

University parallel computing micro-cluster build with second-hand computer systems

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Abstract. *This article presents an innovative approach to build a parallel computing micro-cluster for educational and research purposes at New Bulgarian University by using second-hand server systems. The project demonstrates how refurbished hardware can provide significant computational power for physics simulations and scientific research at a fraction of the cost of new equipment. The article details the selection, upgrading, and integration of used computers, and discusses the benefits, challenges, and educational value of this sustainable solution. The micro-cluster supports advanced research and hands-on learning, promoting both technological innovation and resource efficiency in a university setting.*

Keywords – *Parallel computing, Second-hand computers, Micro-cluster.*

Университетски паралелен изчислителен микро-кълъстер, изграден с компютърни системи втора употреба (Георги Петров, Росен Пасарелски, Красен Ангелов) В статията е представен иновативен подход за изграждане на микро-кълъстер за паралелни изчисления в Нов български университет чрез използване на компютърни системи втора употреба. Проектът показва как обновеният хардуер може да осигури значителна изчислителна мощ за симулации и научни изследвания на много по-ниска цена в сравнение с нова техника. Описани са процесите по избор, обновяване и интегриране на използваните компютри, както и предимствата, предизвикателствата и образователната стойност на този устойчив подход. Микро-кълъстерът подпомага научните изследвания и практическото обучение, насърчавайки технологичните иновации и ефективното използване на ресурси в университетската среда.

Ключови думи – *паралелни изчисления, компютри втора употреба, микро-кълъстер*

Introduction

The exponential growth of data-driven scientific inquiry, particularly in disciplines such as physics and semiconductor, fluid dynamics, research, has precipitated an ever-increasing demand for computational resources capable of supporting large-scale simulations, modeling, and data analysis. High-performance computing (HPC) has become indispensable in enabling researchers to conduct complex experiments, process vast datasets, and explore phenomena that are otherwise inaccessible through conventional means. However, the acquisition and maintenance of modern HPC infrastructure pose significant financial challenges, especially for academic institutions operating within limited budgets [1].

To address this issue, the Department of Telecommunications at New Bulgarian University has explored a novel and sustainable approach: the reusing of second-hand computer systems to construct parallel computing micro-clusters. This strategy is predicated on the premise that refurbished server hardware, when strategically selected, upgraded, and integrated, can deliver substantial computational power at a fraction of the cost of new, state-of-the-art equipment. Such micro-clusters offer a viable and pragmatic solution for meeting the computational requirements of advanced physics [2] simulations and related scientific research.

This article systematically examines the technical and economic feasibility of employing second-hand hardware for the development of HPC micro-clusters

in an academic context. It presents detailed methodologies for hardware selection, system refurbishment, cluster assembly, and hypervisor configuration, complemented by performance benchmarking and comparative analysis with conventional solutions. By presenting empirical results and case studies, the research clarifies the benefits and limitations of this approach, highlighting its potential to democratize access to computational resources in higher education.

Furthermore, the adoption of technology reuse and circular economy principles aligns with global sustainability goals, contributing to the reduction of electronic waste and promoting responsible resource management. The integration of pre-owned systems into scientific computing workflows not only advances the frontiers of computational physics but also fosters a culture of innovation, adaptability, and environmental management within the academic community.

System Description

The development of the micro-cluster is an integral component of the larger research initiative, *“Study of Processes Induced by Radiation and Chemical Reactions Occurring at Various Temporal and Spatial Scales: Technological Applications.”* The primary objective of this undertaking is to establish an accessible and economically viable computational infrastructure, tailored for experimental and educational research activities, with a particular emphasis on laser technologies and related scientific domains like computational fluid dynamics.

The resultant architecture comprises a 10-node computing cluster (see Fig. 1), designed to deliver robust computational capabilities required for contemporary scientific investigations. This infrastructure enables the efficient deployment, customization, and execution of a wide array of research software. Educational researchers benefit from the system’s flexibility, which supports the rapid prototyping, modification, and benchmarking of specialized applications pertinent to both foundational and applied scientific studies.

