2024 IEEE International Conferences on Internet of Things (iThings) and IEEE Green Computing & Communications (GreenCom) and IEEE Cyber, Physical & Social Computing (CPSCom) and IEEE Smart Data (SmartData) and IEEE Congress

2024 IEEE International Conferences on Internet of Things (iThings) and IEEE Green Computing & Communications (GreenCom) and IEEE Cyber, Physical & Social Computing (CPSCom) and IEEE Smart Data (SmartData) and IEEE Congress on Cybermatics | 979-8-3503-5163-7/24/$31.00 ©2024 IEEE | DOI: 10.1109/iThings-GreenCom-CPSCom-SmartData-Cybermatics62450.2024.00081

Low-Cost Green Computing-as-a-Service Testbed for SMEs: Leveraging AI and 6G for Enhanced Productivity

Mohammad N. Patwary[‡], Samiya Khan[†], and Syed Junaid Nawaz[§]

[‡] Faculty of Science and Engineering, University of Wolverhampton, Wolverhampton, WV1 1LY, UK.
[†] School of Computing and Mathematical Sciences, University of Greenwich, London, SE10 9LS, UK.
[§]Department of Electrical & Computer Engineering, COMSATS University Islamabad, Islamabad, Pakistan.

e-mail: *patwary@wlv.ac.uk*, *samiya.khan@greenwich.ac.uk*, and *junaidnawaz@gmail.com*

***Abstract*—The exponential growth in computing devices and the emergence of high-computing-dependent applications have led to a significant increase in energy demand. In response, this paper proposes the development of a novel green computing testbed aimed at addressing energy efficiency and sustainability in computing infrastructure. The testbed integrates highly energy-efficient computing infrastructure, a virtual machine-driven on-demand computing ecosystem, and Green AI model development as a service. The state-of-the-art 5G/6G infrastructure and services, such as ultra-low-latency communications, are investigated and identified as suitable for connecting the zero clients (with minimal capabilities) to remote computing and other facilities. Through a comprehensive measurement campaign, the testbed's energy efficiency and sustainability have been evaluated. This research presents a pioneering effort towards achieving sustainability in computing to support Small and Medium-sized Enterprises (SMEs) to enhance productivity with AI, with reduced cost, energy, and minimizing e-waste.**

***Index Terms*—6G, AI, computing-as-a-Service, green computing, testbed**

I. Introduction

The ubiquity of computing devices and the rise of high-computing-dependent applications have raised concerns about energy consumption and sustainability in the computing domain [1]. In response, this paper proposes the development of a green computing testbed that integrates energy-efficient infrastructure and innovative computing models. By addressing the energy efficiency and sustainability challenges, the proposed testbed aims at paving the way for a more sustainable future in computing.

The escalating demand for digital services has spotlighted concerns surrounding the energy consumption and environmental ramifications of data centres and telecommunication networks [2]. Data centres in the European Union (EU) consumed approximately 45–65 TWh of electricity in 2022, representing 1.8–2.6% of the region's total electricity consumption [3]. Notably, the top four data centre markets can be named as Germany, France, the Netherlands, and Ireland that collectively consumed about two-thirds of the region's data centre energy. Whereas, the telecommunication networks consumed an estimated 25–30 TWh of electricity, i.e., about 1–1.2% of total EU electricity consumption. Moreover, the largest member states by population and GDP, i.e., Germany, France, Italy, and Spain, were also reported as the primary energy consumers for telecommunication networks which accounted for about 65% of the total energy consumption.

A. Energy Consumption Landscape

The energy consumption landscape in the context of state-of-the-art emerging applications/use-cases such as Machine Learning (ML), Blockchain, cloud gaming, Internet-of-Things (IoT) – to name a few, is discussed in the following paragraphs.

a) Artificial Intelligence (AI) and Machine Learning (ML): The effectiveness of AI/ML methods heavily relies on the quality of the training data provided and the computational capabilities available. The training phase uses about 20–40% of the overall ML-related energy consumption [4]. Whereas, the inference (application/use) comprises 60–70% of energy use, with up to 10% for model development (experimentation). For instance, ChatGPT consumed around 4 GWh in January 2023, which is three times more electricity consumption than that used to train GPT-3. It is important to note that AI is reported to consume less than 0.2% of global electricity usage in 2021. ML accounted for 10–15% of Google's total energy use in recent years. ML compute demand at Meta has been observed to increase by over 100% per year, with overall data centre energy consumption growing about 40% per year. These statistics motivate the development of an AI-driven on-demand green computing framework.

b) Blockchain and Cryptocurrencies: Blockchain technology and cryptocurrencies represent another use case that demands significant processing capabilities. Bitcoin utilized around 95 TWh in 2022, which corresponds to 0.4% of global electricity usage [5]. Ethereum consumed around 18 TWh

