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# Virtual Power Plants: Challenges, Opportunities, and Profitability Assessment in Current Energy Markets

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**Abstract:** The arrival of virtual power plants (VPPs) marks important progress in the energy sector, providing optimistic solutions to the increasing need for energy flexibility, resilience, and improved energy systems' integration. VPPs harness several characteristics to bring together distributed energy resources (DERs), resulting in economic gains and improved power grid reliability. Nevertheless, VPPs encounter major challenges when it comes to engaging in energy markets, mainly because there is no all-encompassing policy and regulatory framework specifically designed to accommodate their unique characteristics. This underscores the necessity for research endeavours to develop more advanced methods and structures for the long-term viability of VPPs. To address this concern, the study advocates for the implementation of a multi-aspect framework (MAF) as a systematic approach to thoroughly examine each aspect of virtual power plants (VPPs). A STEEP (social, technological, environmental, economic, and political) analytical tool is utilized to evaluate the challenges, opportunities, and benefits of a VPP in the existing energy markets. The proposed approach highlights important factors and actions that need to be taken to tackle the challenges related to VPP' entry into energy markets. This study suggests that further support is required to promote the fast and widespread adoption of long-term VPP implementations. For this reason, a more favourable policy and regulatory framework based on social, technological, economic, environmental, and policy considerations is necessary to realize the genuine contributions of VPPs.

**Keywords:** virtual power plants; challenges; opportunities; profitability; climate change; sustainability; electricity markets

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**Citation:** Ullah, Z.; Arshad, A.; Nekahi, A. Virtual Power Plants: Challenges, Opportunities, and Profitability Assessment in Current Energy Markets. *Electricity* **2024**, *5*, 370–384. https://doi.org/10.3390/electricity5020019

Academic Editor: Andreas Sumper

Received: 13 March 2024
Revised: 30 May 2024
Accepted: 3 June 2024
Published: 12 June 2024



## 1. Introduction, Background, and Motivation

Traditional power systems face several challenges due to deteriorating infrastructure and increasing electricity demand. The incapacity of the grid to react fast to disruptions leads to problems with network congestion. Due to communication challenges, an imbalance in supply and demand is a concern for utility firms [1–4]. People (households) must understand energy consumption and make the most financially sensible decisions, and the current incapacity of the grid to accommodate new developing technologies such as renewable energy, all contribute to the current problem [5,6]. The existing infrastructure of the distribution networks are mostly based on passive operation. The primary objective was to supply power with one-way flow from the transmission to the consumer. However, the future distribution network will need to be more proactive with a fully utilized network and better DER unit utilization. It is therefore essential to implement smart grid technology in the form of VPPs to address these challenges [7–9].

To understand the usefulness and advantages that VPPs could provide, we need to leverage our understanding of the subject matter. We begin by discussing the primary driver behind the emergence of VPPs. Due to the rapid evaluation of technology, power is in high demand in both national and international markets. This is the rationale for technological advancements that are currently being made to improve performance and optimize the electricity consumption of the electrical grid. Therefore, the most popular electrical grid update in this scenario is the implementation of VPPs [10,11]. A VPP is a platform that is continuously updated and improved by the addition of new technologies that would allow for two-way communication between the supplier and consumer [12,13]. By incorporating VPPs into the current power network, it is possible to increase supply and demand consistency while also lowering costs for both suppliers and consumers.

