

Enterprise Private Cloud Platforms: A Systematic Review of Key Vendors

Mykhailo Khomchak

Faculty of Computer Science and Technology, National Aviation University, Kyiv, 03058, Ukraine
E-mail: mykhailo.khomchak@gmail.com, 8288211@stud.nau.edu.ua
ORCID iD: <https://orcid.org/0009-0000-4127-556X>

Received: 19 February, 2024; Revised: 25 March, 2024; Accepted: 24 May, 2024; Published: 08 August, 2024

Abstract: Cloud computing has revolutionized the way organizations manage and deploy their Information Technology infrastructure. With an increasing emphasis on data security and residency, regulatory compliance, and the need for customization, private cloud platforms have emerged as a pivotal solution in the enterprise Information Technology landscape. This paper presents a comprehensive review of private cloud technologies, delineating their key features, advantages, and capabilities. Through an exhaustive research methodology, we explore various private cloud solutions, ranging from open-source offerings to proprietary systems. A reference architecture is formulated to provide a holistic understanding of the essential components and interactions inherent to a private cloud platform. Furthermore, 18 categories and 43 subcategories of features and capabilities for the 13 most popular private cloud solutions are identified to assist organizations in evaluating and selecting the most suitable platform based on their specific requirements. This study aims to offer valuable insights to enterprises navigating their cloud adoption journey, emphasizing the significance of making informed decisions in the rapidly evolving cloud computing domain.

Index Terms: Cloud Computing, Private Cloud, Cloud Taxonomy, Cloud Selection.

1. Introduction

The evolution of cloud computing has transformed the landscape of modern enterprise IT infrastructure. As organizations grapple with the challenges of data security, regulatory compliance, and the need for customization, private cloud technologies have emerged as a viable solution to address these concerns. Unlike public clouds, which are hosted by third-party providers and shared among multiple tenants, private clouds are dedicated to a single organization, offering greater control and customization (Mell & Grance, 2011) [1]. These solutions, characterized by their scalability, self-service capabilities, and resource pooling, provide enterprises with the flexibility to adapt to rapidly changing business environments while ensuring that their data remains secure and within their control in regulatory required location (Buyya, Yeo, Venugopal, Broberg, & Brandic, 2009) [2].

The rise in the adoption of private clouds can be attributed to their potential benefits, including reduction of vendor lock-in, cost optimization, expanded service availability, and improved operational efficiency (Gartner, 2020) [3].

Based on Flexera 2023 State of the Cloud Report [4], 74% of organizations have private cloud in place.

Despite the widespread adoption of private cloud platforms as mentioned before, there are significant gaps in the current research landscape. Most existing studies focus on open-source solutions like OpenStack [5, 6, 7], with limited attention to commercial platforms. Additionally, while many papers address the technical aspects of private clouds [8, 9, 10], there is a lack of comprehensive comparative evaluations. With the proliferation of private cloud solutions in the market, organizations face the challenge of selecting the most suitable technology that aligns with their specific requirements. Private cloud selection processes required to be addressed by proper selection of private cloud platforms to manage hybrid corporate workloads. This gap in the literature makes it challenging for organizations to make informed decisions when selecting private cloud platforms that best meet their needs. Considering that managing cloud spend, security issues and lack of expertise are top cloud adoption challenges (Fig.2) a systematic private cloud taxonomy, which covers all the aspects in a holistic way, is essential for decision-making process.

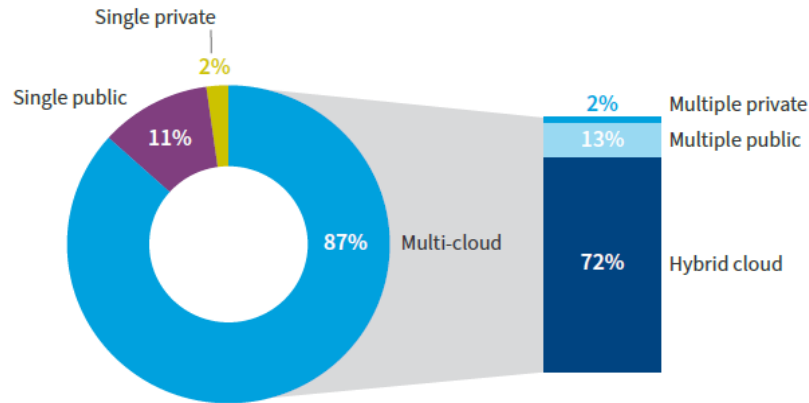


Fig.1. How organizations embrace clouds.

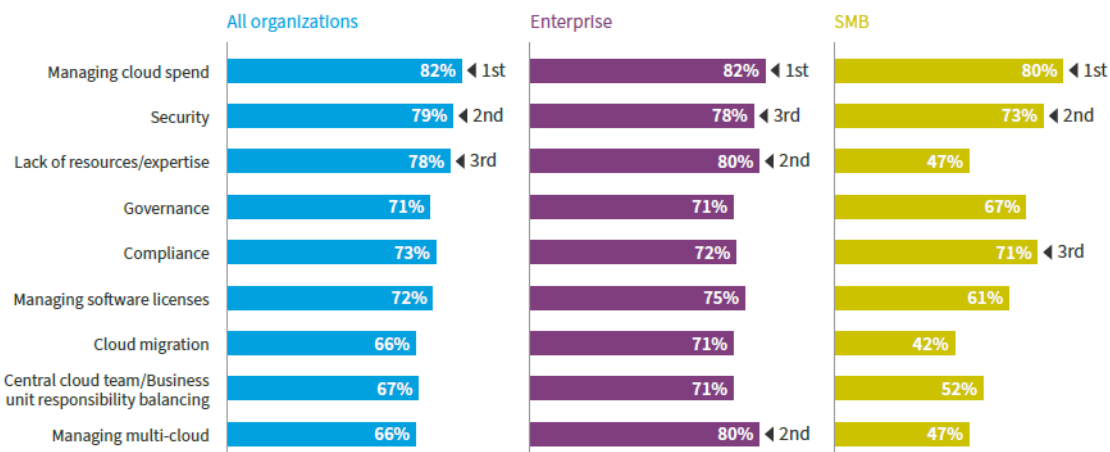


Fig.2. Top cloud adoption challenges.