DOI 10.1109/iThings-GreenCom-CPSCom-SmartData-Cybermatics62450.2024.00081
Authorized licensed use limited to: AISSMS's Institute of Info Technology - PUNE. Downloaded on January 22,2025 at 06:38:33 UTC from IEEE Xplore. Restrictions apply.

during the first three quarters of the year 2022. The energy consumption of cryptocurrencies globally was approximately 150 TWh in 2022.

c) Streaming Media and Cloud Gaming: The increasing quality and definition of streaming media and cloud gaming are promising future applications that require significant computational capabilities. Estimates for streaming video energy consumption vary widely, from 50 Wh per hour to 382 kWh for 35 hours of HD video. Cloud gaming can be up to 300% more energy-intensive than local gaming. Online gaming could consume 34 TWh in 2016 in the United States [6].

d) 5G and the Internet of Things (IoT): Mobile data traffic projected to triple between 2023 and 2028. Also, the advent of massive Machine-Type Communications (mMTC) in 5G is anticipated to drastically increase the number of connected devices. 5G's share of global mobile data traffic projected to rise to 70% by 2028 [7]. IoT adoption expected to reach 35 billion connections by 2028 [8]. Cellular IoT adoption is anticipated to double to 5.5 billion connections. Besides, 5G networks are expected to be more energy efficient than 4G networks, but their higher traffic volumes may increase overall energy and emissions.

B. Key Contributions

The key contributions of this research work are discussed in the following paragraphs.

a) Cost Measurement: The development of a testbed that provides a cost-effective solution for Small and Medium-sized Enterprises (SMEs) by reducing the need for individual hardware components through zero/thin client architecture is proposed. It leverages the centralized computing resources and virtualization, and suggests the minimization of upfront investment by SMEs in hardware procurement and maintenance. Additionally, it provides tools for accurate cost measurement, allowing SMEs to effectively track, manipulate, and optimize their AI-related expenses.

b) Energy Efficiency: With the focus on energy-efficient computing and eco-friendly end-user device ecosystem, the proposed testbed prioritizes energy efficiency as a key feature. Employing zero/thin client technology alongside High-Performance Computing (HPC) in the proposed testbed assists the SMEs to reduce their energy consumption. Besides, it also contributes to environmental sustainability by reducing the carbon emissions.

c) E-waste Reduction Benchmarking: The proposed testbed promotes reducing e-waste in SMEs by decreasing the requirement for standalone hardware components. This is achieved by promoting a centralized computing and virtualization framework, which reduces the generation of e-waste. Moreover, benchmarking tools are also provided to quantify as well as track the progress of e-waste reduction. This enables the SMEs to easily monitor their environmental impact and make appropriate decisions to further optimize it.

d) Productivity Enhancement: The proposed testbed aims at boosting productivity by addressing the main challenges that SMEs face when adopting AI. The proposal includes offering comprehensive training programs,access to external experts, and simplified AI deployment. This can help SMEs to fully use AI technologies to improve their processes, better manage their resources, and improve their decision-making. The testbed also offers tools and metrics to enhance productivity and to quantify the impact of AI initiatives for empowering SMEs to achieve sustainable growth and competitiveness in the market.

The rest of the paper is organized as follows: Sec. II presents the proposed testbed. Sec. III comprehensively presents the productivity gains through AI adoption in SMEs. Sec. IV concludes the paper.

II. Proposed On-Demand Green Computing-as-a-Service Testbed

This section describes the proposed testbed. The architecture of the proposed AI-driven low-cost and on-demand green computing-as-a-service testbed for SMEs is illustrated in Fig. 1. The end user devices with minimal capabilities (e.g., processing and storage), termed as Zero Clients (ZCs), can demand such capabilities as a network service through Ethernet, WiFi, or 5G/6G network connectivity. Such user device design with minimal capabilities promotes a reduction in device cost as well as the overall optimization of computations/processing in a centralized fashion to support energy-efficient green computing. The proposed AI-driven services classifier and provider extend the HPC and/or Graphics Processing Units (GPU) provisions available at the network edge/fog/cloud through minimal latency 5G/6G communication links. The prime connectivity scenarios are illustrated in Fig. 2 and 3. The key testbed components and associated gains are highlighted in Fig. 4. The objectives, development phases, productivity gains, e-waste reduction feasibility, carbon footprint, and measurement metrics are discussed as following subsections.