### 1.1. Existing Literature and Research Gap

The following studies were cited in the literature review as being particularly significant and relevant. The authors of [14] provided a comprehensive analysis of the challenges and solutions associated with the functioning of VPPs. The fact that it explores the intricacies that arise from uncertain resource characteristics, control features, information systems, and strategic relationships among stakeholders is notable. The authors of [15] provided a thorough examination of the progress of VPP technologies, specifically emphasizing the significance of data in tackling the technical obstacles related to the inherent unpredictability of DERs. The paper provides valuable insights into the use of data in different decision phases of VPP operations by adopting a data-centric perspective. The authors of [16] recommended a dynamic aggregation approach to enhance the VPP's ability to regulate flexibility. They developed a VPP aggregation model that takes into account the limitations of the network and the time-dependent nature of DERs. A two-stage robust optimization model was used to propose an aggregation strategy for uncertain scenarios. The dynamic aggregation technique enhanced the coordination and control of the spinning reserve, enabling more effective practical implementation. The authors of [17] identified grid tariff design studies and the effects of regulatory frameworks on regional energy markets as important pillars for the establishment of localized energy markets. The initial results from the case studies carried out in Ireland, Norway, and Austria showed the community's ability to leverage economic gains following the adoption of peer-to-peer markets. The potential and economic benefits of a hybridized VPP strategy that combines a wind farm with a seawater pumped-hydro energy storage (sPHES) facility were examined by the authors of [18]. It was observed that in the energy market, a hybridized VPP approach maximizes the economic benefits of a combined sPHES and wind farm facility. A non-linear stochastic model was presented by the authors of [19]. The proposed model integrated renewable, and non-renewable resources and ESSs under the VPP environment. The proposed model aimed to maximize the benefits of a VPP while minimizing emissions. The authors found that the proposed model was useful for increasing profit while reducing emissions which benefits the environment. The authors of [20] recommended the implementation of a DR with ESSs in a VPP environment as a means to reduce the unpredictable behaviour or RESs and enhance the reliability of the power system. The proposed strategy attempted to optimize social wellbeing. The numerical results demonstrated a fair increase in social welfare and the active power dispatch of WTs, PV systems, and ESSs through the implementation of the proposed strategy. A bi-level algorithm was formulated in [21] for a technical virtual power plant (TVPP) to manage its available energy resources to optimize its profit in both the day-ahead and the local energy market. According to the proposed model, it was found that establishing local markets for heat can boost the VPP's economic effectiveness while also enhancing the operation of combined heat and power (CHP) units and the day-ahead market. The challenges associated with technological, governmental, and policy issues connected with electricity distribution networks were discussed in [22]. It highlighted the major challenges faced by policymakers when it comes to the market and regulatory frameworks that promote the provision of energy and flexibility. The development of well-designed procedures to support innovation is one of these challenges, as is the obligation to respect the technological limitations of the system and guarantee its operational effectiveness. The authors of [23] provided useful insights into the potential advantages and challenges of implementing VPPs in Indonesia. They also provided practical recommendations for policymakers, regulators, and industry players to take into account. Nevertheless, they did not consider the environmental dimension. The authors of [24] made a significant contribution to the area by focusing on the important problem of cybersecurity in VPPs. They proposed an innovative mitigation strategy that utilizes artificial intelligence to improve the ability to withstand cyber assaults. However, they failed to take into account the policy dimension associated with cybersecurity and cyber risks. For the benefit of the community, the authors of [25] proposed a community-based energy model under the VPP setup. The authors found that the existing regulatory and institutional frameworks pose a challenge to the proposed model. Therefore, it was concluded that regulatory and institutional reforms that hampered commercial virtual power (CVPP) developments must be prioritized. The authors of [26] presented a power system paradigm that takes into account the functions and inter-relationships of the economic, environmental, technological, and social aspects of the energy system. The goal of the proposed paradigm was to develop a comprehensive and practical commercial model of the energy system that can be used to effectively inform energy policymakers.

Although there are continuing efforts to increase the availability of clean energy worldwide, the essential strategic factors that restrict the entry of VPPs into energy markets are still not being thoroughly investigated. This ongoing challenge calls for research initiatives that take into account cutting-edge techniques, paradigms, and models that could help develop and implement sustainable VPPs in energy markets. This study aims to evaluate and look at the challenges, opportunities, and advantages of VPPs in the existing energy markets. What factors limit its development and implementation, and what lessons may be learned from this research for future development to make it more successful?

To the best of the author's knowledge, this work is the first of its kind to report a detailed systematic analysis of multi-dimensional aspects of VPPs. This study provides valuable insights, better understanding, and solutions for optimizing energy generation and consumption, benefitting participating members, individuals, and energy communities more flexibly and efficiently. The authors of this work have presented a MAF as a structured approach to analyze the challenges, opportunities, and advantages of implementing VPPs in the existing energy markets. STEEP is an analytical tool utilized to evaluate various external factors that have the potential to impact the energy sector. Using the STEEP analysis tool enables stakeholders to understand the wider framework within which VPPs function. This comprehensive analysis confirms that all external aspects are taken into account in the strategic planning and development of VPPs, resulting in more informed decision-making and improved alignment with needs and regulatory requirements. This is subsequently used to suggest solutions for addressing the previously mentioned challenges. This work is important because it offers a critical evaluation of the challenges associated with the VPP paradigm in the context of energy markets while taking the existing situation and circumstances into consideration

### *1.2. Contributions and Study Layout*

The main contribution of this work can be summarized in the following points:

1. This study provides a comprehensive framework for decision-makers, utilities, and communities to understand the factors that could affect VPP entry in current energy markets. The proposed approach helps identify opportunities, risks, and potential barriers associated with social acceptance, technological readiness, economic viability, environmental sustainability, and regulatory support. Equipped with these valuable insights, operators and stakeholders can develop appropriate strategies to maximize the benefits of VPPs and address potential challenges effectively.
2. The proposed approach helps in recognizing emerging trends in energy markets, technological advancements, and shifts in consumer behaviour. This can help electricity market participants, such as prosumers, consumers, and utilities, to identify new opportunities and adapt strategies to the changing market dynamics, ultimately enhancing their competitive position.

3. This study provides a better understanding of the proposed MAF that serves as a comprehensive tool to explore and anticipate different factors that can shape the future of VPPs in global power markets. The proposed approach can be used as a based model to optimize the design and operation of VPPs, ensuring their alignment with societal needs, technological advancements, economic viability, environmental sustainability, and political frameworks.

The rest of the paper is arranged as follows: Section 2 describes the operation of the VPP. Section 3 presents the followed methodology. The proposed multi-aspect framework is presented in Section 4. A detailed discussion is presented in Section 5. Finally, the conclusion is made in Section 6.

