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# NextGen Infrastructures: Enhancing Cyber-Physical Resilience/Sustainability by Virtual Energy Storage

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**Abstract.** This systematic review investigates the pivotal role of virtual energy storage (VES) in enhancing the resilience of energy systems. By systematically selecting and analyzing 158 articles, we address four key research questions about specific features of VES that enhance energy system resilience, how these features influence the overall resilience of energy systems, the enabler technologies associated with VES that impact the resilience of cyber-physical systems, and lastly, we discuss the challenges, and future research directions pertaining to the utilization of VES for bolstering resilience. Highlighting the importance of VES, the findings provide insights for policymakers, energy practitioners, and researchers aiming to enhance the resilience of energy systems in the face of increasing uncertainties and disruptions. Furthermore, this study provides valuable insights for the resilience engineering and energy engineering communities by identifying main features of energy resilience and key enabler technologies of VES for enhancing energy storage and system resilience.

***Keywords***— Virtual Energy Storage, Energy Storage Systems, Sustainable Energy Storage, Smart Energy Systems, Energy System Resilience, Critical Infrastructure Resilience, Resilient Complex Systems, Cyber-Physical Systems (CPS)

## 1. Introduction

In the realm of Smart Energy Systems (SES), resilience stands as a crucial consideration, and a key factor of future SES, especially given the increasing complexities and vulnerabilities associated with modern cyber-physical infrastructures. Virtual energy storage (VES) emerges as a promising solution, offering dynamic capabilities to enhance system resilience. This study delves into the effective features of VES and their potential impact on enhancing the resilience of smart energy systems.

Previous research has indeed emphasized the critical role of resilience in safeguarding energy systems against disruptions. However, the specific contribution of Virtual Energy Storage (VES) in bolstering resilience remains relatively underexplored, primarily due to its status as an emerging technology. The widespread implementation of VES on a large scale has yet to be fully realized. Energy Storage, as a method to augment system resilience, holds promise not only in theoretical discussions but also in practical applications, potentially bridging the gap between research and real-world implementation of renewable energy production such as solar energy. While existing literature offers foundational insights into resilience frameworks, the dynamic connection between Smart Energy Systems and virtual energy storage technologies, alongside their enablers, presents research lines for systematic investigation.

Employing a systematic literature review approach, this study aims to identify and analyze the features of virtual energy storage that contribute to the resilience of smart energy systems. The following research questions guide the selection and synthesis of relevant literature, ensuring a comprehensive exploration of the topic.

- *Research Question 1:* What specific features of virtual energy storage contribute to increasing the resilience of energy systems?
- *Research Question 2:* How do these identified features of virtual energy storage impact the overall resilience of energy systems?
- *Research Question 3:* Which technology enablers are involved in virtual energy storage that influence the resilience of cyber-physical systems?
- *Research Question 4:* What are the challenges, gaps and future studies to be considered regarding the utilization of virtual energy storage as a technology for enhancing resilience?

The findings of the systematic literature review unveil a spectrum of features within virtual energy storage that significantly influence system resilience. The resilience features for smart energy systems are extracted from the literature to find the links. these features encompass aspects such as redundancy, robustness, responsiveness, etc. Through synthesis of the results, a map of effective features emerges, providing valuable insights into the mechanisms through which VES can enhance resilience.

The article explores the underlying mechanisms by which VES influences system dynamics and resilience metrics. Moreover, the involvement of enabler technologies, such as advanced control algorithms and communication protocols, is elucidated, highlighting their synergistic role in fortifying cyber-physical systems. In conclusion, this study contributes to the burgeoning literature on resilience in smart energy systems by elucidating the pivotal role of virtual energy storage. By delineating effective features and identifying challenges and gaps, it offers valuable insights for practitioners and researchers alike. Future studies should delve deeper into the interactions between VES and resilience, fostering a more comprehensive understanding of this critical domain.