A. Objectives

The key objectives of the proposed testbed are enlisted as follows:

- Designing and implementing highly energy-efficient computing infrastructure.
- Selecting and optimizing hardware components for energy efficiency, including development of energy-efficient cooling solutions.
- Developing a virtual machine and wireless communication-driven on-demand computing ecosystem.
- Designing software frameworks and protocols for on-demand computing services.
- Evaluating the energy efficiency and sustainability of the testbed through a comprehensive measurement campaign. Conducting experiments to measure energy consumption

Authorized licensed use limited to: AISSMS's Institute of Info Technology - PUNE. Downloaded on January 22,2025 at 06:38:33 UTC from IEEE Xplore. Restrictions apply.

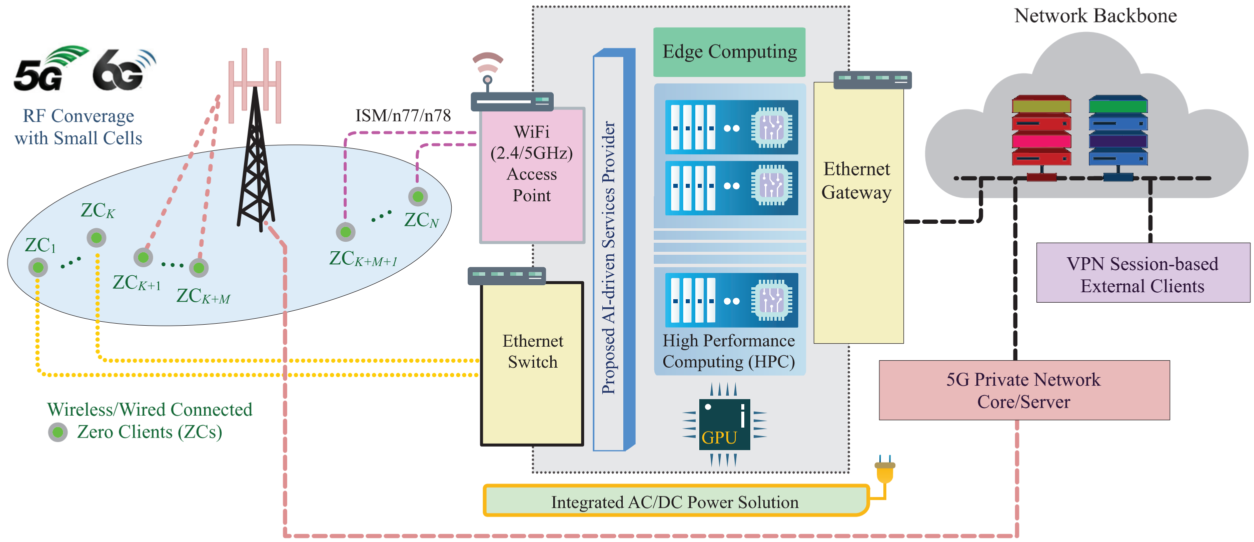

Fig. 1. Architecture of the Proposed AI-driven Green Computing-as-a-Service Testbed for Small and Medium-sized Enterprises (SMEs).

and assess the environmental impact of the proposed testbed.

B. Development Phases

The development of the proposed green computing testbed involves several key steps, which are described as follows:

- Step 1: Designing and implementing energy-efficient computing infrastructure
- Step 2: Selection of energy-efficient hardware components. This includes hardware components such as processors, memory modules, and storage devices selected and optimized for energy efficiency.
- Step 3: Optimization of power management strategies. Integration of renewable energy sources.
- Step 4: Developing a virtual machine and wireless communication-driven computing ecosystem. Designing virtualization software for on-demand computing.
- Step 5: Implementing wireless communication protocols for seamless connectivity. Integrating AI-driven resource allocation algorithms.
- Step 6: Evaluating the energy efficiency and sustainability of the testbed through a comprehensive measurement campaign. Benchmarking the testbed against existing computing infrastructure.

C. Logical session-based computing node formation

Considering our proposed testbed's focus on energy-efficient and eco-friendly computing and end-user device ecosystem, we are focusing on the adoption of ZC and thin client interfaces. ZC and thin clients are both energy efficient end-user devices that establish connections to a remote server and gain access to the centralized computing systems. However, ZCs are notably lighter as they lack an operating system, whereas thin clients possess a minimalistic operating system. When an end-user device requests a session, an AI-based system evaluates important factors such as the device's specifications, usage history, requested service, user behaviour (if available), available computing resources, and network capacity. Based on this assessment, a specific class of computing resources is allocated. These allocated resources are then assigned to the local zero-client node, functioning as a logical end-user computing device throughout the session. Key Performance Indicators (KPIs) for this logical computing device include connectivity reliability, session setup time, security, and virtual machine (VM) interaction speed.