## 2. Virtual Power Plant

The power industry revolution has been made possible by the digitalization of the industry. Two-way communication between system operators and consumers has been made possible by the introduction of smart meters. Also, the emergence of new players in the power markets, such as VPPs, demand response (DR) programs, and energy storage systems (ESSs), has contributed to this shift. New players ensure the security and reliability of the power supply given the increasing adoption of renewable energy sources (RESs) [27,28]. A VPP is a modular designed entity based on information and communication technologies (ICTs) that offers a better setup for renewable energy generation, distribution, and consumption [29]. VPPs represent the most optimistic future of energy management, and this allows for intelligent energy utilization in a dispersed setting through smart control mechanisms. This means consumers are more actively involved in the decision-making process because they generate and consume their own energy. Additionally, VPPs are invaluable tools for integrating renewable energy and promoting grid stability. They better adjust for possible forecasting inaccuracies in terms of generation and demand [30].

VPPs entail the stability and reliability of the electrical network. Nevertheless, disturbances in the grid, including power outages or variations in voltage, might affect the efficiency of VPPs. To reduce the impact of this risk, VPP operators can set up redundancy mechanisms like ESSs or backup power sources to keep operations running even when the grid goes down. Variations in supply, demand, and price in energy markets can have an impact on VPPs' revenue streams. To effectively handle fluctuations in the market, VPP operators have the option to diversify their sources of income by engaging in other market sectors, including wholesale energy markets, capacity markets, and ancillary service markets. Diversification serves to reduce the effects of price volatility in a particular market and ensures a more consistent source of revenue for the VPP. The trustworthiness of VPPs is contingent upon the efficacy of several technologies, including hardware, software, and communication systems. Equipment malfunctions, software issues, or interruptions in communication networks can impede the functioning of VPPs and harm their financial success. To mitigate this risk, VPP operators should establish and enforce rigorous maintenance and monitoring procedures to promptly identify and resolve possible problems.

A VPP, as demonstrated in Figure 1, interacts with energy service providers, wholesale market participants, retailers, and system operators. The VPP exchanges information data with DERs as well as consolidated energy production and consumption profiles to distribution system operators (DSOs) and transmission system operators (TSOs). Once the VPP receives control activation signals from system operators of control centres, it sends activation commands to energy service suppliers. Then, the energy service suppliers release the requested quantity of energy. Typically, a VPP's participation in day-ahead power and auxiliary services markets is often accomplished through the aggregation of DERs which then jointly submit offers and bids in the electricity and flexibility services markets.

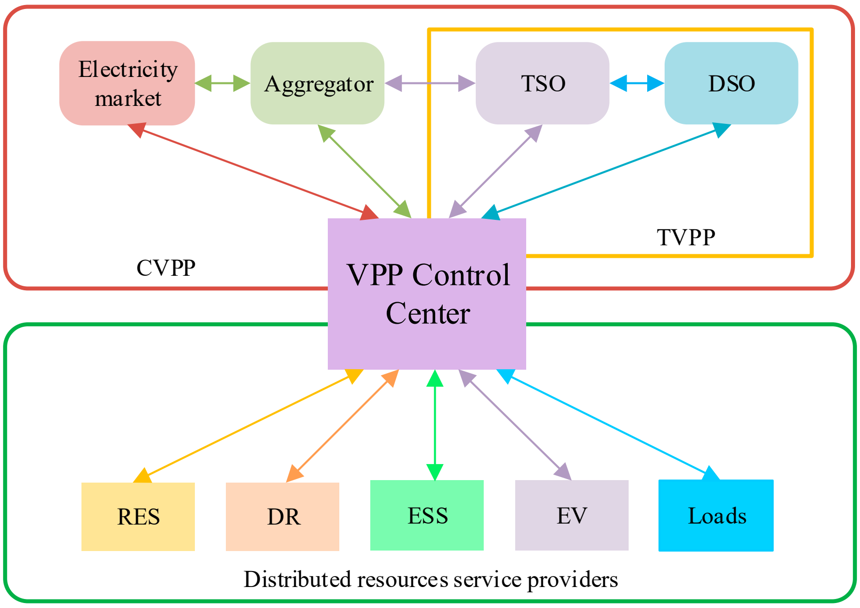


**Figure 1.** Virtual power plant structure.

## 3. Methodology

The followed methodology is outlined in this section. The authors used a three-step approach, as shown in Figure 2.

- First, a detailed review of recent and related research was carried out. The authors conducted a thorough analysis of earlier work that supported the use of VPPs in the electricity market, noting the research gap that needs to be addressed. The authors used Science Direct, Web of Science, Google Scholar, and Scopus as their main databases to search recently published articles including terms and keywords like "virtual power plant", "challenges", "opportunities", "benefits", and "renewable energy sources". Based on the analysis of these articles, this study resulted in the classification of VPP challenges into the following categories: social, technological, environmental, economic, and political.
- The second step is the collection and detailed analysis of secondary data sources pertinent to this study. For example, Government regulations on energy policy such as those on the feasibility of VPP operation in energy markets and standard guidelines for industry best practices were also assessed.
- Finally, in the third step, the authors presented a new MAF as a structured approach, and the data collected from different sources were comprehensively analyzed using a "STEEP" analytic tool to address the research gap that was identified.

