcome technological, economical, and regulatory obstacles, policymakers, energy stakeholders, and the scientific community will need to work together.

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References

1. Nwokolo, S.C.; Obiwulu, A.U.; Okonkwo, P.C. *Africa's Propensity for a Net Zero Energy Transition*; CRC Press: Boca Raton, FL, USA, 2024; ISBN 9781003483175.
2. Williams, M.; Chang, C.K. Proposed Architecture of the Virtual Power Plants for the South African Power Grid. In Proceedings of the Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Republic of Korea, 9–10 May 2024.
3. Lou, Y.; Sun, F.; Ni, J. Optimizing energy storage plant discrete system dynamics analysis with graph convolutional networks. *Heliyon* **2024**, *10*, e31119. [CrossRef] [PubMed]
4. Morales, J.M.; Conejo, A.J.; Madsen, H.; Pinson, P.; Zugno, M. *Integrating Renewables in Electricity Markets-Operational Problems*, 1st ed.; Springer: New York, NY, USA, 2014; Volume 205, ISBN 9781461494102.
5. Zia, M.F.; Elbouchikhi, E.; Benbouzid, M. Microgrids energy management systems: A critical review on methods, solutions, and prospects. *Appl. Energy* **2018**, *222*, 1033–1055. [CrossRef]
6. Vandoorn, T.L.; Vasquez, J.C.; De Kooning, J.; Guerrero, J.M.; Vandevelde, L. Microgrids: Hierarchical Control and an Overview of the Control and Reserve Management Strategies. *IEEE Ind. Electron. Mag.* **2013**, *7*, 42–55. [CrossRef]
7. Gunduz, M.Z.; Das, R. Cyber-security on smart grid: Threats and potential solutions. *Comput. Netw.* **2020**, *169*, 107094. [CrossRef]
8. NDC Partnership. *South Africa's Renewable Energy Independent Power Producer Procurement Programme*; NDC: Washington, DC, USA, 2016.
9. Hong, T.; Pinson, P.; Fan, S.; Zareipour, H.; Troccoli, A.; Hyndman, R.J. Probabilistic energy forecasting: Global Energy Forecasting Competition 2014 and beyond. *Int. J. Forecast.* **2016**, *32*, 896–913. [CrossRef]
10. Nosratabadi, S.M.; Hooshmand, R.A.; Gholipour, E. A comprehensive review on microgrid and virtual power plant concepts employed for distributed energy resources scheduling in power systems. *Renew. Sustain. Energy Rev.* **2017**, *67*, 341–363. [CrossRef]
11. Liu, J.; Hu, H.; Yu, S.S.; Trinh, H. Virtual Power Plant with Renewable Energy Sources and Energy Storage Systems for Sustainable Power Grid-Formation, Control Techniques and Demand Response. *Energies* **2023**, *16*, 3705. [CrossRef]
12. Zarate-Perez, E.; Grados, J.; Rubiños, S.; Solis-Tipian, M.; Cuzcano-Rivas, A.; Astocondor-Villar, J.; Grados-Espinoza, H. Virtual power plant for energy management: Science mapping approach. *Heliyon* **2023**, *9*, e19962. [CrossRef] [PubMed]
13. Dai, H.; Jiang, B.; Hu, X.; Lin, X.; Wei, X.; Pecht, M. Advanced battery management strategies for a sustainable energy future: Multilayer design concepts and research trends. *Renew. Sustain. Energy Rev.* **2021**, *138*, 110480. [CrossRef]
14. Davuluri, S. Smart Regulatory Frameworks to Accelerate Smart Energy Solutions: Policies to Scale VPPs. 2023. Available online: https://www.auto-grid.com/resources/white-papers/vpp-policy-brief/ (accessed on 5 September 2024).
15. Department of Energy. Integrated Resource Plan 2019. 2019. Available online: https://www.thepresidency.gov.za/download/file/fid/2649 (accessed on 30 July 2023).