Fig. 2. Connectivity Scenario 1

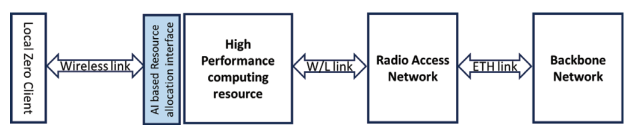

Fig. 3. Connectivity Scenario 2

Authorized licensed use limited to: AISSMS's Institute of Info Technology - PUNE. Downloaded on January 22,2025 at 06:38:33 UTC from IEEE Xplore. Restrictions apply.

III. Productivity Gains Through AI Adoption in SMEs

AI adoption presents significant opportunities for SMEs to enhance productivity and efficiency across various business sectors. Studies have indicated substantial potential for productivity growth associated with AI utilization, albeit with some distinctions compared to larger enterprises.

A. Quantifiable Productivity Increase

Research published in Sustainability in 2023 reveals that for every 1% increase in AI adoption, there is a corresponding 0.5% increase in firm productivity. While the productivity gains from AI tend to be higher for larger firms, SMEs can still realize substantial improvements through strategic AI implementation.

a) Catch-Up Potential for SMEs: A recent study published in the International Entrepreneurship and Management Journal in 2023 found that smaller firms operating at the productivity frontier can experience significant productivity gains by adopting AI technologies. This indicates that AI can play a crucial role in assisting SMEs to bridge their productivity gap with larger companies and hence ultimately enabling them to more effectively compete in the market.

b) Unrealized Productivity Benefits: The OECD's report highlights that despite there is a clear potential, the SMEs face several difficulties in AI adoption. This leads to unrealized productivity benefits. These difficulties include the lack of data culture, awareness, and necessary resources for effective AI implementation. Addressing these challenges is crucial for SMEs to fully capitalize the productivity-enhancement potential of AI.

By leveraging AI technologies tailored specifically to their needs, the SMEs can streamline their processes, optimize their resource utilization, and enhance their decision-making. This can ultimately lead to quantifiable productivity gains and improved competitiveness in the market.

B. Overcoming Challenges in AI Implementation for SMEs

To fully leverage the potential productivity gains offered by AI, SMEs are required to overcome various challenges associated with its implementation, requiring a multi-faceted approach. Firstly, fostering a data-driven culture and raising awareness of AI's benefits among managers and employees is paramount. This can be achieved through comprehensive training programs tailored to educate stakeholders on AI capabilities and use cases. Secondly, securing adequate resources, including funding and expertise, is essential. SMEs can explore cloud-based AI solutions to reduce capital expenditure and collaborate with external AI specialists to access necessary skills and resources. Demonstrating the business value of AI initiatives is another critical step, requiring SMEs to carefully evaluate Return On Investment (ROI) and start with small-scale pilots to showcase tangible benefits. Additionally, building AI expertise in-house through upskilling existing

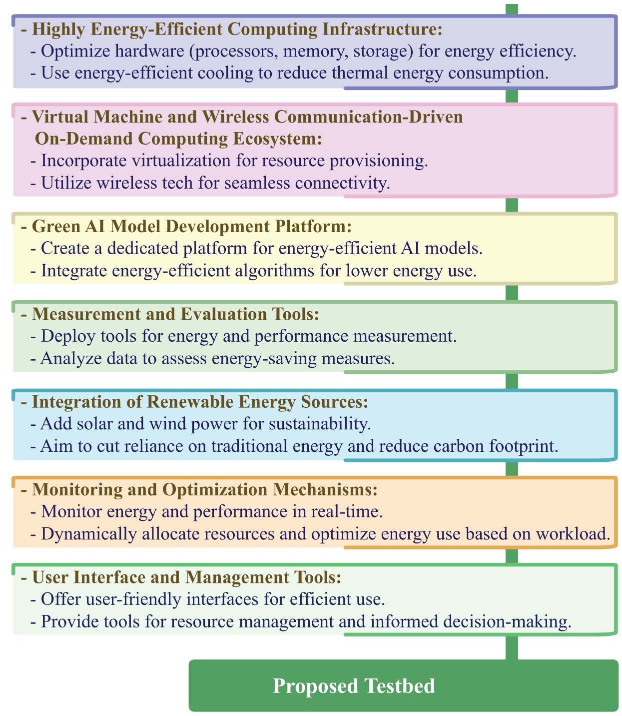

Fig. 4. Outline of testbed Components

employees and hiring AI specialists can facilitate smoother implementation. Ensuring robust data management practices and garnering top management support are also vital components of a successful AI adoption strategy. By adopting these comprehensive strategies, SMEs can effectively overcome the challenges of AI implementation and position themselves for sustained productivity growth.