A qualitative research method is applied to the study of VPPs to gain insights into the subjective experiences, perceptions, and social dynamics associated with their implementation and operation. An in-depth study is carried out on published scholarly research articles, energy reports, and governmental policies. Rich qualitative data are collected based on VPP content. The authors critically analyze the social, technological, environmental, economic, and policy implications of VPP implementation, including factors influencing their success or failure, interactions between different stakeholders, and impacts on the energy system.

The followed methodology enables a comprehensive evaluation of the social, technological, economic, environmental, and political factors relevant to VPPs. It helps identify key trends, drivers, and challenges that shape the VPP landscape. It provides a systematic approach to gathering and analyzing information about various factors. This ensures a holistic understanding of the broader context in which VPPs operate. The proposed approach also promotes stakeholder engagement by considering social and economic factors.

It helps identify the interests, concerns, and preferences of various stakeholders, such as consumers, utilities, regulators, and communities. Understanding these perspectives enables the design of VPP models that align with stakeholder needs and promote acceptance and participation.

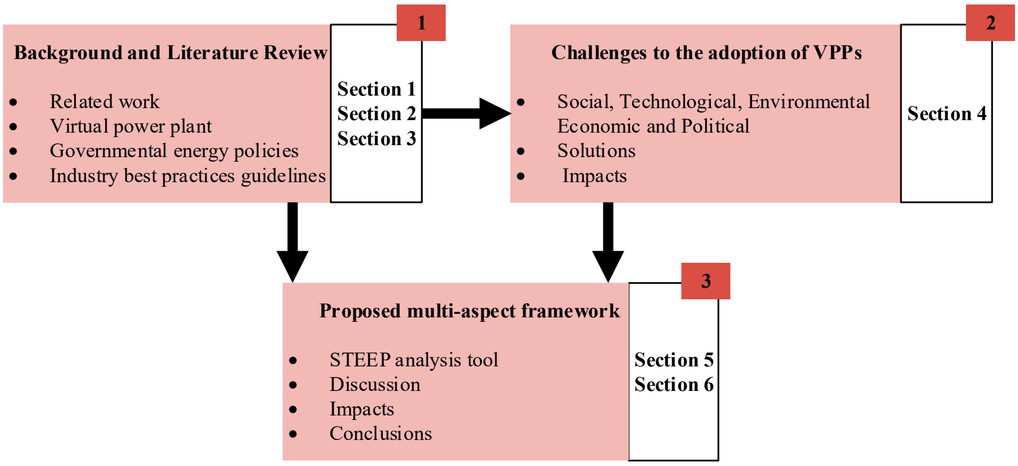


**Figure 2.** Followed methodology.

Overall, the followed methodology contributes by providing a structured framework to evaluate external factors and their implications for VPPs. It aids in understanding the broader context, anticipating future developments, and making informed decisions, thereby enhancing the theoretical, methodological, and practical aspects of VPP implementation in the existing electricity markets.

This study presents a MAF for analyzing the role of a VPP in today's energy markets and then employs a STEEP analytic tool to evaluate the challenges, opportunities, and benefits of a VPP business model, as shown in Figure 3. The proposed approach evaluates VPPs social, technological, environmental, economic, and political aspects. It evaluates whether a VPP business model's objectives will be achieved. The STEEP analytical tool is used because it streamlines the complex structure of a VPP business model into small manageable sections. It is also effective for adequately detailing the financial and environmental aspects of sustainable VPPs. Therefore, to make it possible for future planning and the long-term adoption of VPPs, energy designers, developers, decision-makers, researchers, and other interested parties must address the abovementioned challenges.

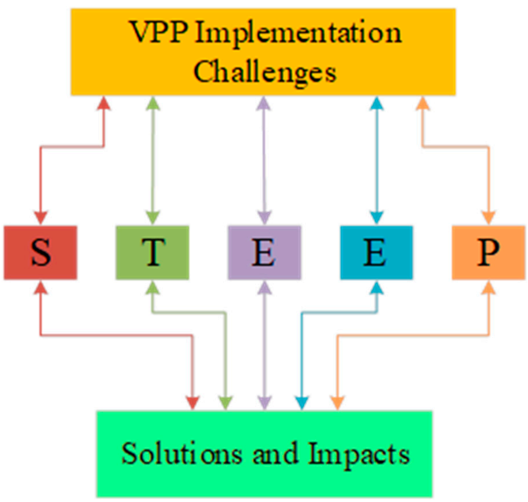


**Figure 3.** STEEP model application.

This study shows that a solution to the problem (the VPP system) that lacks any of the five components of the STEEP model is insufficient, as seen in Figure 3. One of the most important features of the proposed MAF is that it requires cooperation among all of the abovementioned aspects to address the challenges and achieve the necessary sustainable energy transformation, which falls outside the scope of the traditional techno-economic perspective.