The remaining sections of the article are structured as follows: Section 2 presents a comprehensive review of the current state of the art in the domain, providing valuable insights into existing research and developments. In Section 3, the research design methodology employed for the systematic literature review is thoroughly elucidated, offering clarity on the approach taken to gather and analyze relevant literature. Section 4 constitutes a detailed presentation of the obtained results, accompanied by an in-depth discussion that delves into the implications and significance of the findings. Furthermore, Section 4.2.3 outlines potential future research directions and identifies challenges that need further exploration in the field. Finally, Section 5 serves as the conclusion, summarizing the key points discussed throughout the article and providing a cohesive closure to the study.

## 2. Latest Developments Examination

### *2.1. Cyber-Physical Systems*

A Cyber-Physical System (CPS) is a combination of computers or computer networks [45], computational algorithms and physical processes that are closely integrated and coordinated [24]. These systems involve the seamless merging of computer-based algorithms with physical processes, allowing them to interact, monitor, and control each other in real-time [56].

CPS typically incorporates embedded systems, sensors, actuators, communication networks, and computational elements to achieve this integration [6]. The integration of cyber and physical elements in CPS leads to improved efficiency [5], resilience [36], sustainability and functionality [33], across a wide range of applications.

CPS finds applications in various domains, including manufacturing, healthcare, transportation, smart cities, energy systems, and more. The distribution of the literature about CPS in different Subject areas is illustrated in Figure 1(The keyword for serch query is 'Virtual Energy Storage'). The data depicted in the Figure 2 reveals that nearly 4% of the studies concentrate on energy systems, highlighting a trend in examining these systems through the lens of cyber-physical integration.

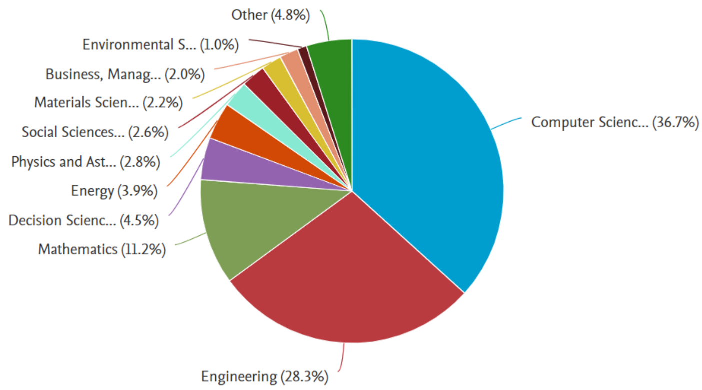


Figure 1: Distribution of the retrieved documents on Cyber-physical systems by subject area

*2.2. NextGen Energy Infrastructures*

A significant characteristic of next-generation (NextGen) energy infrastructures is the increased reliance on renewable energy sources[29]. Because of this, NextGen energy systems are moving towards a more decentralized model[46]. Decentralized distribution prioritize the development and integration of advanced energy storage technologies[54]. Even the most efficient existing energy storage solutions, can not ensure resilience and reliability in the face of challenges of emerging decentralized energy system technologies[46]. This is the reason why new energy storage paradigms are playing crucial role in improving NextGen energy systems resilience and sustainability.

*2.3. Virtual Energy Storage*

Virtual Energy Storage (VES), offers a cost-effective solution that leverages existing assets in energy network and Thermostatically Controlled Loads (TCLs) to reduce high energy storage system (ESS) requirements. VES often associated with demand response and energy management strategies, plays a crucial role in optimizing the utilization and efficiency of energy systems[10].

Figure 3 depicts a remarkable raise in studies concerning Virtual Energy Storage (VES) starting in 2018. Meanwhile, Figure 4 reveals that over half of these studies are conducted in China, with the United States and the United Kingdom following closely. This highlights a significant gap in the ongoing research landscape, particularly within the European Union context.