C. Key Considerations in AI Solution Selection for SMEs

The SMEs are required to carefully consider all the related aspects such as their business objectives and operational requirements when choosing an AI solution. The following is a list of key considerations:

a) Customization and Scalability: It is critical for SMEs to prioritize potential AI solutions that can tailor functionalities to their business needs. Moreover, scalability is also crucial to support business demands for future growth and evolution.

b) Integration and Compatibility: It is essential to adopt those AI solutions that can be seamlessly integrated with the existing system and workflow within an SME. Compatibility with other software and technologies is also critical to ensure smooth implementation and operation.

c) Ease of Use and Implementation: The AI solutions that are user-friendly and require minimal technical expertise for the deployment and maintenance are suggested to be opted. Besides, detailed documentation and intuitive interfaces

Authorized licensed use limited to: AISSMS's Institute of Info Technology - PUNE. Downloaded on January 22,2025 at 06:38:33 UTC from IEEE Xplore. Restrictions apply.

TABLE I

CLASSES OF AI MODEL DEVELOPMENT TASKS FOR SMES

Class	Data Size	Computing Requirements	Training and Deployment	Example
Class I – Basic AI (straightforward tasks such as linear regression, logistic regression, or simple decision trees)	Upto 10 GB	Moderate CPU, occasional GPU for training	Quick and cost-effective	A simple AI model to analyze customer feedback for sentiment analysis using natural language processing (NLP)
Class II – Medium AI (sophisticated machine learning models such as random forests, SVMs, or basic neural networks)	50-100 GB	Frequent GPU usage for model training	Requires moderate resources and tuning	A medium complexity model that uses machine learning to recommend products based on user history and behavior.
Class III – Advanced AI (deep learning models with multiple layers, which are computationally intensive and data-hungry)	Over 100 GB (large datasets, potentially hundreds of GB to TBs)	High-end GPUs or Tensor Processing Units (TPUs)	Extensive and costly, requiring significant computational resources	A complex AI model utilizing deep learning to detect fraudulent transactions in real-time.
Class IV – LLM	Extremely large, often terabytes of textual data	High-end GPU or TPU for training and CPU for inference.	Extremely high cost, complex infrastructure needs, and significant time investment	Example 1 - An LLM-based chatbot that answers frequently asked questions and handles customer inquiries on a company website. Example 2 - An LLM for generating high-quality, original content for blogs, reports, and marketing materials.

TABLE II

SUMMARY OF CLOUD PROVIDERS

Cloud Provider	Services	Benefits	Cost
Amazon Web Services (AWS)	Comprehensive suite of AI services, including SageMaker for easier model development and deployment, EC2 instances for flexible compute capacity, and specific GPU instances like the P4 and G4 families.	Extensive integration with other AWS services, strong security features, and a large community with extensive documentation and support.	AWS charges based on the resources consumed. Prices for GPU instances vary for basic GPU capabilities, scaling upwards based on the instance type and additional features.
Google Cloud Platform (GCP)	AI and machine learning services through AI Platform, Compute Engine, and specific GPU and TPU resources. TPUs are particularly optimized for TensorFlow.	Deep integration with TensorFlow, innovative TPU offerings for faster computations, and strong data handling and analytics capabilities with BigQuery.	Similar to AWS, the cost depends on usage, with GPU instances. TPUs can be more expensive but offer high performance for TensorFlow-based models
Microsoft Azure	Azure Machine Learning for model management and deployment, and a range of VM types including GPU-based VMs for intensive compute tasks.	Good integration with Microsoft products and services, which is beneficial for enterprises using the Microsoft ecosystem extensively.	Pricing is competitive with AWS and Google, with GPU-enabled VMs.

facilitate the adoption process and utilization across the organization.

d) Affordability and Total Cost of Ownership (TCO): It is recommended for SMEs to carefully evaluate the Total Cost of Ownership (TCO), including upfront, maintenance, and training costs/expenses. Choosing a cost-effective solution that can ensure a measurable value over time is essential for maximizing the ROI.

e) Data Management and Security: It is important for SMEs to ensure that the opted AI solution adheres to robust data management practices and complies with relevant privacy regulations. Data security and privacy assurance measures, such as encryption and access control, are imperative to protect sensitive information.

f) Support and Training Resources: It is recommended to search for such AI solution providers that offer comprehensive support services, including training, technical support, and troubleshooting. Access to reliable support resources enhances the SME's ability to exploit the full potential of the AI solution.

g) Vendor Reputation and Reliability: It is important to carefully evaluate the reputation of the under-consideration AI solution providers in serving SME clients. References, case studies, and customer testimonials can provide valuable insights into the vendor's reliability and commitment to customer satisfaction.