## 4. Proposed Multi-Aspect Framework

The authors of this paper suggested a MAF as a structured approach to systematically evaluate and analyze the prospects, benefits, and limitations of VPP deployment in the current electricity markets. The STEEP analytical tool was used for this investigation because it considers not only the technical, economic, and environmental factors but also the social and political factors that are equally important for the future deployment of VPPs. The following is a comprehensive evaluation of the social, technical, environmental, economic, and political aspects of VPP deployment within the existing electricity markets.

### *4.1. Social Aspects and Their Impacts on VPPs*

The social acceptability of VPPs is comparatively a new idea in energy management by individual citizens (attitude, tolerance, and conduct), and it has the potential to alter our energy system. It would benefit energy generators and consumers at the same time. The extent of societal participation in the energy market will be primarily determined by how effectively the proposed energy technology is embedded in society. For instance, upscaling the consumer understanding of the social benefits of VPPs improves consumer choice and strengthens harmony within the energy community. This shows the importance of incorporating community members and stakeholders in the energy demand and supply process. Therefore, engaging the community is essential. Without widespread social recognition, it is challenging to adapt innovations in the power sector, especially the smart grid. The implementation of VPPs typically is unimportant to the bulk of the population because they are not aware of what they are, how they work, or what advantages they might offer. Therefore, it is necessary to acknowledge that schooling plays an important role in this predicament. A successful awareness campaign can inform the public about the advantages of using VPP technology at the most basic levels. This would considerably raise the public awareness of improvements being made to the power system of today. Energy distributors and electric power networks would find it simpler to maintain their operations if more people recognized and accepted smart grid business models. Table 1 shows the societal impacts and implementation challenges of VPPs in power systems. There are several reasons why users might want to change their opinions toward smart energy systems. One of them, for instance, is environmental concerns. This is the main argument put up to inspire consumers to install smart meters. It is considered that giving timely feedback to consumers about their energy consumption with associated costs will encourage them to use as little as possible.

VPP technology can provide a great opportunity for the UK energy sector. Strong public awareness, financial support, and clear regulation in the UK proved essential for the development of the VPP business model. However, to achieve this aim, the power of the people is crucial. Analysis suggests that the mass adoption of VPPs and the achievement of net-zero emissions by 2050 are not conceivable without a change in people's behaviour. Public engagement and awareness efforts should be prioritized to ensure the successful implementation of the VPP and define the roles that all stakeholders must play in reaching net-zero emissions by 2050. It is also essential to mention that to achieve net-zero targets, civil society, local governments, and individuals must work together for the benefit of the common good.

**Table 1.** Social aspects of VPPs.

| Challenges | Solutions | Impacts |
|---|---|---|
| Lack of awareness and social benefits of VPPs. | Introduce social awareness programs to promote the public's understanding of VPPs societal benefits. | Strengthens consumer choice and energy community cohesion. |
| There are no clear policies that support the DER and RES community. | Strengthen the DER and RES community-supporting policies. | Drive economic growth, social equity, and technological innovation. |
| Partial implementation can lead to uneven distribution of benefits. | Strengthening government support for the implementation of VPPs can significantly enhance their deployment and efficacy. | Generates profit for members who participate. |
| No favourable legislation for the adoption of VPPs | Introduce more favourable energy regulations for VPPs inclusion in energy markets. | Provides an equal opportunity for new market entrants to succeed. |
| Lack of social involvement in the provision of electricity. | Benefits should be shared among all stakeholders. | Supports RES research opportunities to advance the understanding of energy conservation and its benefits to society and the economy. |

### *4.2. Technological Aspects and Their Impacts on VPPs*

Technology aspects are concerned with technological innovations that could affect how the power system operates, either positively or negatively. The advent of new technologies has a significant impact on the productivity of the power sector. In a larger sense, it can help in retaining skilled personnel, especially the next generation of young scientists and researchers. The introduction of new technologies, such as smart grids and VPPs, is still in the early stages. The integration of wind and solar power into the grid necessitates more training in the smart metering and control of the utility grid, this demonstrates a new approach to research study, and capacity development in the area of renewable energy. However, RESs are very intermittent and impacted by weather patterns, so monitoring and sustaining these technologies in the power network are challenges to the industry's continued development.

The VPP control system is its technological hub. The central control system can efficiently coordinate, monitor, and control all resources that are integrated under the VPP setting. Control signals and information are sent over encrypted data links that are secured from other data traffic. All the information required to determine the optimal operation schedules for electricity generation and usage is stored in the control system. Some of the examples are a spectrum of capabilities for balancing energy, actual power, and power consumers.

The UK has made considerable progress in lowering $CO_2$ emissions through technological advancements and their adoption by the industry with no obvious effect on the general public. This should persist, but the government needs to concentrate more on making it simpler for people to accept new technological innovations and alter their consumption patterns. We must reduce demand and change transportation modes to reach net-zero emissions and the long-term environmental objectives of the UK. The technological challenges and their impacts are shown in Table 2.