Enterprise private cloud platforms refer to a category of cloud computing solutions specifically designed for large-scale businesses and organizations. Unlike public clouds, which are shared by multiple users, a private cloud is dedicated to a single organization, ensuring enhanced security, control, and customization. These technologies combine the benefits of traditional data centers with the agility, scalability, and efficiency of cloud computing.

An enterprise private cloud is a computing environment that mimics the capabilities of public cloud services but operates solely for a single organization, whether managed internally or by a third-party provider. Key characteristics include:

- dedicated resources when all computing resources, from servers to storage, are dedicated to a single organization;
- customization capabilities which allow organizations to tailor their private cloud environment to meet specific business and IT requirements.
- enhanced security with dedicated resources and no shared infrastructure, private clouds offer a higher level of security, making them suitable for businesses with stringent compliance and data protection needs.

Enterprise private cloud platforms encompass various components, including:

- Infrastructure as a Service (IaaS): provides virtualized computing resources over the internet, allowing businesses to rent IT infrastructure components.
- Platform as a Service (PaaS): offers a platform allowing customers to develop, run, and manage applications without dealing with infrastructure complexities.
- Software-Defined Data Centers (SDDC): an advanced infrastructure where all elements of the data center, including networking, storage, and computing, are virtualized, and delivered as a service.

Adopting private cloud platforms offers several advantages to enterprises:

- increasing cost efficiency, by optimizing resource utilization, enterprises can achieve significant cost savings;
- business agility by rapid provisioning and de-provisioning of resources enable businesses to respond quickly to market changes;
- control and compliance when enterprises have full control over their data, ensuring compliance with industry regulations and standards;
- performance increase when dedicated resources ensure consistent and high-performance levels, crucial for mission-critical applications.

The landscape of enterprise private cloud platforms has evolved over the years, with several trends shaping its future:

- **Hybrid Cloud Integration:** many enterprises are adopting a hybrid approach, integrating private and public cloud resources to achieve greater flexibility.
- **Containerization:** the rise of container technologies like Docker and Kubernetes has revolutionized application deployment in private clouds.
- **Automation and orchestration:** advanced automation tools are simplifying the management of private cloud environments, reducing manual interventions and errors.

Enterprise private cloud platforms offer a robust and flexible solution for businesses looking to harness the power of cloud computing while maintaining control, security, and customization. As technology continues to evolve, it is imperative for organizations to stay abreast of the latest trends and innovations in this domain to leverage the full potential of private cloud solutions.

This paper aims to provide a systematic review of these key vendors, shedding light on their strengths, capabilities, and the value they bring to the enterprise cloud ecosystem. By synthesizing information from various sources, a systematic review offers practical insights and recommendations with respect to features and capabilities availability for particular solutions that can guide organizations in making informed decisions regarding private cloud adoption and implementation. The subsequent sections will delve into the methodologies employed for this review, present a comparative analysis of the leading private cloud vendors, and conclude with recommendations for enterprises embarking on their private cloud journey.

The reminder sections of the paper are organized as follows. “Related works” section presents a survey of existing papers related to our study. In “Research methodology” section, the methodology of our study is described. In “Private Cloud Platforms Reference Architecture and Taxonomy” we defined the scope of key vendor to consider, based on their features, created private cloud platform reference architecture and comprehensive taxonomy which has been validated in “Taxonomy validation” section. In “Future research challenges”, the key area of future research has been identified.

2. Related Works

The landscape of enterprise private cloud platforms has been the subject of numerous scholarly investigations. A synthesis of these studies provides a comprehensive understanding of the current state of research in this domain.

In one of the first [11] comprehensive researches, the basic components of private cloud platform were identified. Author built the solution using KVM [12] virtualization technology and Eucalyptus [13], an open-source system that enables the organization to establish its own cloud computing environment.

Improved reference architecture was presented in [14].

Next study with similar reference architecture focused on performance evaluation and comparison of three platforms: Ubuntu Enterprise Cloud (UEC), Xen Cloud Platform (XCP), and Proxmox virtual environment (PVE) [15].

As abovementioned studies most of the scientific publications are mostly concerned about open-source private cloud solution such as OpenStack [16, 17, 18, 19] with very limited focus on commercial solutions.

In case of private cloud platforms available solution market researches and industry report provide much better view on a technology. In Forrester's 61-criteria evaluation of private cloud solution vendors [20], we identified the 10 most significant software providers – ASG Software Solutions, BMC Software, CA Technologies, Cisco Systems, Citrix Systems, Eucalyptus Systems, HP, IBM, Microsoft, and VMware. Forrester's high-level overview [21] of more than 30 software-only private cloud service providers is also a valuable resource to create a list of solutions to become input for taxonomy creation.

Private cloud technologies continue to play a pivotal role in the multi-cloud, hybrid approach adopted by many organizations. Microsoft Azure Stack, for instance, has seen an increase in workload runs, marking its prominence in the private cloud domain. AWS Outposts and VMware vSphere/vCenter are also notable contenders in the private cloud space. However, it's worth noting the decline in OpenStack's popularity over the years, dropping to 11% in 2023 from 15% in the previous year (Flexera, 2023).

The report also emphasizes the importance of understanding application dependencies and assessing technical feasibility, which are identified as the top challenges faced by organizations when migrating workloads to the public cloud. This underscores the complexities involved in cloud migration and the need for comprehensive planning and strategy (Flexera, 2023).

A recent review by Data Centre Magazine highlighted the top private cloud solution providers, emphasizing their contributions to the evolving enterprise cloud ecosystem. The list includes industry giants such as AWS, Microsoft Azure, Google Cloud, and Oracle Cloud, as well as other notable providers like VMware, SAP, and HPE GreenLake (Derrick, 2020) [22].

Gartner's Cloud management Tooling Review and Rating [23] and Strategic Cloud Platform Services [24] are also considered to create a short list of private cloud platforms.