16. Next Kraftwerke. Virtual Power Plant. 2023. Available online: https://www.next-kraftwerke.com/vpp/virtual-power-plant (accessed on 21 October 2024).

17. Sarmiento-Vintimilla, J.C.; Torres, E.; Larruskain, D.M.; Pérez-Molina, M.J. Applications, Operational Architectures and Development of Virtual Power Plants as a Strategy to Facilitate the Integration of Distributed Energy Resources. *Energies* **2022**, *15*, 775. [CrossRef]
18. Li, M.; Xu, S.; Jiang, Y. A Two-Stage Optimization Framework for Power Systems Containing Virtual Power Plants with Distributed Generators and EV Charging Demand. In *IFAC-PapersOnLine*; Elsevier: Amsterdam, The Netherlands, 2020; Volume 53, pp. 618–623.
19. Behi, B.; Arefi, A.; Jennings, P.; Gorjy, A.; Pivrikas, A. Advanced monitoring and control system for virtual power plants for enabling customer engagement and market participation. *Energies* **2021**, *14*, 1113. [CrossRef]
20. Bello, M.; Carter-Brown, C.; Smit, R.; Davidson, I.E. Power planning for renewable energy grid integration-case study of South Africa. In Proceedings of the 2013 IEEE Power & Energy Society General Meeting, Vancouver, BC, Canada, 21–25 July 2013; pp. 1–5.
21. Ren, L.; Peng, D.; Wang, D.; Li, J.; Zhao, H. Multi-objective optimal dispatching of virtual power plants considering source-load uncertainty in V2G mode. *Front. Energy Res.* **2023**, *10*, 983743. [CrossRef]
22. Kim, J. How Virtual Power Plants Are Shaping Tomorrow's Energy System. *MIT Technology Review*, 7 February 2024. Available online: https://www.technologyreview.com/2024/02/07/1087836/how-virtual-power-plants-are-shaping-tomorrows-energy-system/ (accessed on 5 September 2024).
23. Rouzbahani, H.M.; Karimipour, H.; Lei, L. A review on virtual power plant for energy management. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101370. [CrossRef]
24. CSIR. *Statistics of Utility-Scale Power Generation in South Africa in 2021*; CSIR: Pretoria, South Africa, 2022; Volume 2022.
25. Pierce, W.; Ferereira, B. Statistics of Utility-Scales Power Generation in South Africa. CSIR Energy Centre, 2022; pp. 1–122. Available online: https://www.csir.co.za/sites/default/files/Documents/StatisticsofpowerinSA2022-CSIR-[FINAL].pdf (accessed on 30 September 2023).
26. Matsuda-dunn, R.; Mckenna, K.; Desai, J.; Mukoma, P. *Determining and Unlocking Untapped Demand-Side Management Potential in South Africa: Demand Response at the Grid Edge*; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2024; pp. 1–103.
27. Shropshire, D.; Purvins, A.; Papaioannou, I.; Maschio, I. Benefits and cost implications from integrating small flexible nuclear reactors with off-shore wind farms in a virtual power plant. *Energy Policy* **2012**, *46*, 558–573. [CrossRef]
28. Project Finance International. Transforming South Africa's Energy Landscape. 2024. Available online: https://www.pfie.com/story/4520520/transforming-south-africas-energy-landscape-xdnwgbbcsm (accessed on 5 September 2024).
29. CSIR. *SANEDI Wind and Solar PV Resource Aggregation Study for South Africa (RfP No. 542-23-02-2015)*; CSIR: Pretoria, South Africa, 2016.
30. Council for Scientific and Industrial Research (CSIR). Additional Renewable Energy Development Zones Proposed for Wind and Solar PV. 2019. Available online: https://www.csir.co.za/renewable-energy-development-zones (accessed on 26 November 2024).