In addition to facilitating ongoing research efforts, the cluster serves as a developmental platform for the optimization and validation of scientific software

destined for deployment on larger, commercial-scale high-performance computing (HPC) systems. The cost-effectiveness and modularity of the micro-cluster not only bolster the university’s research capacity but also stimulate innovation and foster technological progress in fields where advanced computational resources are indispensable.

Through this integration of affordability, scalability, and adaptability, the micro-cluster enhances the institution’s ability to support multidisciplinary research and hands-on training, ultimately contributing to the advancement of both scientific discovery and computational education.



Fig.1. 10 Node NBU Micro Cloud Installed

Setup of Servers and Software Defined Network

The hardware infrastructure is organized within a single rack comprising a total of 11 servers (see Fig. 2, block diagram). Notably, two servers (Srv_09 and Srv_10) are engineered for high-performance tasks, equipped with 64 GB of RAM each and a combined storage capacity of 1.2 TB. This storage is provisioned via three 2.5” SAS 3.0 drives per server, configured in a RAID 5 array to ensure both data redundancy and fault tolerance, thereby maintaining data integrity and high performance.

To further enhance computational capabilities, the cluster incorporates eight Nvidia Quadro M4000 GPUs, significantly boosting the general-purpose GPU (GP-GPU) resources available for parallel processing. This balanced hardware setup ensures that the system can efficiently manage a broad spectrum of computational workloads, from demanding scientific simulations to less intensive educational tasks.

The flexible server architecture allows for the streamlined deployment and execution of research software, fostering an environment conducive to the development and optimization of scientific applications intended for larger, commercial-scale clusters.

By accommodating a diverse array of computational needs, the system empowers researchers and students to experiment with novel algorithms and methodologies, thereby driving innovation in parallel computing and maximizing the utility of available hardware resources.

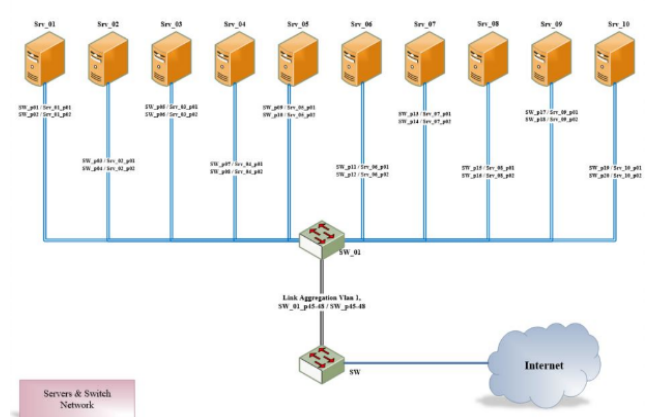


Fig.2. Block Diagram of Servers & Switch Network

System Configuration

This project establishes a robust and secure network architecture within a 10-node Xen server cluster by deploying OPNsense for VLAN segmentation and firewall management. Logical partitioning through VLANs [3] isolates network traffic, significantly enhancing security and reducing exposure to vulnerabilities. OPNsense provides advanced firewall features, including granular traffic filtering and real-time intrusion prevention, which collectively reinforce network protection. This configuration not only safeguards inter-server communication but also ensures efficient resource utilization and offers scalability for future expansion and customization.

Network Architecture

The network architecture was systematically designed by defining VLANs and establishing a structured IP addressing scheme, enabling logical segmentation tailored to specific connectivity and security requirements. The configuration process involved setting up VLAN interfaces across Xen

server nodes and integrating OPNsense as the primary firewall solution. OPNsense was deployed to enforce granular security policies, control access, and protect sensitive data, while its flexible rule management [4] ensures secure inter-VLAN communication.

Comprehensive testing and ongoing optimization were performed to validate firewall performance, optimize configurations, and monitor network traffic for potential threats. This approach not only enhances security—providing robust protection against unauthorized access and malware—but also improves bandwidth management and overall resource utilization. The infrastructure’s scalability allows for the seamless addition or modification of VLANs and firewall rules as network demands evolve, ensuring compliance with industry security and privacy standards.