As we can see, several key vendors, both proprietary and open-source, dominate the private cloud landscape, each offering a unique set of features.

3. Research Methodology

The objective of this research is to provide a systematic review of key vendors in the domain of enterprise private cloud platforms. To ensure the comprehensiveness, reliability, and validity of the findings, a structured research methodology was adopted. This section outlines the methods and procedures employed during the research process.

The research methodology adopted for this systematic review is based on a qualitative approach, ensuring that the assessment of enterprise private cloud platforms is comprehensive, replicable, and unbiased. The methodology is divided into the following phases:

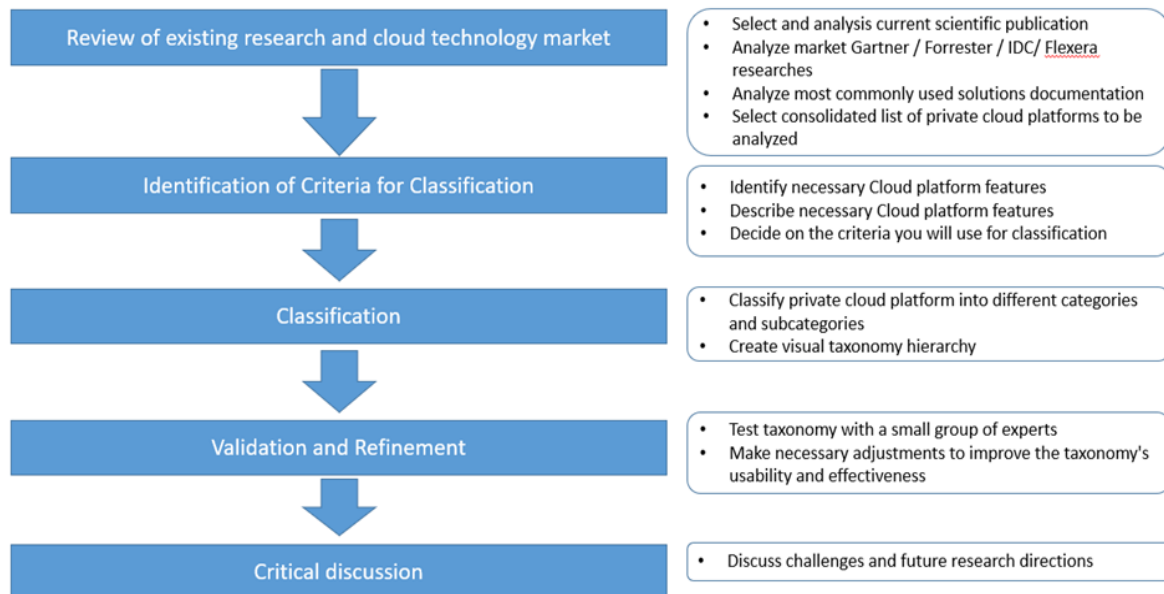


Fig.3. Research methodology steps.

3.1. Review of Existing Research and Cloud Technology Market

On the first step selection and analysis of different sources has been performed:

- Literature Databases: peer-reviewed articles, conference proceedings, and white papers were obtained from recognized academic databases such as IEEE Xplore, Google Scholar, ACM Digital Library, and ScienceDirect.
- Vendor documentation: official documentation, whitepapers, and case studies provided by private cloud vendors were considered to understand the technical specifications, features, and capabilities of their solutions.
- Industry reports: reports from industry analysts, such as Gartner, Forrester, and IDC, were incorporated to gain insights into market trends, vendor evaluations, and future predictions.

For each selected document, relevant data was extracted and categorized.

3.2. Identification of Criteria for Classification

A thematic analysis approach was employed to assess the extracted data on the second step. The analysis sought to identify recurring themes and patterns concerning the capabilities and market proposals of the considered private cloud vendors. To provide a comprehensive review of key vendors, the following evaluation criteria were established:

- Market presence: the overall footprint of the vendor in the enterprise private cloud market.
- Technological innovations: the vendor's contribution to technological advancements in the domain.
- Customer reviews: feedback and reviews from enterprises that have adopted the vendor's solution.
- Security and compliance: the robustness of the vendor's solutions in terms of data protection and regulatory compliance.
- Scalability and flexibility: the ability of the vendor's solutions to adapt to varying enterprise needs.

As a result, on the second step reference architecture for private cloud platforms was built, necessary technical features were identified, and 18 classification groups established.

3.3. Classification

Step three was dedicated to classification private cloud platform to different categories and subcategories created on the previous step and visual taxonomy creation. On this stage, classification of the various enterprise private cloud platforms based on the criteria identified in the previous steps was performed. The classification aims to provide a structured overview, helping organizations in selecting the most suitable platform according to their specific needs.

3.4. Validation and Refinement

On step four this taxonomy was validated. To ensure the accuracy and relevance of the proposed classification, a validation and refinement process was conducted involving a group of experts (Senior DevOps Engineers and Developers) from a leading Ukrainian telco operator Kyivstar PJSC Information Technology Department. This process aimed to test the practical applicability of the classification criteria and refine them based on expert feedback.

An initial session was organized to familiarize the experts with the proposed classification. This included a detailed presentation of the classification criteria and the rationale behind each category and subcategory. Experts were asked to classify different private cloud platforms using the proposed taxonomy. This hands-on approach helped in identifying any discrepancies or ambiguities in the classification.

After the taxonomy testing, experts provided detailed feedback on the classification criteria. They highlighted areas of strength and suggested improvements for criteria that were either too broad or too specific. Based on the feedback, the classification criteria were refined to enhance clarity and applicability. For instance, the integration of public clouds was limited to key hyperscalers.

The refined classification was re-tested with the same group of experts to ensure that the modifications addressed the previously identified issues. This iterative process helped in achieving a robust and practical classification framework.

The validation process underscored the importance of involving domain experts in refining theoretical models. Their practical insights ensured that the classification is not only theoretically sound but also practically applicable in real-world scenarios. This iterative approach of validation and refinement ensures that the classification remains relevant and useful for organizations in selecting and implementing private cloud platforms.