31. Ruan, G.; Qiu, D.; Sivaranjani, S.; Awad, A.S.A.; Strbac, G. Data-driven energy management of virtual power plants: A review. *Adv. Appl. Energy* **2024**, *14*, 100170. [CrossRef]
32. City of Cape Town Requirements for Small-Scale Embedded Generation Application and Approval Process for Small-Scale Embedded Generation in the City of Cape Town; Cape Town, 2023. Available online: https://resource.capetown.gov.za/documentcentre/Documents/Procedures,guidelinesandregulations/Requirements%20for%20Small-Scale%20Embedded%20Generation.pdf (accessed on 5 September 2024).
33. Guise, L.; Berry, T.; Cleveland, F. Semantic Interoperability of DERs Obtained by Standardized Designs and Mappings to DER Protocols, Thanks to IEC 61850-7-420 Ed 2.0. 2021. Available online: https://www.pacw.org/semantic-interoperability-of-ders-obtained-by-standardized-designs-and-mappings-to-der-protocols-thanks-to-iec-61850-7-420-ed-2-0 (accessed on 9 September 2024).
34. City of Cape Town. City Wheeling Toward Energy Secure Future. 2024. Available online: https://www.capetown.gov.za/Media-and-news/City%20wheelingtowardenergysecurefuture (accessed on 5 September 2024).
35. Jacobs, Y. Cash for Power Programme: How It Works. *IOL News*, 28 February 2024. Available online: https://www.iol.co.za/news/south-africa/western-cape/cash-for-power-programme-how-it-works-4132b5a5-def0-4878-ab3e-e5a480dfce8b (accessed on 5 September 2024).
36. Naval, N.; Yusta, J.M. Virtual power plant models and electricity markets-A review. *Renew. Sustain. Energy Rev.* **2021**, *149*, 111393. [CrossRef]
37. Mahmud, K.; Khan, B.; Ravishankar, J.; Ahmadi, A.; Siano, P. An internet of energy framework with distributed energy resources, prosumers and small-scale virtual power plants: An overview. *Renew. Sustain. Energy Rev.* **2020**, *127*, 109840. [CrossRef]
38. Sakr, W.S.; el-Ghany, H.A.A.; EL-Sehiemy, R.A.; Azmy, A.M. Techno-economic assessment of consumers' participation in the demand response program for optimal day-ahead scheduling of virtual power plants. *Alex. Eng. J.* **2020**, *59*, 399–415. [CrossRef]
39. Heydarian-Forushani, E.; Bahramara, S.; Sheikhahmadi, P.; Zeraati, M.; Elghali, S. Ben A proactive strategy for virtual power plants including multiple private owners equipped with energy storages. *J. Energy Storage* **2023**, *66*, 107514. [CrossRef]
40. Liu, X. Research on optimal dispatch method of virtual power plant considering various energy complementary and energy low carbonization. *Int. J. Electr. Power Energy Syst.* **2022**, *136*, 107670. [CrossRef]
41. Srivastava, A.K.; Latif, A.; Shaoo, S.C.; Das, D.C.; Hussain, S.M.S.; Ustun, T.S. Analysis of GOA optimized two-stage controller for frequency regulation of grid integrated virtual power plant. *Energy Rep.* **2022**, *8*, 493–500. [CrossRef]

42. Fan, S.; Ai, Q.; Piao, L. Fuzzy day-ahead scheduling of virtual power plant with optimal confidence level. *IET Gener. Transm. Distrib.* **2016**, *10*, 205–212. [CrossRef]
43. Lu, C.; Chen, S. Distributed Scheduling Strategy of Virtual Power Plant Using the Particle Swarm Optimization Neural Network under Blockchain Background. *Comput. Intell. Neurosci.* **2022**, *2022*, 3222249. [CrossRef]
44. Rekik, M.; Chtourou, Z.; Mitton, N.; Atieh, A. Geographic routing protocol for the deployment of virtual power plant within the smart grid. *Sustain. Cities Soc.* **2016**, *25*, 39–48. [CrossRef]
45. AL-Jumaili, A.H.A.; AI-Mashhadany, Y.I.; Sulaiman, R.; Alyasseri, Z.A.A. A Conceptual and Systematics for Intelligent Power Management System-Based Cloud Computing: Prospects, and Challenges. *Appl. Sci.* **2021**, *11*, 9820. [CrossRef]
46. Cao, J.; Zheng, Y.; Han, X.; Yang, D.; Yu, J.; Tomin, N.; Dehghanian, P. Two-stage optimization of a virtual power plant incorporating with demand response and energy complementation. *Energy Rep.* **2022**, *8*, 7374–7385. [CrossRef]
47. World Bank Group. South Africa's Renewable Energy IPP Procurement Program: Success Factors and Lessons. World Bank Group. Available online: https://ppp.worldbank.org/public-private-partnership/library/south-africa-s-renewable-energy-ipp-procurement-program-success-factors-and-lessons-0 (accessed on 9 September 2024).