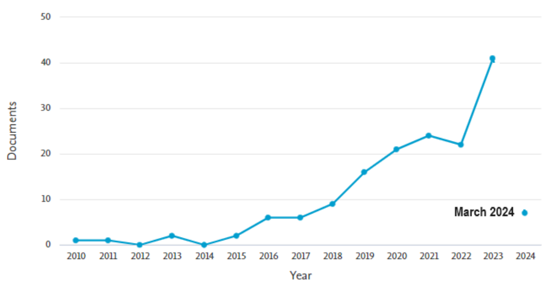


Figure 2: Statistical analysis of the search results about CPS: documents by year

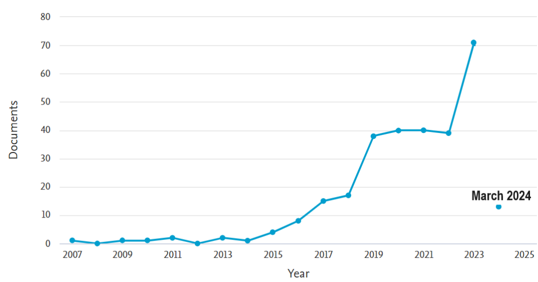


Figure 3: Statistical analysis of the search results about VES: documents by year

Since Energy Systems (ES) are providing an essential service for the society, the ES is a critical infrastructure; and VES which is a new paradigm for improving energy storage technologies are also sub-systems of critical infrastructures.

### *2.4. Critical Infrastructure Resilience*
As figure 5 shows main sponsors of the VES studies. Most of the funders of these studies are national research centers. The sponsors of the related research projects consist of national research entities from developed countries that have already established sustainable and efficient energy networks; they are now focused on enhancing the resilience of their country's critical energy infrastructure. The growing interest in this topic stems from the concept of resilience that that promise to maintain operational stability and bounce back from disturbances, guaranteeing the uninterrupted delivery of essential services and functions amidst adverse events or attacks.

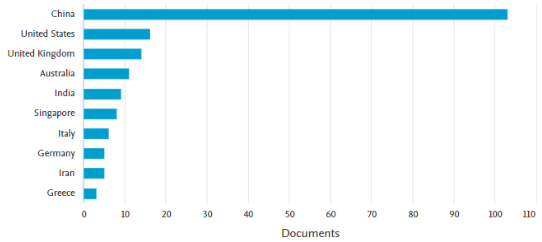


Figure 4: Statistical analysis of the search results: documents by founding country/territory

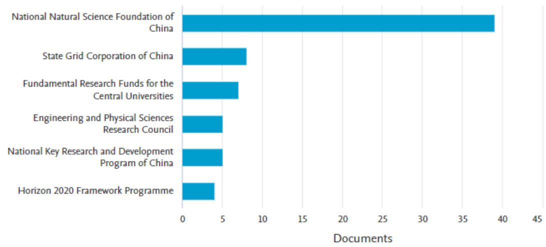


Figure 5: Statistical analysis of the search results: documents by founding sponsor

## 3. Methodology
To explore the relationship between Virtual Energy Storage (VES) and resilience, a scoping review was undertaken. Initially, the primary characteristics of resilience in critical infrastructures were identified. Subsequently, a thorough examination of the literature on VES was conducted to uncover connections and address the research inquiries.

### *3.1. Scoping Review*
The methodology employed in this study involved a systematic and structured approach to address 5 specific research questions. These questions were carefully defined, ensuring precision and alignment with the research objectives. In order to identify relevant literature, a comprehensive search strategy was developed, encompassing various academic databases, journals, conference proceedings. The inclusion and exclusion criteria were established to filter studies based on topic. Figure 6 illustrates the screening steps. Synthesizing the main findings and the links between VES and resilience are reported in the Results and discussion section explaining the influence of VES on resilience of energy system.

## 4. Results and Discussion
By identifying resilience Factors that characterise a resilient system, it is possible to implement comprehensive resilience strategies. Therefore, in this section the critical infrastructure resilience factors are reported; then, how does energy system can better withstand disruptions and continue to provide essential services to communities exploiting VES will be discussed answering the research questions.

### *4.1. Resilience Features*
Resilience of infrastructure elements refer to their capacity to endure and recover from various disruptions while maintaining operational functionality and performance. The resilience of infrastructure is influenced by several key factors, however in this article the factors are selected from the highly cited articles. The selected factors are described in Table 1.