3.5. Critical discussion

On this step, we critically examined the findings of the study, highlighting the strengths, limitations, and areas for future research.

4. Private Cloud Platforms Reference Architecture and Taxonomy

In this section, we defined the scope of key vendor to consider, based on their features introduce private cloud platform reference architecture and create classification of private cloud platforms capabilities to different categories and subcategories of features based on technical criteria.

Based on related survey and industrial reports review the following open-source and commercial platforms were selected to be a part of evaluations scope:

- OpenStack [25]: OpenStack has been one of the most popular open-source solutions for building private clouds. Organizations of various sizes have adopted it, especially large enterprises and telecoms. Its modular architecture and active community support have contributed to its widespread adoption.
- KVM (Kernel-based Virtual Machine) [12]: as an integral part of the Linux kernel, KVM has seen significant adoption as a hypervisor for both private clouds and general virtualization needs. Its integration with other open-source projects like OpenStack and oVirt has further boosted its popularity.
- oVirt: oVirt [26], built on top of KVM, has been adopted by organizations looking for a comprehensive virtualization management platform. While it might not have the same market share as OpenStack, it has a dedicated user base.
- Proxmox VE [27]: Proxmox has gained traction among small to medium-sized businesses and individual users due to its user-friendly interface and combined support for KVM virtualization and LXC containerization.

- CloudStack [28]: Apache CloudStack, while not as popular as OpenStack, has its niche, especially among organizations looking for a more straightforward cloud management platform.
- Xen [29]: Xen, another open-source hypervisor, has been around for a long time and has seen adoption in various sectors. Some cloud providers, like Amazon EC2, initially used Xen as their underlying hypervisor.
- VMware [30]: VMware's vCloud Suite and vSphere are popular solutions for building private clouds. VMware is often recognized for its mature and comprehensive virtualization and cloud management capabilities.
- Microsoft [31]: Microsoft's Azure Stack offers a private cloud solution that brings many of Azure's public cloud features to on-premises environments.
- IBM: IBM Cloud Private (ICP) [32] is a solution that allows enterprises to build their own private cloud environments using Kubernetes and other open-source technologies.
- Oracle: Oracle's Private Cloud [33] at Customer is a solution that offers the benefits of Oracle's public cloud but in an on-premises environment.
- Cisco: Cisco's Unified Computing System (UCS) and CloudCenter [34] are solutions designed to help enterprises build and manage private clouds.
- Nutanix [35]: Known for its hyper-converged infrastructure solutions, Nutanix also offers the Nutanix Cloud Platform for private cloud deployments.
- Red Hat: Red Hat OpenShift [36] is a popular choice for enterprises looking to deploy private clouds using open-source technologies.

The selection of these platforms was based on a set of comprehensive criteria designed to ensure that the evaluation encompasses a diverse range of capabilities, market presence, and technological innovations. The criteria and rationale are as follows:

- market presents with market share more than 0,5%;
- vendors known for their technological innovations based on market researches and reports mention earlier;
- positive customer reviews and feedback with 3+ score based on market researches and reports mention earlier.

Post our related work survey and abovementioned vendors documentation analysis, we formulated a reference architecture that encapsulates the quintessential components and interactions inherent to a private cloud platform.

The reference architecture provides a high-level overview of the components and interactions within a private cloud platform:

- User: represents the end-users or applications accessing the private cloud platform.
- Private Cloud Platform: the main entry point for all cloud-related operations.
- Orchestration Layer: manages and orchestrates various resources such as VMs, storage, and networking.
- VMs & Containers: virtual machines and container instances running on the cloud.
- Storage: represents storage solutions like block storage, object storage, etc.
- Networking: represents the networking components like virtual networks, load balancers, etc.
- API Gateway: provides APIs for accessing and managing cloud resources.
- External Services: represents third-party services or applications integrated with the cloud platform.
- Monitoring & Logging: tools and services for monitoring the health and performance of the cloud resources.
- Security & Compliance: ensures that the cloud platform is secure and meets compliance requirements.

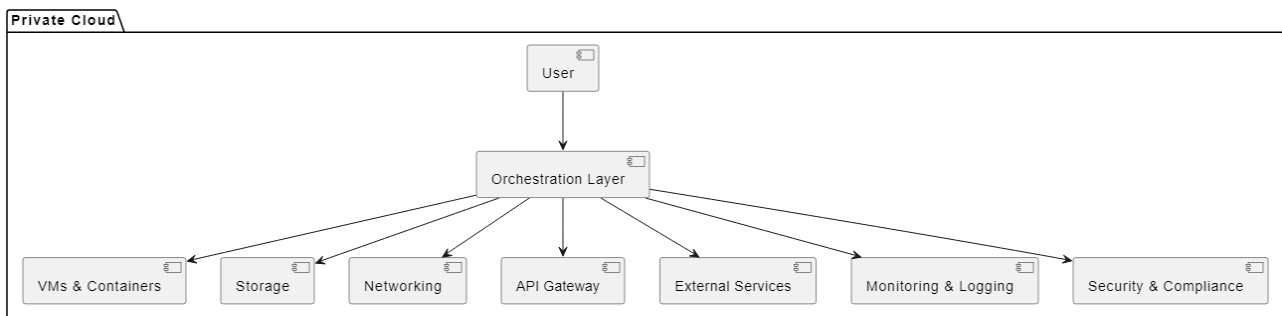


Fig.4. Reference Architecture of a Private Cloud Platform

This analysis and reference architecture provide a foundational understanding of private cloud platforms and their components. As organizations continue to adopt and evolve their cloud strategies, it is crucial to select the right platform and architecture that aligns with their unique needs and goals.