48. Mflathelwa, S.; Zinman, D. How SA Can Make the Most of Its Fast-Growing Network of Virtual Power Plants. *News24*, 1 May 2024. Available online: https://www.news24.com/fin24/opinion/opinion-how-sa-can-make-the-most-of-its-fast-growing-network-of-virtual-power-plants-20240501 (accessed on 11 September 2024).
49. SolarQuarter. Sungrow to Supply EDF Renewables on South Africa's First Hybrid Wind-Solar-Battery VPP Project. *SolarQuarter*, 5 December 2023. Available online: https://solarquarter.com/2023/12/05/sungrow-to-supply-edf-renewables-on-south-africas-first-hybrid-wind-solar-battery-vpp-project/ (accessed on 11 October 2024).
50. Mflathelwa, S.; Zinman, D. SA's Fast-Growing Numbers of Virtual Power Plants to Be Optimised with AI. *RMB/Oya Energy*, 2 May 2024. Available online: https://www.rmb.co.za/news/sas-fast-growing-numbers-of-virtual-power-plants-to-be-optimised-with-ai?utm_medium=social&utm_source=linkedin&utm_campaign=RMB_Virtual_Power_Plants (accessed on 11 October 2024).
51. Mining Review Africa. Oya Hybrid Project to Power 180,000 SA Homes with Clean Energy. Mining Review Africa, 2023. Available online: https://www.miningreview.com/energy/oya-hybrid-project-to-power-180-000-sa-homes-with-clean-energy/ (accessed on 9 September 2024).
52. Tellefsen, G. Powering the Future: The Potential of Virtual Power Plants in South Africa. LinkedIn, Cape Town, 2023. Available online: https://www.linkedin.com/pulse/powering-future-potential-virtual-power-plants-south-africa-geir (accessed on 5 October 2024).
53. Wilder, P. What to Know About Operating Virtual Power Plants (VPPs). 60 Hertz. Available online: https://60hertzenergy.com/virtual-power-plant/ (accessed on 4 October 2024).
54. Next Kraftwerke. The Power of Many. 2023. Available online: https://www.next-kraftwerke.com/vpp (accessed on 5 September 2024).
55. Next Kraftwerke. Next Kraftwerke Passes 10,000 Megawatt Milestone of Aggregated Capacity. 2022. Available online: https://www.next-kraftwerke.com/news/10000-megawatt-of-aggregated-capacity (accessed on 5 October 2024).
56. CECF. *SA Creates Australia's Largest Virtual Power Plant*; CECF: Columbia, MD, USA, 2023.
57. Government of South Australia (Department of Energy & Mining). South Australia's Virtual Power Plant. Department of Energy & Mining. Available online: https://www.energymining.sa.gov.au/consumers/solar-and-batteries/south-australias-virtual-power-plant (accessed on 3 October 2024).
58. Tesla. South Australia's Virtual Power Plant: Frequently Asked Questions. 2024. Available online: https://www.tesla.com/en_au/support/energy/savpp-faqs (accessed on 3 October 2024).