**Table 2.** Technological aspects of VPPs.

| Challenges | Solutions | Impacts |
|---|---|---|
| Power quality issues and distribution grid stability. | Flexible generation resources, energy storage, advanced grid management systems, and enhanced forecasting techniques. improve security, and deliver safe and reliable grid operation. | Significantly enhances the security, safety, and reliability of grid operations. |
| The implementation of VPPs is negatively impacted by the absence of a smart grid system. | The Internet of Things and smart metering technologies have the potential to greatly impact the generation and consumption of VPPs. | Increases system reliability, security, and the enhancement of power quality. |

**Table 2.** *Cont.*

| Challenges | Solutions | Impacts |
|---|---|---|
| Prosumers avoid the energy market when challenges to privacy and cybersecurity are not addressed seriously. | Policies must guarantee the privacy and security of customer data by adhering to protection regulations. | Ensures the confidential nature of prosumers in energy market, promoting their participation without concerns of privacy. |
| The uncertainties in market prices, RESs, and load demand present significant challenges for the efficient and reliable operation of electricity grids. | Integration of advanced technologies, robust planning, regulatory support, and market innovations. | Mitigates the effects of uncertain parameters in electrical systems. |

### *4.3. Environmental Aspects and Their Impacts on VPP*

There has been increasing concern about the environmental effects of power plants. Power plants are large industrial installations that produce energy for industrial, commercial, and domestic use. There are many ways to produce electricity, but the vast majority of power plants worldwide use fossil fuels like coal, oil, and natural gas. These energy options add carbon to the atmosphere, leading to pollution and climate change. Alternative power generation options include wind, solar, nuclear, hydroelectric, and wave power; all of these have their own set of benefits concerning environmental protection and human wellbeing. The European Union Horizon 2020 Project focuses on investigating the environmental effects of VPPs. The INVADE project specifically aims to include renewable energy sources and electric vehicles in VPP setup. Projects such as INVADE have produced research findings that offer concrete proof of the ability of VPPs to optimize the use of renewable energy, reduce wastage, and reduce $CO_2$ emissions. These findings contribute to the European Union's climate objectives. VPPs have the potential to improve our quality of life by leading to cleaner air, less power costs, less $CO_2$, and the improved health of end users. Furthermore, the VPP is a type of environmentally sustainable development as it generates income for local communities without harming the environment.

The UK has committed to being carbon neutral by 2050, in its historic Climate Change Act. Scotland's potential to reduce emissions is higher than the rest of the UK's, hence, the country has set a net-zero goal by 2045. It has been recommended that Wales achieve a 95% reduction in greenhouse gas emissions by 2050. Since VPPs are already integrating RESs, they will play a crucial role in enhancing the UK's energy systems' flexibility and reliability in the near future. The generation mix that supplies households and businesses with electricity is being evaluated as we move toward a net-zero economy. It has been discovered that cloud-based power plants are key to the UK's 2050 net-zero ambitions. The current policies are inadequate to accomplish the current net-zero emissions targets. Table 3 shows environmental challenges and their impacts.

**Table 3.** Environmental aspects of VPPs.

| Challenges | Solutions | Impacts |
|---|---|---|
| There are no obvious environmental effects, yet environmental awareness is inadequate. | It is necessary to use emission-regulating schemes to control carbon footprint. | Encourages global focus on renewable energy sources. |
| | Research and development programs propagate knowledge and awareness of renewable technologies. | R&D findings inform policy-making and market strategies, facilitating broader adoption of renewable energy |
| | Provide useful information relevant to environmental standards for new energy development programs. | Reduced $CO_2$ Emissions. Positive environmental impact. |
| | Government should offer incentives based programs to encourage people toward the widespread adoption of renewable technologies. | Encourages consumers in recognizing and endorsing eco-friendly technologies. |

### *4.4. Economic Aspects and Their Impacts on VPPs*

VPPs have the potential to provide several benefits to satisfy their customers. The entrance of smaller generators into the market, the application of demand response to reduce the load in case of emergencies, and the localization of DERs to achieve better grid balance are examples. The ultimate flexibility of the grid strengthens with the formation of a market where utilities could buy DRs or DERs from customers. By pooling the power of several small generators, a VPP may boost competitiveness and provide savings to end users. However, the initial capital expenditure necessary for setting up a VPP is huge. It covers a range of components, including hardware, software, communication infrastructure, and installation expenses. Furthermore, there are costs associated with acquiring permits, adhering to regulations, and overseeing project management. Performing a comprehensive examination of these expenses assists stakeholders in understanding the first monetary obligation needed to implement a VPP. VPPs provide cost savings by enhancing energy efficiency, optimizing energy generation and usage, and decreasing charges associated with high energy demand. Operators can optimize energy use and improve system efficiency by consolidating and managing DERs utilizing VPPs. VPPs can generate income through a range of methods, such as engaging in energy markets, participating in demand response programs, and offering grid support services. Stakeholders can obtain a thorough understanding of the financial feasibility of VPP projects by simultaneously assessing investment costs, operating savings, and the potential of revenue generation. By integrating DERs into a VPP, the operation of a VPP should be economical for its operators and participating members. The current price mechanisms will play an important role in determining how decisions are made in VPPs along with existing RES support programs. However, a VPP's aggregation may not find a flat tariff structure to be very attractive. It is possible to encourage DER units to take part in a VPP by using the energy pricing structure. To encourage individuals in the process of developing a VPP, an incentive-based strategy can be implemented. When DERs are integrated into the VPP environment, they are better positioned to deliver services. Regulating the market environment will not be an encouraging indicator for the establishment of a VPP; nevertheless, incentive-based systems can mitigate the impact of the regulatory framework. Economic challenges and their impacts are shown in Table 4.