### *4.2. Synthesis of results and discussion*
#### *4.2.1. Research question 1 and 2 - VESS and resilience of CIs*
Energy systems are the backbone of modern society, and their uninterrupted operation is crucial. As

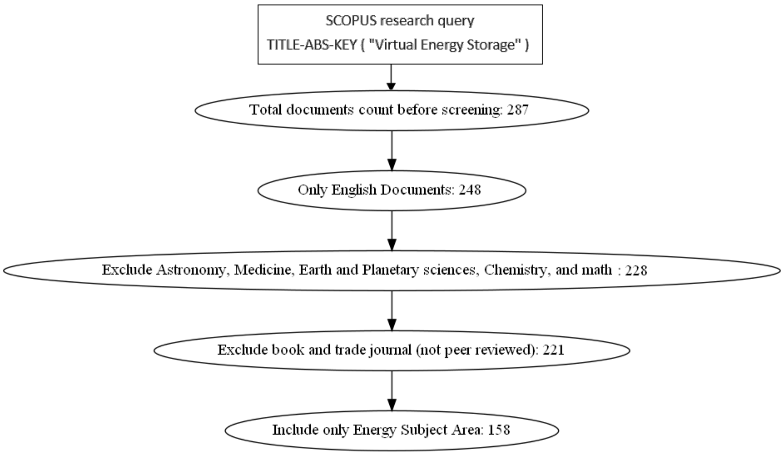


Figure 6: Screening process and the exclusion/inclusion criteria and statistics

Table 1: Key factors of infrastructure resilience extracted from literature

| No. | Key Elements | Description | References |
|---|---|---|---|
| 1 | **Redundancy and Backup Systems** | Resilient infrastructure incorporates redundant components or backup systems to mitigate the impact of failures and ensure continuous operation | [3] |
| 2 | **Adaptive Capacity** | Resilient elements can adapt to changing conditions by adjusting their operations or configurations in response to emerging challenges | [15] |
| 3 | **Robust Design** | Infrastructure resilience is enhanced by robust design considerations, including the use of durable materials and construction techniques to withstand various stresses and threats | [19, 34, 37] |
| 4 | **Interconnectedness and Interdependency Management** | Understanding the interdependencies among different infrastructure elements helps manage dependencies and prevent cascading failures | [34, 11, 42] |
| 5 | **Emergency Preparedness and Response Planning** | Resilient infrastructure has well-defined emergency preparedness and response plans, enabling rapid and effective responses to disruptions | [44, 12] |
| 6 | **Continuous Monitoring and Maintenance** | Regular monitoring and maintenance help identify vulnerabilities and address them proactively, ensuring infrastructure resilience over time | [28] |
| 7 | **Community Engagement and Collaboration** | Engaging local communities in planning, response, and recovery efforts enhances the adaptability and effectiveness of infrastructure resilience strategies | [32, 25] |
| 8 | **Incorporation of Smart Technologies** | Integrating smart technologies such as sensors and real-time monitoring systems enables early detection of issues and data-driven decision-making to enhance infrastructure resilience | [2, 1] |
| 9 | **Regulatory Compliance** | Compliance with regulatory standards ensures that infrastructure elements meet specified safety and performance criteria, contributing to resilience | [17, 39] |
| 10 | **Investment in Research and Innovation** | Continued investment in research and innovation supports the development of technologies, materials, and methodologies that enhance infrastructure resilience, promoting long-term sustainability | [38, 12] |

a result, resilience has become a central focus in this sector. However, the challenges are multifaceted. Energy systems not only face their complexities but also underpin the functionality of other critical infrastructures. Consequently, rapid response and the ability to handle significant fluctuations are essential for energy infrastructure. This is where Energy Storage Systems (ESS) play a vital role [1].