59. Skok, P.; Jenkins, L.M. It's an unsettled time for VPPs in California. *Latitude Media*, 7 June 2024. Available online: https://www.latitudemedia.com/news/its-an-unsettled-time-for-vpps-in-california-pge (accessed on 3 October 2024).
60. Tesla. Tesla Virtual Power Plant With PG&E. 2024. Available online: https://www.tesla.com/support/energy/virtual-power-plant/pge (accessed on 3 October 2024).
61. Publicover, B. Sunverge to Build VPP Project for TEPCO in Japan. *pv Magazine*, 12 December 2017. Available online: https://www.pv-magazine.com/2017/12/12/sunverge-to-build-vpp-project-for-tepco-in-japan/ (accessed on 11 October 2024).
62. Mitsubishi Motors Corporation. Construction of Virtual Power Plant (VPP) Using Electric Vehicles. Challenge Zero. Available online: https://www.challenge-zero.jp/en/casestudy/601 (accessed on 11 October 2024).
63. Abdelkader, S.; Amissah, J.; Abdel-Rahim, O. Virtual power plants: An in-depth analysis of their advancements and importance as crucial players in modern power systems. *Energy Sustain. Soc.* **2024**, *14*, 1. [CrossRef]
64. ARENA. Tesla Virtual Power Plant. Australian Renewable Energy Agency, 2024. Available online: https://arena.gov.au/projects/tesla-virtual-power-plant/ (accessed on 11 October 2024).
65. Renew Economy. Tesla Seeks Buyer for Australian Virtual Power Plant, as Long as It can Supply the Batteries and Software. 2024. Available online: https://reneweconomy.com.au/tesla-seeks-buyer-for-australian-virtual-power-plant-as-long-as-it-can-supply-the-batteries-and-software/ (accessed on 13 October 2024).
66. Nhede, N. Tepco Reaches 20 Million Smart Meter Milestone. *Smart Energy International*, 5 May 2019. Available online: https://www.smart-energy.com/industry-sectors/smart-meters/tepco-reaches-20-million-smart-meter-milestone/ (accessed on 13 October 2024).

67. eZine. Game-Changer: TEPCO's Smart Grid Strategy Could Impact Grid Modernization Worldwide. Landis+Gyr, 2024. Available online: https://www.landisgyr.com.au/ezine-article/game-changer-tepcos-smart-grid-strategy-impact-grid-modernization-worldwide/ (accessed on 15 October 2024).
68. TEPCO. Expanding Business Areas Through Advanced Technology. TEPCO Power Grid. Available online: https://www.tepco.co.jp/en/pg/development/domestic/index-e.html (accessed on 13 October 2024).
69. Quak, N. How Are Units in a VPP Selected to Provide Ancillary Services? Next Kraftwerke, 2020. Available online: https://www.next-kraftwerke.com/energy-blog/algorithm-vpp-ancillary-services (accessed on 13 October 2024).
70. Sklar-Chik, M.D.; Brent, A.C.; De Kock, I.H. Critical Review of The Levelised Cost of Energy Metric. *S. Afr. J. Ind. Eng.* **2016**, *27*, 124–133. [CrossRef]
71. Eskom Holdings Limited. The South African Grid Code—The Network Code. National Energy Regulator of South Africa 2019. Available online: https://www.nersa.org.za/wp-content/uploads/2021/08/SAGC-Network-Version-10.pdf (accessed on 2 September 2024).
72. SARS. Taxation in South Africa. Pretoria, 2022. Available online: https://www.sars.gov.za/wp-content/uploads/Ops/Guides/Legal-Pub-Guide-Gen01-Taxation-in-South-Africa.pdf (accessed on 5 October 2024).
73. The Department of National Treasury. *Media Statement Publication of The 2019 Carbon Tax Act*; The Department of National Treasury: Washington, DC, USA, 2019; Volume 15, pp. 10–13.