**Table 4.** Economic aspects of VPPs.

| Challenges | Solutions | Impacts |
|---|---|---|
| Lack of financial support for institutions, academics, researchers, and engineers for VPP mapping in power markets. | Institutions, academics, engineers, and energy market mapping agencies all need more financial support to better understand and implement the VPP concept. | Postponed investments for facilities' upgrade. |
| Lack of market structure, market forces, and market price mechanisms. | The foundation of market structure and pricing mechanisms is based on complex processes. Mechanisms for obtaining market entry should be made as clear, economical, and simple to support the involvement of small-scale producers. | Aggregation-based reduction in economic risk. Democratic environment support small scale participants access to the electricity market. |
| Lack of incentive-based programs. | Government financial support may accelerate the growth of VPPs. Establishing incentive based programs would reward small scale renewable generators | Encourages financial certainty and steadiness, hence fostering investment in small-scale renewable energy projects. |

VPPs' entry into the energy market must surmount market barriers. The participation of VPPs in power markets is limited by barriers like stringent reserve capacity requirements in the existing markets. Finally, the markets might be unable to fully reap the benefits of the unique characteristics of VPPs such as flexibility. Therefore, in the current markets, a VPP may not even receive adequate compensation for such services. Several countries around the world have implemented subsidies and support mechanisms to promote RE technologies for economic benefits. Germany is known for its successful RE transition and has been a leader in providing subsidies. The country introduced feed-in-tariffs (FiTs) in 2000, guaranteeing fixed, premium prices for renewable energy producers. China has become a global leader in RES deployment. China has implemented a range of subsidies including FiTs, tax incentives, and low-interest loans. Other countries, including the United States, Sweden, Denmark, and Spain, heavily subsidize to promote RES integration in the electricity markets for economic benefits. It also aligns with the global trend towards sustainable and environmentally friendly energy solutions.

### *4.5. Political Aspects and Their Impacts on VPPs*

Electricity is distributed in a range of methods around the world. There are both regulated and deregulated systems. Deregulated power grids provide a wider range of market arrangements. The rules and regulations in each region might be rather different from one another concerning the practical aspects of a VPP. In the electrical market, a VPP may have challenges in operating due to regulatory constraints. Different resource types, such as VPPs are subject to specific laws in various energy markets. Enforcing flexible market access policies that enable VPPs to participate on an equitable footing with traditional power producers can facilitate their smooth integration. Conversely, inflexible regulations that are significant to participation may discourage the development of VPPs and restrict their capacity to offer valuable services to the power grid. Therefore, it is crucial for a VPP provided at the utility scale to participate in the grid balancing market which is reliant on wholesale energy trading. Due to the complexities and cost of supplying energy to large facilities and users, suitable rules and policies are required as VPP usage increases.

RE, smart grids, and ESSs have been the focus of several policies and legislation in the EU, the UK, China, the US, and other developed countries. The complex nature of the power grid and the rapid evolution of cutting-edge technology make it clear that VPPs need a rigorous regulatory framework. The classification of regulatory barriers is presented in Table 5.

**Table 5.** Classifications of regulatory challenges.

| Market Design and Mechanisms | Role and Actors in Liberalized Markets | Retail Energy Prices and Network Tariffs |
|---|---|---|
| Production and service definition<br>Market mechanisms<br>Standardization | DSO<br>Prosumers<br>New market players<br>DR and ESS | Renewable energy support schemes<br>Retail energy price structure<br>Network tariffs |

The political dimensions of VPPs in current electrical markets comprise the adjustment of regulations, involvement in the market, ensuring energy security, addressing environmental and implications, and engaging with stakeholders. It is essential to consider these factors to fully utilize the capabilities of VPPs and guarantee their role in creating a sustainable and resilient energy future. Table 6 shows political aspects challenges, solutions and their impacts.

**Table 6.** Political aspects of VPPs.

| Challenges | Solutions | Impacts |
|---|---|---|
| Lack of a clear policy and regulatory bodies regarding how VPPs should be regulated in power markets. | It is clear that proper policies must be developed and stated to facilitate the inclusion of VPPs into the electricity markets. The future growth of VPPs should necessitate a clear regulatory policy from governments worldwide. | Improving the utilization of RESs and minimizing costs while maintaining safety standards.<br>Make energy markets accessible to small-scale participants. |

**Table 6.** *Cont.*

| Challenges | Solutions | Impacts |
|---|---|---|
| Lack of government incentives to encourage flexibility among consumers. | The government needs to provide incentives and investment programs to improve irrational energy policies. | Accelerate the deployment of RESs and the reduction in carbon footprints. |
| Lack of ownership provisions. | Making the necessary changes to policy, regulation, and markets to help everyone in society shift to a low-carbon future. | Offer more options for consumers. Prospects for new business opportunities |