Now after definition of private cloud platform's reference architecture, classification criteria should be identified. Considering previous material, we have created a comprehensive list of 18 feature-categories for classifying private cloud platforms:

- **Deployment Model:**
 - On-Premises: cloud infrastructure is deployed within the organization's own premises.
 - Hybrid: a combination of on-premises and public cloud infrastructure.
 - Hosted: cloud infrastructure is hosted by a third-party provider.
- **Licensing:**
 - Open Source: the platform's source code is available to the public, allowing modifications and distributions.
 - Proprietary: the platform's source code is owned by an organization and is not publicly available.
- **Supported Hypervisors:**
 - KVM: kernel-based Virtual Machine.
 - Xen: an open-source hypervisor.
 - VMware: a proprietary hypervisor.
 - Hyper-V: a hypervisor developed by Microsoft.
 - Acropolis: Nutanix AHV is a modern and secure virtualization platform that powers VMs and containers for applications and cloud-native workloads on-premises and in public clouds.
- **Scalability:**
 - Horizontal: ability to add more machines to the system to improve performance.
 - Vertical: ability to add more power (CPU, RAM) to an existing machine.
- **High Availability:**
 - Active-Active: Both systems are running simultaneously and can handle requests.
 - Active-Passive: One system is active and handles requests, while the other is on standby.
- **Storage Integration:**
 - Ceph: an open-source storage platform.
 - GlusterFS: an open-source scale-out filesystem.
 - NFS: Network File System for file sharing.
- **Network Configuration:**
 - SDN Support: Support for Software-Defined Networking.
 - VLAN: Virtual Local Area Network for segmenting a network.
 - VXLAN: Virtual Extensible LAN for overlay networks.
- **API Availability:**
 - RESTful API: An architectural style for distributed systems based on HTTP.
 - GraphQL: A query language for APIs.
- **User Interface:**
 - Web UI: a graphical interface accessible via a web browser.
 - CLI: command-Line Interface for interacting with the platform.
- **Multi-tenancy Support:**
 - Yes: supports multiple tenants or users on a single instance.
 - No: does not support multi-tenancy.
- **Integration with Public Clouds:**
 - AWS: integration with Amazon Web Services.
 - Azure: integration with Microsoft Azure.
 - GCP: integration with Google Cloud Platform.
- **Security Features:**
 - RBAC: Role-Based Access Control for defining user roles and permissions.
 - Multi-factor Authentication: additional security layer requiring multiple methods of authentication.
- **Monitoring and Logging:**
 - Built-in: inherent monitoring and logging capabilities.
 - Integration with External Tools: ability to integrate with third-party monitoring and logging tools.
- **Backup and Disaster Recovery:**
 - Snapshot: a point-in-time copy of data.
 - Replication: duplicating data across multiple locations for redundancy.
- **Container Support:**
 - Kubernetes: an open-source container orchestration platform.
 - Docker: a platform for developing, shipping, and running applications in containers.
- **Service Catalog:**
 - VMs: Virtual Machines as a service.
 - Databases: database services.
 - Applications: application hosting and deployment services.
- **Cost Management:**
 - Built-in Billing: inherent billing capabilities.
 - Integration with External Billing: ability to integrate with third-party billing systems.

- Extensibility:
 - Plugins: extend functionality using plugins.
 - API Extensions: extend API capabilities. Migration Tools: Tools and features that assist in migrating workloads to and from the platform.

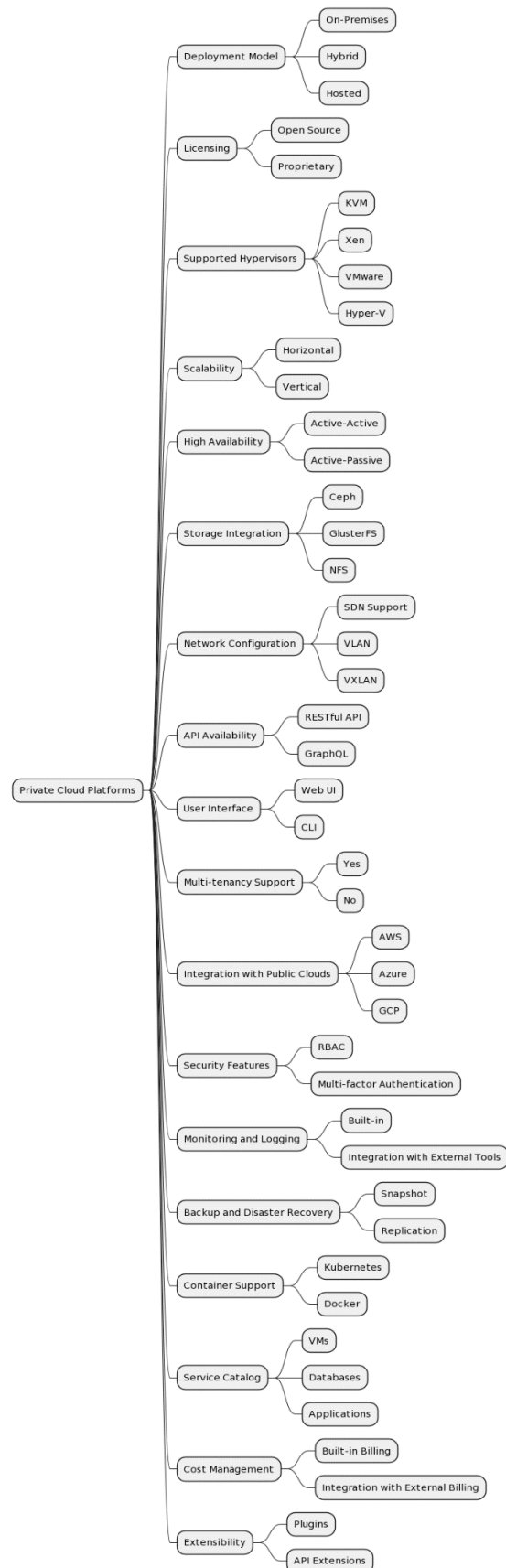


Fig.5. Private cloud platforms taxonomy.

These feature-categories and subcategories will allow enterprise to perform a holistic evaluation that covers a wide range of enterprise needs and technological capabilities. Thus, become a valuable input for private cloud selection process.