OPNsense was selected for its open-source nature, extensive feature set, and proven reliability in previous deployments. Its support for multiple VPN protocols (IPsec, OpenVPN), advanced traffic shaping (QoS), and integrated Intrusion Detection and Prevention System (IDPS) provide comprehensive network protection. The intuitive web interface further facilitates management and configuration, making it an effective educational tool for students studying network security, administration, and IT management. By engaging with OPNsense, learners gain practical experience with firewall configuration, VPN deployment, and real-time network monitoring.

Virtualization Solutions for Education

The cluster infrastructure incorporates a variety of advanced firewall and virtualization technologies to ensure network security, flexibility, and a rich educational environment.

pfSense is an open-source, FreeBSD-based firewall platform widely used for its flexibility, advanced routing, VPN support (IPsec, OpenVPN), load balancing, and integrated intrusion detection (Snort, Suricata). It allows granular control over network traffic and is an excellent tool for learning real-world network security concepts.

Sophos XG Firewall offers centralized management and comprehensive next-generation security features, including application control and threat intelligence. Its intuitive interface makes it suitable for both professional environments and advanced educational use.

Untangle NG Firewall integrates firewall, VPN, and content filtering in a user-friendly package. It is ideal for educational labs and training in network management and security, with features for traffic monitoring, reporting, and policy enforcement.

Systems like Snort, Suricata, Bro/Zeek, and Security Onion allow students and researchers to experiment with real-time network traffic analysis, anomaly detection, and incident response, deepening their understanding of cybersecurity. XCP-ng is an open-source hypervisor built on the Xen Project, enabling flexible management of virtual machines and network configurations. It supports advanced features such as high availability, clustering, and live migration, making it suitable for both research and practical training.

Compared to alternatives like VMware ESXi, Proxmox VE, and KVM, XCP-ng offers an optimal balance between openness, feature set, and scalability for educational HPC environments. Through the integration of these technologies, students and faculty can design, deploy, and test real-world network and virtualization scenarios, fostering practical skills in secure, high-performance computing environments.

Hardware-Dependent Software Platforms and Educational Integration

The cluster's software environment is carefully tailored to leverage hardware acceleration and modern parallel programming models for both research and teaching purposes. A particular focus is placed on GPU virtualization technologies, primarily utilizing the NVIDIA Compute Unified Device Architecture (CUDA) platform. CUDA [5], along with open standards such as OpenCL, enables the efficient exploitation of GPU resources for parallel computing in scientific simulations, image processing, and heterogeneous system programming. These frameworks support a wide range of architectures, including GPUs, CPUs, (attempt to incorporate place for FPGA online resources support is in progress incorporating several Cologne Chip AG boards for encryption algorithms educational purposes), making them highly suitable for advanced computing courses and multidisciplinary research projects.

To further broaden the scope of instruction and future-proof the cluster, plans are underway to implement AMD's open-source ROCm (Radeon Open

Compute Platform). This will provide additional tools and libraries for GPU acceleration, facilitating hands-on experience with diverse high-performance computing (HPC) ecosystems.

On the CPU side, the educational curriculum is enhanced through intensive training in multi-core programming with Intel Xeon processors. Key concepts such as parallelism, concurrency, and optimization are addressed through the use of industry-standard development tools, including Intel Parallel Studio, Threading Building Blocks (TBB), and OpenMP. Students develop and profile parallel applications, gaining real-world skills in scientific computing, data processing, and performance tuning. The program is complemented by collaborative research opportunities, workshops with industry experts, and participation in programming competitions. This holistic approach ensures that graduates are well-prepared for careers in technology, equipped with both theoretical knowledge and practical expertise in high-performance and heterogeneous computing.