Conventional ESS solutions face inherent limitations such as the number of charging/discharging cycles they can endure [2], their overall lifespan [3], and the challenge of optimal sizing for specific needs [4]. Virtual Energy Storage Systems (VESS) offer an innovative and cost-effective approach to address these limitations, potentially replacing or reducing the reliance on larger, traditional ESS implementations. This aspect contributes to robust design feature of resilience. Ji et al. [22] shows utilizing the supply and demand-side resources in different systems to handle various uncertainties and improve overall efficiency and reliability, which embodies a Robust Design along with Adaptive capacities and Emergency Response[41, 9]. Bringing the demand-side VES capacity into action, supports Community Engagement and Collaboration[40].

A significant advantage of VESS in enhancing resilience lies in its ability to store energy without relying on extra physical batteries [5]. This translates to a simpler system with fewer physical assets, which inherently reduces complexity, maintenance requirements, and overall risk. This inherent simplicity strengthens the system's resilience. This aspect aligns with robust design feature of resilience. By reducing reliance on grid-scale battery storage, VESS contributes to mitigating the potential hazards associated with large-scale battery deployments[11]. This supports the regulatory efforts promoting the reduction of toxic materials and fostering sustainable development[12]. Finally, decreasing the extra batteries for grid-scale storage systems decreases the maintenance and facilitate more efficient energy management. These advantages of VESS supports robust design through decreasing complexity of system, energy management and Continuous Monitoring and Maintenance, and also Regulatory Compliance via eliminating toxic material from the system[30].

A VESS integrates various controllable elements within the energy system, including traditional ESS. This integration provides Redundancy and Backup Systems within the overall ESS structure [6]. This feature significantly bolsters the system's resilience, enabling a swift and dependable response to disruptions; therefore contributes to Adaptive Capacity of the system too. Furthermore, VESS implementation improves the system's ability to adapt to fluctuating loads. Energy synchronization enables a balanced and proportional exchange of power between Battery Energy Storage Systems (BESS) and the flexible loads managed by VESS [7]. Integrating these elements involves the Incorporation of Smart Technologies and Emergency Preparedness and Response Planning together.

While renewable energy sources enhance the resilience of distribution systems, they also introduce additional variability and uncertainty in power generation [8]. This necessitates careful management of interconnected and interdependent decentralized generators. VESS can significantly improve resilience in this context by offering a distributed and scalable ESS solution that can be strategically located near generators and prosumers (consumers who also produce energy) [9]. This aspect embodies Interconnectedness and Interdependency Management feature of resilience.

VESS dynamically adjusts its energy exchange with the power grid based on external signals, seamlessly integrating with grid operations. This allows flexible loads, small-scale energy storage systems, and distributed renewable energy sources to participate in the market and provide valuable services to the power grid, such as transmission and distribution support. Bringing the market factor and end users in the evaluations, reinforces Community Engagement and Collaboration. Unlike virtual power plants that aggregate distributed energy resources to mimic a single large power plant, VESS focuses on accumulating excess electricity and discharging it when needed. This represents a new paradigm shift in decentralized energy systems, made possible by incorporating cutting-edge technologies like the Internet of Things (IoT) [10]. This is only possible through Incorporation of Smart Technologies.

In conclusion, VESS facilitates the creation of services with customizable resilience and availability levels. The incorporation of smart technologies represents a significant paradigm shift from conventional power grids, offering a more robust, adaptable, and efficient energy infrastructure.