5. Taxonomy Validation

These criteria can be used to evaluate and categorize different private cloud platforms based on their features, capabilities, and use cases. In Table 1 and Table 2 selected platforms capabilities analyzed.

Table 1. Taxonomy validation (part 1).

Groups & subgroups	OpenStack	KVM	oVirt	Proxmox VE	CloudStack	Xen	VMware
Deployment Model							
On-Premises	+	+	+	+	+	+	+
Hybrid	+	-	-	+	+	-	+
Hosted	+	-	-	-	+	-	+
Licensing							
Open Source	+	+	+	+	+	+	-
Proprietary	-	-	-	+	-	-	+
Supported Hypervisors							
KVM	+	+	+	+	+	-	-
Xen	+	-	-	+	+	+	-
VMware	+	-	-	-	+	-	+
Hyper-V	+	-	-	-	+	-	-
Acropolis	-	-	-	-	-	-	-
Scalability							
Horizontal	+	+	+	+	+	+	+
Vertical	+	+	+	+	+	+	+
High Availability							
Active-Active	+	+	+	+	+	+	+
Active-Passive	+	+	+	+	+	+	+
Storage Integration							
Ceph	+	+	+	+	+	+	-
GlusterFS	+	+	+	+	+	+	-
NFS	+	+	+	+	+	+	+
Network Configuration							
SDN Support	+	+	+	+	+	+	+
VLAN	+	+	+	+	+	+	+
VXLAN	+	+	+	+	+	+	+
API Availability							
RESTful API	+	-	+	-	+	-	+
GraphQL	-	-	-	-	-	-	-
User Interface							
Web UI	+	-	+	+	+	-	+
CLI	+	+	+	+	+	+	+
Multi-tenancy Support							
Yes	+	-	+	+	+	-	+
No	-	+	-	-	-	+	-
Integration with Public Clouds							

AWS	+	-	-	-	+	-	+
Azure	+	-	-	-	+	-	+
GCP	+	-	-	-	+	-	+
Security Features							
RBAC	+	-	+	+	+	-	+
Multi-factor Authentication	+	-	+	-	-	-	+
Monitoring and Logging							
Built-in	+	-	-	+	-	-	+
Integration with External Tools	+	+	+	+	+	+	+
Backup and Disaster Recovery							
Snapshot	+	+	+	+	+	+	+
Replication	+	+	+	+	+	+	+
Container Support							
Kubernetes	+	+	+	+	+	+	+
Docker	+	+	+	+	+	+	+
Service Catalog							
VMs	+	-	+	-	+	-	+
Databases	-	-	-	-	-	-	-
Applications	-	-	-	-	-	-	-
Cost Management							
Built-in Billing	-	-	-	-	-	-	+
Integration with External Billing	+	+	+	+	+	+	+
Extensibility	+	+	+	+	+	+	+
Plugins	+	+	+	+	+	+	+
API Extensions	+	+	+	+	+	+	+

Table 2. Taxonomy validation (part 2).

Groups & subgroups	Microsoft	ICP	OPC	CloudCenter	Nutanix	OpenShift
Deployment Model						
On-Premises	+	+	+	+	+	+
Hybrid	+	+	+	+	+	+
Hosted	+	+	+	+	+	+
Licensing						
Open Source	-	-	-	-	-	+
Proprietary	+	+	+	+	+	+
Supported Hypervisors						
KVM	-	-	-	+	-	+
Xen	-	-	-	+	-	-
VMware	-	-	-	+	+	-
Hyper-V	+	-	-	+	-	-
Acropolis	-	-	-	-	+	-
Scalability						
Horizontal	+	+	+	+	+	+
Vertical	+	+	+	+	+	+
High Availability						

Enterprise Private Cloud Platforms: A Systematic Review of Key Vendors

Active-Active	+	+	+	+	+	+
Active-Passive	+	+	+	+	+	+
Storage Integration						
Ceph	-	+	+	+	+	+
GlusterFS	-	+	+	+	+	+
NFS	-	+	+	+	+	+
Network Configuration						
SDN Support	+	+	+	+	+	+
VLAN	+	+	+	+	+	+
VXLAN	+	+	+	+	+	+
API Availability						
RESTful API	+	-	-	+	+	+
GraphQL	-	-	-	-	-	-
User Interface						
Web UI	+	+	+	+	+	+
CLI	+	+	+	+	+	+
Multi-tenancy Support						
Yes	+	+	+	+	+	+
No	-	-	-	-	-	-
Integration with Public Clouds						
AWS	+	+	+	+	+	+
Azure	+	+	+	+	+	+
GCP	+	+	+	+	+	+
Security Features						
RBAC	+	+	+	+	+	+
Multi-factor Authentication	+	+	+	+	+	+
Monitoring and Logging						
Built-in	+	+	+	+	+	+
Integration with External Tools	+	+	+	+	+	+
Backup and Disaster Recovery						
Snapshot	+	+	+	+	+	+
Replication	+	+	+	+	+	+
Container Support						
Kubernetes	+	+	+	+	+	+
Docker	+	+	+	+	+	+
Service Catalog						
VMs	+	-	-	+	+	-
Databases	+/-	-	-	+	+	-
Applications	-	-	-	-	-	-
Cost Management						
Built-in Billing	+	-	-	+	+	-
Integration with External Billing	+	+	+	+	+	+
Extensibility	+	+	+	+	+	+
Plugins	+	+	+	+	+	+
API Extensions	+	+	+	+	+	+

Based on the evaluations provided in Table 1 and Table 2, the following conclusions can be drawn regarding the best and least favorable solutions for various features of enterprise private cloud platforms.

CloudCenter, Nuatanix, Openshift and VMware stand out as the overall solutions with largest capabilities due to its comprehensive features, robust support, and extensive scalability. They support all deployment models, including on-premises, hybrid, and hosted, and offers proprietary licensing with extensive support and enterprise-grade features.

OpenStack and CloudStack are the open-source solutions with largest amount of features and capabilities, offering high customizability and flexibility. They support on-premises, hybrid, and hosted deployments, and provides open-source licensing that enable organizations to modify and extend the platform's capabilities.