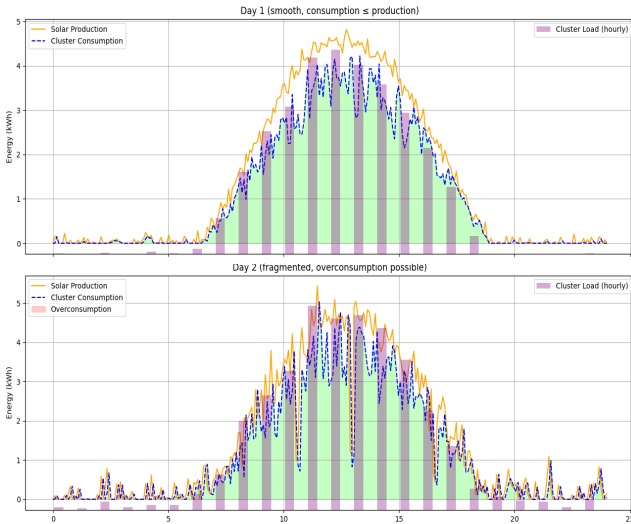
Connection Between Second-Hand Computers and Solar Battery Integration

Integrating second-hand computers with solar energy systems and battery storage creates an efficient and sustainable solution for educational micro-clouds. Leveraging pre-owned hardware significantly reduces capital and maintenance costs for university IT infrastructure, while solar panels and batteries provide a reliable, renewable power source that minimizes reliance on conventional energy and lowers operational expenses.

Although legacy computer architectures typically consume 30–70% (per G-FLOPS) more energy than modern systems, their deployment becomes economically and environmentally viable when paired with smart scheduling and adaptive energy management. By aligning computational workloads with periods of peak solar generation and utilizing battery storage to buffer fluctuations—such as cloud cover or shading—universities can maximize renewable energy utilization, minimize carbon emissions, and maintain stable cluster operations.

The simulation is augmented with real solar system extra production data (Fig. 3) illustrates these dynamics: the orange curve shows hourly solar

production, while the blue curve represents cluster consumption, including periods where generation drops by 50% due to cloud interruptions. Adaptive energy management [6] enables the micro-cluster to adjust activity in real time, ensuring efficient operation even when solar availability varies [7]. This approach not only supports sustainable development goals and reduces overall IT costs, but also provides valuable educational opportunities [8]. Students gain hands-on experience with concepts such as circular economy, green IT, resource optimization, preparing them for future challenges in technology and sustainability. The advanced 10-node HPC cluster at New Bulgarian University exemplifies this model. By combining virtualization (XCP-ng), GP-GPU acceleration, and robust security (IDS, firewalls like OPNsense), the project delivers a practical, scalable,



and secure research and platform.

Fig.3. Cluster Operation Profile — Solar Power, Energy Consumption, and Computational Activity per Hour

Intelligent Energy-Aware HPC Scheduling: Mathematical Model

To enhance the sustainability and efficiency (1) of the university's micro-cloud infrastructure, we propose a formal energy-aware scheduling (2) model that aligns the operation of the HPC cluster with the real-time availability of solar power and battery storage. The goal is to dynamically manage computational workloads based on energy constraints (1), thereby minimizing dependency on grid power

and extending battery autonomy, especially during partial irradiance or night-time periods.

Power Balance Equation (for each time step t):

$$(1) \quad P_s(t) + P_{bdis}(t) + P_g(t) = P_c(t) + P_{bchg}(t)$$

Battery constraints:

$$P_{bdis}(t) \geq 0$$

$$P_{bchg}(t) \geq 0$$

Battery state update:

$$B(t+1) = B(t) + (P_{bchg}(t) - P_{bdis}(t)) * \Delta t$$

Battery capacity limits:

$$B_{min} \leq B(t) \leq B_{max}$$

Cluster state variable:

$$S(t) \in \{0, 1\} \quad (1 = \text{ON}, 0 = \text{OFF})$$

Cluster power consumption:

$$P_c(t) = S(t) * P_{cmin} + P_{gpu}(t)$$

Cluster activation policy:

If $P_s(t) + P_{bdis}(t) \geq P_c(t)$, then $S(t) = 1$ (cluster ON)

Otherwise $S(t) = 0$ (cluster OFF)