## 5. Discussion

The proposed approach allows VPP operators and stakeholders to have a more comprehensive understanding of the external environment in which a VPP operates. It helps identify potential challenges and opportunities related to social aspects (e.g., public opinion and behaviour towards energy consumption), technological advancements (e.g., renewable energy technologies), economic aspects (e.g., energy prices and market dynamics), environmental concerns (e.g., carbon emissions and sustainability), and political factors (e.g., government policies and regulations). Stakeholders can gain insights into potential opportunities and challenges that may arise in the power sector. This knowledge empowers operators and stakeholders of VPPs to make well-informed decisions, enhance their competitiveness, align their strategies with the changing market dynamics, and create more efficient and sustainable energy solutions

The proposed structured framework enhances the VPP by providing a deeper understanding of the market, increasing market relevance, creating a competitive advantage, enabling adaptability, and mitigating risks. Adapting this approach to the VPP process helps in developing a more robust and effective value proposition that aligns with the external environment and meets customer needs more effectively.

The proposed approach also demonstrated the empowerment of individuals and communities to take control of their energy generation and consumption. VPPs enable individuals to generate their own energy, reducing their reliance on traditional centralized power sources. This energy independence can enhance an individual's sense of control over their energy usage and contribute to a more decentralized and democratized energy system.

This approach provides a comprehensive mechanism for capturing the challenges and supporting factors of energy systems and their solutions. VPPs may be better understood, and their future contributions to energy markets can be increased. The solution to the global challenge will be considered unsatisfactory if one of the five factors of the STEEP analysis model is missing. This is so that the intended sustainable development of VPPs can be accomplished by combining all the characteristics. Therefore, due to the interconnectivity of the contributing aspects, a coordinated effort is required for a successful outcome.

The results of this study demonstrated that several stakeholders are engaged in diverse STEEP analysis areas and persuading the market's future direction. For example, the UK government is arguably the largest of these stakeholders with its participation in formulating policies and regulations. The environment grants licensing and provides financial support. As long as they remain fully committed to the development and implementation of VPPs in the energy sector, the general public will at least have a positive attitude and tolerance soon.

It is evident from this work that VPPs are important to national and global energy balance, and they have a big impact on meeting net-zero carbon ambitions. VPPs enable the synchronization of demand and supply with the greatest efficiency and flexibility. Integrating readily available energy-balancing assets, and fostering peer-to-peer energy exchange help regional energy output and utilization.

For VPP projects to be successful, stakeholders such as customers, regulators, utilities, communities, and technology suppliers must be involved. By actively engaging stakeholders in the decision-making process, seeking their input, and resolving any issues they may have, VPP projects can establish trust, improve transparency, and gain support from a wide range of individuals and groups. Engaging stakeholders also helps in the collaborative development of VPP programs that are in line with the requirements and preferences of the communities they serve, therefore enhancing their acceptance and long-term viability.

## 6. Conclusions

This study introduced a multi-aspect framework as a structured approach to assess and analyze the potential benefits and constraints of implementing VPPs in the current electricity markets. This study examined multiple factors, including social, technological, environmental, economic, and political, that influence the design and implementation of VPPs in current electricity markets. The following are some of the specific conclusions drawn from this study.

1. To encourage a greater utilization of VPPs, it is essential to employ a combination of consciousness, incentives, and user-friendly technologies. To accelerate the adoption of VPPs and achieve a more sustainable and efficient energy system, it is essential to address concerns, explain misconceptions, and involve stakeholders at all levels. The collaborative efforts of the Government, utilities, communities, and other stakeholders are essential in creating a favourable climate for the development and growth of VPPs.
2. Cutting-edge technology such as information and communication technologies (ICTs), machine learning, and artificial intelligence (AI) could assist VPPs to better analyze, monitor, and measure their energy usage. Future energy pattern forecasting can be more accurately predicted by these algorithms. These technologies' implementation into VPP operations improves the effectiveness of energy management while also fostering a more robust and sustainable energy environment.
3. VPPs are important for harnessing renewable energy sources such as wind turbines (WTs) and photovoltaics (PVs), leading to environmental improvement, cleaner air, improved health, and less $CO_2$ emissions.
4. VPPs pave the way for participation in energy markets, benefitting both power generators and end users by adjusting their energy production, and consumption, and offering flexible services to the grid.
5. A supportive policy and regulatory framework that considers multiple factors, including social, technical, economic, environmental, and policy concerns, is essential for maximizing the potential of VPPs in energy markets.

**Author Contributions:** Conceptualization, Z.U.; supervision, A.A.; project administration, A.N.; methodology, Z.U.; writing—review and editing, A.A.; data curation, A.N.; investigation, Z.U.; writing—original draft preparation, Z.U.; formal analysis, A.A. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** No new data were created or analyzed in this study. Data sharing is not applicable to this article.

**Conflicts of Interest:** The authors declare no conflict of interest.

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