KVM and Xen are identified as solutions with the most limited list of available features and capabilities.

The taxonomy outlined in the preceding section was the result of meticulous research, examination of primary vendors, and rigorous criteria classification. However, any proposed taxonomy, no matter how comprehensive, requires validation in real-world scenarios to ascertain its efficacy and applicability. This section delves into the validation process of our taxonomy, emphasizing its testing with a select group of experts and its subsequent use for selection of top private cloud platforms.

For the purpose of validation, experts were chosen from of Ukraine's largest telco operator Kyivstar PJSC which provides services to 24mln subscribers and its subcontractors. The selected group consisted of Senior Cloud Architect, with extensive experience in designing and deploying cloud solutions, Senior DevOps Engineers and Developers who oversee the day-to-day functionalities of various cloud services and IT Strategists and decision-makers responsible for choosing and integrating cloud solutions.

This diverse group ensured that the taxonomy was evaluated from multiple perspectives, ranging from technical design to operational feasibility.

A structured framework was established to guide the testing process. This consisted of:

- Orientation Session: an initial session to familiarize the experts with the proposed taxonomy. This included a detailed walkthrough of the classification criteria and the reasoning behind each category and subcategory.
- Scenario-based Testing: experts were presented with two scenarios where they had to apply proposed taxonomy for selection best-fit private cloud solution for large bank and mid-size IT service company.
- Feedback Collection: after the testing, experts shared their insights, potential discrepancies they observed, and suggestions for refinements.

Post the orientation and scenario-based testing, experts were tasked to select private cloud platform for Kyivstar PJSC using the proposed taxonomy together with analytical hierarchy process methodology. This exercise aimed to evaluate the taxonomy's comprehensiveness, its capacity to accommodate real-world cloud offerings and contribute to decision-making for practical business task. Technical requirements and selection criteria were presented by the group and contributed to selection processes. As a result, considering technical and commercial assessment, VMware platform was selected the most suitable solution and implemented.

Experts have also validated that this approach for selecting a private cloud platform is applicable across other industries.

6. Future Research Challenges

As the landscape of private cloud platforms continues to evolve, several research challenges emerge that warrant attention from the academic and industrial communities. Addressing these challenges will be pivotal in shaping the next generation of private cloud solutions. Here are some of the most pressing challenges:

- Automating and improving informed decision-making process of private cloud platform selection for both commercial sector and academy. The Analytical Hierarchy Process (AHP) method for selecting cloud solutions can be further improved to provide more accurate and tailored recommendations. Future research could focus on refining this method and integrating it with advanced proposed taxonomy.
- Applying Machine Learning for cloud selection as it can significantly enhance the process of selecting the most suitable cloud solution. Research should explore the application of ML algorithms to analyze organizational needs, predict future requirements, and recommend the best-fit cloud platform.
- Energy-efficiency improvement considering growing concerns about environmental sustainability, incorporating energy-efficient requirements and green computing practices for private clouds selection.
- Providing hybrid cloud platform selection methodology as organizations often use multiple cloud solutions, ensuring seamless interoperability between different private cloud platforms and public clouds.

As a result quick emerging technology development such as the rise of quantum computing, edge computing, and 5G technologies as well as constant presented cloud vendors' portfolio updates proposed taxonomy may become outdated over time and will need to be reviewed. When implementing selection criteria and short-listed solutions into

your decision-making processes it also impotent to consider local market specific and availability of engineering resources with necessary expertise.

Addressing these research challenges will not only enhance the capabilities company decision-making process but also ensure they remain relevant and effective in the ever-evolving IT landscape.

7. Conclusions

The rapid evolution of cloud computing has significantly impacted the modern enterprise IT infrastructure landscape. As organizations navigate the complexities of data security, regulatory compliance, and customization needs, private cloud technologies have emerged as a preferred solution. This paper provided a systematic review of enterprise private cloud platforms, focusing on their key features, strengths, and capabilities.

Our research highlighted the important technical criteria and present private cloud platform taxonomy. With 74% of organizations already leveraging private cloud solutions, the importance of selecting the right technology that aligns with specific requirements cannot be overstated.

Through a comprehensive research methodology, we delved into various sources, including academic literature, vendor documentation, and industry reports. Our findings underscored the dominance of several key vendors in the private cloud landscape. From open-source solutions like OpenStack and KVM to proprietary platforms such as VMware and Microsoft Azure Stack, the choices are vast and varied.

The reference architecture formulated in this study encapsulates the essential components and interactions inherent to a private cloud platform. This foundational understanding is crucial for organizations as they strategize and evolve their cloud adoption journey. The classification criteria and detailed description of feature-categories and subcategories are valuable contribution to a structured approach to evaluate and select the most suitable private cloud platform based on specific needs.

In conclusion, as the Cloud Computing domain continues to evolve, staying abreast of the latest trends, innovations, and best practices is paramount. Private cloud technologies, with their promise of control, security, and customization, are poised to play a pivotal role in shaping the future of enterprise IT. Organizations must make informed decisions, leveraging insights such as those presented in this paper, to harness the full potential of private cloud solutions.