Authorized licensed use limited to: AISSMS's Institute of Info Technology - PUNE. Downloaded on January 22,2025 at 06:38:33 UTC from IEEE Xplore. Restrictions apply.

TABLE III
COST COMPARISON (CALCULATED USING COMPUTING COST PER HOUR AND STORAGE COST PER MONTH

	AWS Sagemaker	**Google AI Platform**	**Azure Machine Learning**
I	$3.778	$4.25	$2.78
II	$22.58	$34.8	$28.8
III	$915.76	$222.00	$270.8
IV	$33,111.8	$4,240	$14,544

By carefully considering all the discussed factors, SMEs can make informed decision for selecting an AI solution that matches with their objectives and requirements.

D. Cost Comparison

The SMEs that aim to develop Artificial Intelligence (AI) models have a range of computing requirements depending on the complexity and scale of their AI projects. On the basis of computing requirements, AI model development for SMEs can be categorized into four classes, which are detailed in Table I. Large Language Model (LLMs) are typically characterized by their vast number of parameters, deep architectures, and immense training data requirements. Therefore, they often necessitate specialized hardware and substantial financial investment, especially for training from scratch. It is because of these reasons that LLM development has been considered separate from AI model development because of its distinctive features. However, for many SMEs and even larger organizations, the practical approach often involves leveraging pre-trained models through cloud providers or specialized services, rather than training from scratch, to mitigate these extensive requirements.

There are several cloud service providers in the market. However, some of the most popular options are included in Table II. A use case-based cost analysis to provide understanding of the financial and operational impacts of implementing these technologies is presented in Table III. The cost is calculated for Amazon Sagemaker [9, 10], Google AI Platform [11–14] and Azure Machine Learning [15, 16]. It is worth noting that the cost structures assume constant utilization of the resources for the duration specified and the current pricing as described. Moreover, the costs could vary with different usage patterns, specific regional pricing, any applicable discounts, or changes in pricing policies by the cloud providers. The proposed testbed aims to beat the costing offered by existing service providers. For instance, the cost for Class I AI applications is $1.22 for the proposed testbed.

E. Carbon Footprint of Intel Processors in General

- Intel's total greenhouse gas emissions were 1.54 million metric tons of CO2 equivalent in 2022, down from 3.27 million tons in 2015.
- The carbon footprint of a single Dell PowerEdge R240 server with an Intel processor (i3 processor) was estimated at 5,260 kgCO2e, with 22% from manufacturing and 77% from usage over a 4-year lifecycle [17].
- Larger, more powerful Dell servers with Intel processors had an estimated carbon footprint of up to 13,300 kgCO2e, with 85% from manufacturing [17].
- Transitioning to ARM-based servers can reduce the carbon footprint by around 35% compared to equivalent Intel-based instances [18].

F. E-waste reduction feasibility from the testbed

E-waste, short for electronic waste, encompasses any discarded electronic product powered by a plug or battery. This category includes items like televisions, computers, mobile phones, and home appliances. As technology advances and consumer demand for electronic devices increases, the volume of e-waste generated has surged rapidly, making it one of the fastest-growing waste streams globally. If left unaddressed, projections suggest that e-waste generation could double by 2050, reaching alarming levels.

The disposal of e-waste presents multifaceted environmental challenges. Electronic products often contain hazardous substances such as mercury, cadmium, and lead, alongside valuable non-renewable resources like gold, silver, and copper. When improperly discarded in landfills, these hazardous materials can seep into the soil and groundwater, posing significant environmental and health risks. Additionally, the informal recycling practices prevalent in many developing countries further exacerbate these issues, as they involve the use of harmful chemicals to extract precious metals, leading to pollution and health hazards, particularly for vulnerable populations.

The proposed testbed by integrating zero/thin client technology with HPC offers a viable solution to mitigate e-waste and contributes positively to environmental preservation. Adopting zero/thin client architecture significantly reduced the need for individual hardware components. Such clients rely on centralized computing resources, which leads to minimization of the requirements for standalone devices and subsequently extends the lifespan of the computing equipment.

Through virtualization and HPC capabilities, the testbed enables efficient and scalable computing processes, particularly for resource-intensive tasks like AI model development and training. By consolidating computing resources in a centralized infrastructure, the testbed reduces the overall number of physical devices required, consequently decreasing e-waste generation. Additionally, the centralized management facilitated by virtualization streamlines server lifecycle management, further optimizing resource utilization and minimizing unnecessary hardware replacements.

The employment of zero/thin client technology with HPC offers a sustainable approach for computing-intensive tasks. It significantly cuts down on electronic waste and boosts computing power and scalability. This solution helps protect the environment by reducing e-waste and shows promise in

Authorized licensed use limited to: AISSMS's Institute of Info Technology - PUNE. Downloaded on January 22,2025 at 06:38:33 UTC from IEEE Xplore. Restrictions apply.