Objective Function (Min Grid Energy Usage):

$$(2) \quad \min \sum_{(t)} P_g(t) * \Delta t$$

Abbreviations:

P_s — Solar power generation

P_{bdis} — Battery discharge power

P_{bchg} — Battery charge power

P_g — Grid power consumption

P_c — Cluster power consumption

B(t) — Battery state of charge (SoC) at time t

B_{min} — Minimum battery capacity

B_{max} — Maximum battery capacity

S(t) — Cluster state (1 = ON, 0 = OFF)

P_{gpu} — GPU power consumption

Δt — Time step duration

W_i — Task i

Intelligent Energy-Aware HPC Task Management and Scheduling

As an engineering innovation, this project proposes a system model for real-time management and scheduling of HPC workloads based on predicted and measured solar energy availability, campus activity, and environmental conditions. By leveraging historical data, weather forecasts, and live cloud monitoring using surveillance camera, computational tasks can be dynamically prioritized, delayed, or throttled—maximizing the use of renewable energy while ensuring operational reliability (Fig. 4). This intelligent, data-driven approach provides a sustainable and practical solution for optimizing energy usage [9] in university high-performance computing clusters.

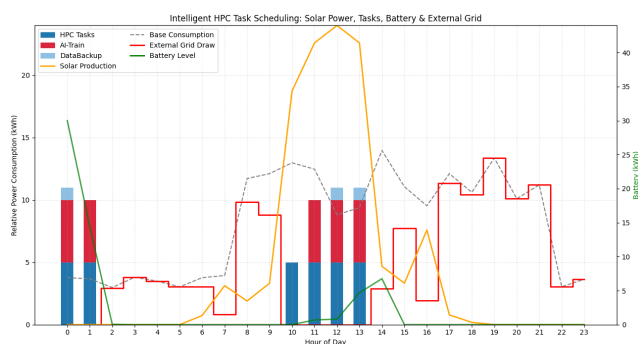


Fig.4. Simulation of Intelligent Energy-Aware HPC Scheduling

The model simulates intelligent scheduling of HPC tasks in a cluster that relies primarily on solar energy and battery storage. It takes into account hourly variations in solar production, reduced energy consumption at night and during lunch breaks, and sudden drops in solar output due to cloud cover [10]. HPC tasks are executed based on priority, while non-critical tasks such as data backup are scheduled only when surplus energy is available. The graph illustrates the hourly distribution of energy use among the different tasks (as stacked bars), baseline consumption, and the moments when additional power must be drawn from the external grid.

Summary and Comparative Analysis

The presented work from New Bulgarian University explores a cost-effective and sustainable approach to building a high-performance micro-cluster using second-hand hardware, solar power, and battery storage. The system is designed to support computationally intensive tasks (including GPU-accelerated simulations) while dynamically adjusting its operation based on available solar energy.

The model integrates simple real-time energy-aware scheduling to extend runtime during peak production hours and conserve power during low-generation periods.

Compared to existing initiatives, the NBU cluster offers a unique blend of:

- Hardware reuse to reduce capital cost and e-waste
- Educational integration of virtualization, GPU computing, and cybersecurity
- Simplified, transparent scheduling using solar surplus thresholds
- Local monitoring and adaptability, including cloud coverage detection via surveillance camera

Comparative Overview of Related Projects

- The proposed system at New Bulgarian University shares key objectives with several international initiatives focused on integrating solar energy into academic and HPC computing environments. Below is a brief comparison of the most relevant projects:

ICARUS (Euro-Par 2016)

The ICARUS project presents a modular and energy-efficient HPC platform powered entirely by solar energy, utilizing Jetson embedded boards and a 7.5 kWp rooftop photovoltaic (PV) array [11]. The design emphasizes low-power ARM architectures and containerized deployment, aiming to reduce the environmental footprint of edge and HPC applications in remote or constrained environments. While ICARUS demonstrates the feasibility of solar-powered HPC with a strong emphasis on mobility and embedded efficiency.