References

- [1] Mell, P., & Grance, T. (2011). The NIST definition of cloud computing. National Institute of Standards and Technology, 53(6), 50.
- [2] Buyya, R., Yeo, C. S., Venugopal, S., Broberg, J., & Brandic, I. (2009). Cloud computing and emerging IT platforms: Vision, hype, and reality for delivering computing as the 5th utility. *Future Generation Computer Systems*, 25(6), 599-616.
- [3] Rimol, M. (2020). 4 trends impacting cloud adoption in 2020. Gartner. <https://www.gartner.com/smarterwithgartner/4-trends-impacting-cloud-adoption-in-2020>
- [4] The Flexera 2023 State of the Cloud Report <https://info.flexera.com/CM-REPORT-State-of-the-Cloud-2023-Thanks>
- [5] Sefraoui, O., Aissaoui, M., & Eleuldi, M. (2012). OpenStack: toward an open-source solution for cloud computing. *International Journal of Computer Applications*, 55(3), 38-42.
- [6] Rosado, T., & Bernardino, J. (2014, July). An overview of openstack architecture. In *Proceedings of the 18th International Database Engineering & Applications Symposium* (pp. 366-367).
- [7] Kumar, R., Gupta, N., Charu, S., Jain, K., & Jangir, S. K. (2014). Open source solution for cloud computing platform using OpenStack. *International Journal of Computer Science and Mobile Computing*, 3(5), 89-98.
- [8] Dhaya, R., Ujwal, U. J., Sharma, T., Singh, P., Kanthavel, R., Selvan, S., & Krah, D. (2022). Energy-efficient resource allocation and migration in private cloud data centre. *Wireless Communications & Mobile Computing* (Online), 2022.
- [9] Virupakshar, K. B., Asundi, M., Channal, K., Shettar, P., Patil, S., & Narayan, D. G. (2020). Distributed denial of service (DDoS) attacks detection system for OpenStack-based private cloud. *Procedia Computer Science*, 167, 2297-2307.
- [10] Patel, H. B., & Kansara, N. (2021). Cloud computing deployment models: A comparative study. *International Journal of Innovative Research in Computer Science & Technology (IJIRCST)*.
- [11] [5] Karpagam, G. R., & Parkavi, J. (2011). Setting up of an open source based private cloud. *IJCSI International Journal of Computer Science Issues*, 8(3).
- [12] What Is KVM (Kernel-Based Virtual Machine)? <https://aws.amazon.com/ru/what-is/kvm/>
- [13] Nurmi, D., Wolski, R., Grzegorzczak, C., Obertelli, G., Soman, S., Youseff, L., & Zagorodnov, D. (2009, July). Eucalyptus: an open-source cloud computing infrastructure. In *Journal of Physics: Conference Series* (Vol. 180, No. 1, p. 012051). IOP Publishing.
- [14] Babar, M. A., & Pantić, Z. (2012). Guidelines for building a private cloud infrastructure.
- [15] Nadeem, F., & Qaiser, R. (2015). An early evaluation and comparison of three private cloud computing software platforms. *Journal of Computer Science and Technology*, 30, 639-654.
- [16] Zou, G. (2015, December). The Design Of Private Cloud Platform For Colleges And Universities Education Resources Based On Openstack. In *2015 4th National Conference on Electrical, Electronics and Computer Engineering* (pp. 991-996). Atlantis Press.
- [17] Z. Kai, L. Youyu, L. Qi, S. C. Hao and Z. Liping, "Building a private cloud platform based on open source software OpenStack," 2020 International Conference on Big Data and Social Sciences (ICBDSS), Xi'an, China, 2020, pp. 84-87, doi: 10.1109/ICBDSS51270.2020.00027.

- [18] Yunxia, J., Bowen, Z., Shuqi, W., & Dongnan, S. (2014). Research of enterprise private cloud computing platform based on openstack. *International Journal of Grid and Distributed Computing*, 7(5), 171-180.
- [19] Diao, Z., & Zhu, Y. (2018). Practice and Research on Private Cloud Platform Based on OpenStack. In *Smart Computing and Communication: Second International Conference, SmartCom 2017, Shenzhen, China, December 10-12, 2017, Proceedings 2* (pp. 259-267). Springer International Publishing.
- [20] The Forrester Wave™: Private Cloud Solutions, Q4 2013 <https://www.forrester.com/report/the-forrester-wave-private-cloud-solutions-q4-2013/RES104661>
- [21] Vendor Landscape: Private Cloud Software Solutions, Q2 2016 <https://www.forrester.com/report/vendor-landscape-private-cloud-software-solutions-q2-2016/RES117955>
- [22] Derrick, M. (2020). Top 10 private cloud solution providers. *Data Centre Magazine*. Retrieved from <https://datacentremagazine.com/top10/top-10-private-cloud-solution-providers>
- [23] Gartner's Cloud management Tooling Review and Rating <https://www.gartner.com/reviews/market/cloud-management-tooling>
- [24] Gartner Strategic Cloud Platform Services <https://www.gartner.com/reviews/market/cloud-infrastructure-and-platform-services>
- [25] OpenStack <https://www.openstack.org/>
- [26] oVirt <https://www.ovirt.org/>
- [27] Proxmox VE <https://www.proxmox.com/en/proxmox-virtual-environment/overview>
- [28] CloudStack <https://cloudstack.apache.org/>
- [29] Xen <https://xenproject.org/>
- [30] VMware <https://www.vmware.com/cloud-solutions.html>
- [31] Azure Stack Hub <https://azure.microsoft.com/ru-ru/products/azure-stack/hub>
- [32] IBM Cloud Private <https://www.ibm.com/docs/en/cloud-private/3.1.1?topic=started-cloud-private-overview>
- [33] Oracle Private Cloud Appliance <https://www.oracle.com/engineered-systems/private-cloud-appliance/>
- [34] Cisco CloudCenter <https://www.cisco.com/c/en/us/support/cloud-systems-management/cloudcenter/series.html>
- [35] Nutanix <https://www.nutanix.com/>
- [36] Openshift <https://www.redhat.com/en/technologies/cloud-computing/openshift>

Authors' Profiles



Mykhailo Khomchak received his Master of Applied Math degree from National Technical University of Ukraine “KPI”, Kyiv, Ukraine, 2010, currently is a Ph.D. scholar at the Faculty of Computer Science and Technology in the National Aviation University in Kyiv, Ukraine. He is Head of Development and Cloud Technology in Kyivstar.Tech Company subsidiary of Kyivstar PJSC (largest telco operator in Ukraine serving need of 24 mln customers). His research interests include Cloud Technology and Information Security.

How to cite this paper: Mykhailo Khomchak, "Enterprise Private Cloud Platforms: A Systematic Review of Key Vendors", *International Journal of Wireless and Microwave Technologies(IJWMT)*, Vol.14, No.4, pp. 1-14, 2024. DOI:10.5815/ijwmt.2024.04.01