TABLE IV
KEY TECHNICAL SPECIFICATION OF THE TESTBED.

Technical Features	Phase 1	Phase 2
CPU/Core	16/64	50/200
GPU	94GB	640GB
Backbone network capacity	1Gbps	10-20Gbps
RAM	32GB/CPU	32GB/CPU
Memory	24TB	100TB
Connectivity (Client to HPC)	Band n77, n78 (5G) and ISM (Wi-Fi)	5G+/6G
Connectivity (HPC to Backbone)	Ethernet (ETH)	ETH/PCIe
Connectivity reliability	100.00%	100.00%
Session establishment delay	Up to 3-sec	Up to 2-sec
Security	Bank grade	Bank grade
Zero client-VM interaction delay	100ms	100ms
End to end communication delay	10ms	100micro sec

supporting efforts to contribute to environmental preservation efforts.

IV. DISCUSSION

There are several testbeds available for SMEs, which include recently proposed technology-specific testbeds [19, 20] and traditional testbeds such as Grid'5000 and GENI [21, 22]. In comparison to existing systems, the proposed testbed's focus on Green AI model development and energy-efficient virtual machine management differentiates it from its counterparts. The use of zero clients to minimize local computing power and energy consumption is a unique feature that enhances the sustainability and practicality of the testbed for SMEs.

Moreover, existing testbeds are primarily focused on and cater to research communities without a specific focus on SMEs. The current proposition stands out by focusing on cost-effectiveness and establishing as well as maintaining standards concerning application-specific environmental impact. Lastly, although existing solutions offer network research capabilities, the emphasis of the proposed testbed on ultra-low-latency 5G/6G connectivity for zero clients is a novel aspect.

The long-term impact of the testbed on SMEs includes reduced operational costs, enhanced productivity, and a reduced environmental footprint. By providing energy-efficient computing infrastructure, SMEs will be able to leverage advanced technologies at reduced costs without compromising on environmental sustainability. This can also lead to increased market competitiveness, innovation, and technology-led growth in the SME sector.

One of the key challenges in the development of such testbeds is to devise them as scalable. As the demands (e.g., infrastructure and resources) for high-computing applications grow, the testbed must be scalable to accommodate multiple zero clients and virtual machines. This can be promised by providing a robust infrastructure to handle peak loads without any degradation in the performance. To ensure a promising trade off between between energy efficiency and efficient resource allocation and management, advanced orchestration tools/techniques will be required. In the context of the reliance on 5G/6G infrastructure for connectivity between zero clients and remote computing facilities, the limited availability of 5G/6G infrastructure in certain regions can affect both the scalability and overall performance.

Future research directions include the integration of the testbed with emerging technologies such as AI-driven automation and edge computing to provide state-of-the-art capabilities and services. As industries evolve and new use cases and applications are identified, the testbed should be advanced to adapt to the advancements in AI and support state-of-the-art communication protocols, including integration with technologies such as the Internet-of-Things (IoT) and blockchain. Moreover, another promising future research direction is to ensure the flexibility to adapt to the changing industrial needs for the testbed's long-term success. Future work also includes advocating for policy and regulatory support to promote green computing practices. This includes incentives for adopting energy-efficient technologies, standards for sustainable computing, and funding for research and development in green computing.

V. CONCLUSION

To address the increasing demands for high processing capabilities at a low cost and with high energy efficiency, a green computing-as-a-demand testbed has been proposed in this paper. An AI-driven network service provider has been proposed that extends the provisions of HPC and GPU processing capabilities to the end users as a network service by exploiting the low-latency 5G/6G communication links. The testbed has provisioned the advantages of low-cost and energy-efficient device design, state-of-the-art 5G/6G connectivity, high processing capabilities furnished at the network access points such as HPCs, GPUs, edge/fog/cloud computing, and overall optimized energy-efficient eco-friendly framework. Various useful insights have been provided that can assist in realizing the computing-as-a-service framework to enhance productivity and move toward a greener future.

Authorized licensed use limited to: AISSMS's Institute of Info Technology - PUNE. Downloaded on January 22,2025 at 06:38:33 UTC from IEEE Xplore. Restrictions apply.

References

[1] M. N. Patwary, S. Junaid Nawaz, M. A. Rahman, S. K. Sharma, M. M. Rashid, and S. J. Barnes, "The potential short- and long-term disruptions and transformative impacts of 5G and beyond wireless networks: Lessons learnt from the development of a 5G testbed environment," *IEEE Access*, vol. 8, pp. 11 352–11 379, 2020.