In contrast, the NBU cluster leverages refurbished enterprise-grade x86 hardware, including Intel Xeon processors and Nvidia Quadro GPUs, enabling significantly higher computational throughput. Moreover, the system integrates general-purpose GPU to support complex simulations in physics, fluid dynamics, and scientific modeling — workloads typically beyond the capabilities of embedded systems. Unlike ICARUS, which is primarily focused on standalone edge HPC applications, the NBU model supports both academic research and teaching, offering a scalable, semi-autonomous infrastructure for virtualization labs.

A further point of distinction lies in the emphasis on circular economy: the NBU cluster is constructed entirely from second-hand hardware, significantly lowering capital expenditure while aligning with sustainability principles.

Ruddick et al. (2022)

Ruddick and colleagues proposed an evolutionary optimization framework for scheduling university activities—such as lectures, laboratory sessions, and administrative operations—based on forecasted renewable energy availability and campus consumption trends [12]. Their approach integrates artificial intelligence techniques with predictive models to align institutional energy use with solar production.

While the Ruddick model is institution-wide and focuses on macro-level scheduling for building energy management, the NBU system takes a more focused, task-level approach, targeting energy-aware scheduling within a localized high-performance computing (HPC) cluster. Specifically, the NBU implementation dynamically regulates the execution of CPU and GPU workloads according to real-time solar energy surplus, battery state, and system thresholds. Instead of rescheduling physical activities or facilities usage, the NBU system prioritizes and throttles computational tasks—such as GPU simulations or student-driven virtualization experiments—based on power availability.

This distinction underscores the different scopes and objectives of the two systems: Ruddick et al. optimize institutional operations at the facility scale, while the NBU cluster provides a modular, scalable solution for sustainable scientific computing, particularly in academic environments with constrained budgets.

Habib et al. (2016)

In their study on the University of California, San Diego campus, Habib et al. developed a model predictive control (MPC) framework for demand-side load management based on short-term solar energy forecasts [13]. Their system dynamically scheduled electrical loads—such as HVAC, lighting, and lab equipment—by anticipating solar generation patterns, weather variability, and grid interaction costs. The MPC algorithm continuously adjusted operational states to optimize energy efficiency and minimize

reliance on external power sources, contributing to campus-wide sustainability goals.

Compared to this sophisticated, forecast-driven control model, the NBU micro-cluster applies a simplified yet educationally effective scheduling strategy. When solar power plus battery output exceeds predefined limits (e.g., 9 kW for full operation), the cluster executes GPU-intensive jobs; under lower availability, it switches to energy-saving or CPU-only modes. This rule-based logic reduces system complexity, making it ideal for academic settings where real-time interpretability, cost efficiency, and ease of student engagement are critical.

Additionally, while Habib's work is rooted in commercial building automation and smart grid integration, the NBU cluster uniquely combines sustainable energy with circular computing. Its reliance on refurbished server hardware, combined with educational use cases (e.g., teaching GP-GPU programming, network security, and virtualization), exemplifies a low-cost, high-impact model of green IT adoption. The system thus bridges the gap between theoretical control methods and practical, scalable implementations in resource-constrained university environments.

Possible Challenges and Limitations

One of the main drawbacks of using second-hand hardware is its higher energy consumption compared to modern systems, which can also result in lower long-term reliability. Additionally, the article does not provide a detailed analysis of the maintenance and repair costs associated with older machines—an important factor when considering the overall cost-effectiveness of such an approach (*we trust on second hands free parts*). Finally, to ensure the broader applicability and sustainability of this model, a more in-depth evaluation of its long-term economic and environmental benefits [1] is needed.

Conclusion

This study demonstrates that combining second-hand computer hardware with solar energy and battery storage provides a highly effective and sustainable framework for university micro-cloud computing. The simulation results underscore the importance of dynamic energy management, especially in the face of fluctuating solar production due to weather variability. Beyond its technical and economic benefits, this

approach offers substantial educational value—preparing students to engage with current challenges in sustainable development. This work highlights the potential of circular economy principles and innovative energy strategies to foster both environmental responsibility and technological advancement within higher education.

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