74. Australian Energy Regulator. Wholesale Demand Response Participation Guidelines. Australian Government, AER, 2024. Available online: https://www.aer.gov.au/industry/registers/resources/guidelines/wholesale-demand-response-participation-guidelines (accessed on 26 November 2024).
75. Chan, C.A. A guide to Virtual Power Plants (VPP) and How They Might Be Able to Replace Fossil Fuel Plants. *Climate Drift*, 14 September 2023. Available online: https://www.climatedrift.com/p/a-guide-to-virtual-power-plants-vpp (accessed on 13 October 2024).
76. European Union Agency for the Cooperation of Energy Regulators. Clean Energy Package. ACER, 2023. Available online: https://www.acer.europa.eu/electricity/about-electricity/clean-energy-package (accessed on 26 November 2024).
77. European Commission. Clean Energy for All Europeans Package. European Commission, 2024. Available online: https://energy.ec.europa.eu/topics/energy-strategy/clean-energy-all-europeans-package_en (accessed on 13 October 2024).
78. Energize. *Over 300% Rise in Renewable Energy Curtailment in First Half of 2024*; Travel & Trade Publishing (Pty) Ltd.: Johannesburg Area, South Africa, 2024; Available online: https://www.energize.co.za/article/over-300-rise-renewable-energy-curtailment-first-half-2024 (accessed on 11 December 2024).
79. Gxasheka, A.; Ndlovu, N.; Mokoena, R.; Moroeng, M.; Makeke, I. Report on Monitoring Renewable Energy Performance of Power Plants: Performance Update During First Half of 2024. Pretoria, 2024. Available online: https://www-nersa-org-za.b-cdn.net/wp-content/uploads/2024/10/Monitoring-Report-Issue-24__September2024_fnl.pdf (accessed on 11 December 2024).
80. Creamer, T. Unlocking Grid Immediately Through Curtailment A Priority, Cassim Confirms. *Engineering News*, 18 October 2023. Available online: https://www.engineeringnews.co.za/article/unlocking-grid-immediately-through-curtailment-a-priority-cassim-confirms-2023-10-18 (accessed on 28 November 2024).
81. Yasuda, Y.; Flynn, D.; Gómez-Lázaro, E.; Holttinen, H.; Martinez, S.M. Latest Wind and Solar Curtailment Information: Statistics and future estimations in various countries/areas. *IET Conf. Proc.* **2023**, *20*, 567–574. [CrossRef]
82. Eskom. Eskom Integrated Report for the Year Ended 31 March 2023. Johannesburg, 2023. Available online: https://www.eskom.co.za/wp-content/uploads/2023/10/Eskom_integrated_report_2023.pdf (accessed on 11 December 2024).
83. CEIC. South Africa ZA: Electric Power Transmission and Distribution Losses: % of Output. CEIC Data, 2021. Available online: https://www.ceicdata.com/en/south-africa/energy-production-and-consumption/za-electric-power-transmission-and-distribution-losses--of-output (accessed on 11 December 2024).
84. Baker, J. Virtual Power Plants: A Revolutionary Shift in Energy Management. *Joule*, 8 November 2023. Available online: https://www.joulecase.com/blog/virtual-power-plants-a-revolutionary-shift-in-energy-management (accessed on 11 December 2024).
85. Developing Virtual Power Plants Through Distributed Energy Resources in Brazil and Colombia. Base, 2024. Available online: https://energy-base.org/projects/developing-virtual-power-plants-vpp-through-distributed-energy-resources-in-brazil-and-colombia/ (accessed on 11 December 2024).
86. Depatrment of Forestry Fisheries and the Environment. *South Africa's First Biennial Transparency Report (Btr1) to the United Nations Framework Convention on Climate Change (Unfccc), Under The Paris Agreement*; Depatrment of Forestry Fisheries and the Environment: Pretoria, South Africa, 2020. [CrossRef]