[2] R. Buyya, S. Ilager, and P. Arroba, "Energy-efficiency and sustainability in new generation cloud computing: A vision and directions for integrated management of data centre resources and workloads," *Software: Practice and Experience*, vol. 54, no. 1, pp. 24–38, 2024.

[3] G. Kamiya, P. Bertoldi *et al.*, "Energy consumption in data centres and broadband communication networks in the EU," *Publications Office of the European Union*, 2024.

[4] L. H. Kaack, P. L. Donti, E. Strubell, G. Kamiya, F. Creutzig, and D. Rolnick, "Aligning artificial intelligence with climate change mitigation," *Nature Climate Change*, vol. 12, no. 6, pp. 518–527, 2022.

[5] S. Ferrey, "Cryptocurrency—legally navigating the "highway to climate hell"," *UC Law Environmental Journal*, vol. 30, no. 1, p. 25, 2024.

[6] E. Mills, N. Bourassa, L. Rainer, J. Mai, A. Shehabi, and N. Mills, "Toward greener gaming: Estimating national energy use and energy efficiency potential," *The Computer Games Journal*, vol. 8, pp. 157–178, 2019.

[7] S. J. Nawaz, S. K. Sharma, B. Mansoor, M. N. Patwary, and N. M. Khan, "Non-coherent and backscatter communications: Enabling ultra-massive connectivity in 6G wireless networks," *IEEE Access*, vol. 9, pp. 38 144–38 186, 2021.

[8] H. Shanmuganathan and A. Mahendran, "Current trend of IoT market and its security threats," in *Proc. of International Conference on Innovative Computing, Intelligent Communication and Smart Electrical Systems (ICSES)*. IEEE, 2021, pp. 1–9.

[9] Amazon Web Services, "Amazon sagemarker pricing," 2024, accessed May 1, 2024. [Online]. Available: https://aws.amazon.com/sagemaker/pricing/

[10] ——, "Amazon EBS pricing," 2024, accessed May 1, 2024. [Online]. Available: https://aws.amazon.com/ebs/pricing/

[11] Google, "Google developer," 2024, accessed May 1, 2024. [Online]. Available: https://download.huihoo.com/google/gdgdevkit/DVD1/developers.google.com/compute/pricing/index.html

[12] Google Cloud - 1, "Google GPU pricing," 2024, accessed May 1, 2024. [Online]. Available: https://cloud.google.com/compute/gpus-pricing

[13] Google Cloud - 2, "Google TPU pricing," 2024, accessed May 1, 2024. [Online]. Available: https://cloud.google.com/tpu/pricing

[14] Google Cloud - 3, "Disk and image pricing," 2024, accessed May 1, 2024. [Online]. Available: https://cloud.google.com/compute/disks-image-pricing

[15] M. 1, "Windows virtual machines pricing," 2024, accessed May 1, 2024. [Online]. Available: https://azure.microsoft.com/en-in/pricing/details/virtual-machines/windows/

[16] M. 2, "Azure blob storage pricing," 2024, accessed May 1, 2024. [Online]. Available: https://azure.microsoft.com/en-in/pricing/details/storage/blobs/

[17] D. Mytton, "Carbon footprint – laptops vs servers, Intel vs ARM," Online, Dec. 2022. [Online]. Available: https://davidmytton.blog/carbon-footprint-laptops-vs-servers-intel-vs-arm/

[18] R. Bruggemann, "Goodbye intel, we reduced our carbon footprint," Online, Sep. 2021. [Online]. Available: https://lune.co/blog/goodbye-intel-hello-lower-carbon-future

[19] P. Li, I. Mavromatis, and A. Khan, "Past, present, future: A comprehensive exploration of ai use cases in the umbrella iot testbed," *arXiv preprint arXiv:2401.13346*, 2024.

[20] S. Roedel, F. Kobzik, M. Peterhansl, R. Poeschl, and S. Kunze, "5g stand-alone test bed for craft businesses and small or medium-sized enterprises," in *International Congress on Information and Communication Technology*. Springer, 2023, pp. 131–141.

[21] A. Angi, A. Sacco, E. Alberti, G. Marchetto, and F. Esposito, "Rlvna: a platform for experimenting with virtual networks adaptations over public testbeds," in *2023 IEEE International Mediterranean Conference on Communications and Networking (MeditCom)*. IEEE, 2023, pp. 406–411.

[22] J. Gomez, E. F. Kfoury, J. Crichigno, and G. Srivastava, "A survey on network simulators, emulators, and testbeds for research and education," *Computer Networks*, vol. 237, p. 110054, 2023.

Authorized licensed use limited to: AISSMS's Institute of Info Technology - PUNE. Downloaded on January 22,2025 at 06:38:33 UTC from IEEE Xplore. Restrictions apply.