#### *4.2.2. Research question 3 - Technology Enablers*

In this section the enabler technology enablers that are involved in virtual energy storage that influence the resilience of cyber-physical systems will be discussed. *Thermal inertia* Thermal inertia refers to a material's ability to conduct and store heat. In the context of smart buildings, thermal inertia is primarily discussed for its role in energy efficiency [55, 21]. However, Chen et al. (2023) [7] propose a novel application: utilizing the heating inertia of pipelines within a Virtual Energy Storage (VES) system to enhance its resilience. Similarly, the thermal inertia of a building itself can be exploited as a form of VES. This approach leverages existing building systems like heat pumps [8] and air conditioners [23] to manage thermal energy. In some cases, district cooling systems [35, 13] or similar technologies can also be integrated. Air conditioning systems can act as virtual energy storage by strategically adjusting the building's indoor temperature[23, 49]. During off-peak hours, when electricity prices are lower, the air conditioner can operate at a cooler setting than usual. This pre-cools the building structure, essentially storing thermal energy within the walls, floors, and furniture. During peak hours, when electricity demand is high and prices surge, the air conditioner can run less frequently or at a slightly warmer setting. The pre-cooled building mass then helps maintain a comfortable temperature without requiring as much energy from the grid [47]. This approach essentially ”shifts” energy consumption from peak to off-peak periods, contributing to a more balanced and resilient energy system.

*Electric vehicles* Emerging technologies like vehicle-to-grid (V2G) and vehicle-to-vehicle (V2V) are revolutionizing energy management. These concepts unlock the potential of electric vehicles (EVs) to act as distributed energy storage units within a VES system which can enhance the resilience of the system through alternative storage options without need to add extra batteries [43, 50]. In the ESS domain EVs contribute: Energy Buffering[48], Time-Shifting[14], Bidirectional Flow[27], Vehicle-to-Vehicle (V2V) charging[43, 50].

*Solar space heating systems* Solar space heating with flat-plate collectors offers a compelling solution to address the high energy consumption of buildings. Gao et al. [16] proposed a novel approach that combines a solar collector with a virtual energy storage system. This innovative solution significantly reduces land use requirements while enabling a substantial shift of daily peak heat load by over 50%. This translates to better utilization of solar energy for space heating, leading to a more sustainable and efficient building operation. This approach contributes performance enhancement of solar collector, solar assistant heat pumps, and peak load shaving problems. As a result, the overall resilience of the system will be increased through VES supported by solar space heating systems.

*Emerging Technologies* There are other technologies that have been considered by researchers and their potentials are studied but still they are in infancy level. The technologies that are warranting further investigation include smart photovoltaic inverters[53], wind systems[20], Water Heaters[31], electricity-gas-heat interconnection[52], and Electrolytic Aluminum Park[18].

### *4.2.3. Research question 4 - Identified challenges and Prospective investigations*

Barala et al [4] studied the challenges and gaps in the VES body of knowledge and reported the main issues. However the issues that are related to resilience enhancement are cost-effective and reliable smart meters design and implementation, a uniform policy needs to be defined to choose appropriate communication technologies, and finally standardizing policies and specifications is vital for integrating various smart grid and microgrid functionalities with VESS.

A possible future work suggested by Song et al[40] will be focused on the application of artificial intelligence technology in load control for the resilience enhancement of the distribution systems that are integrated with VESS. Another potential future study may be focused on applications enabled by the use of active power distribution nodes (APDN) in presence of VES[26]. Kwasinski et al[26] also highlights that microgrids have been identified as a potential improvement in terms of availability and resilience with respect to conventional power grids. And the utilization of the VESS integrated with micro-grids is another promising way to improve the ESS in this domain.

Another future work identified by Yan et al[51] may focus on the integration of the proposed energy management and the virtual thermal energy storage system in the microgrid and its consequent experimental validation.

In summary, to unlock the rapid development of Virtual Energy Storage Systems (VESS), several critical areas require immediate attention[4].

## 5. Conclusion

The findings of this study provide insights for policymakers, energy practitioners, and researchers aiming to enhance the resilience of energy systems in the face of increasing uncertainties and disruptions. Furthermore, it provides valuable insights for the resilience engineering and energy engineering communities by identifying 10 main features of energy resilience along with 4 key enabler technologies that are discussed widely and introducing 5 enabler technologies that are in the early stage of investigation for bringing VES into action and enhancing energy storage and system resilience. The primary limitation of this study lies in its theoretical context. A valuable avenue for our future research would involve examining the identified connections between Virtual Energy Storage (VES) and resilience factors in real-world test beds. This could be achieved by evaluating resilience Key Performance Indicators (KPIs) to gain practical insights.

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