# Sustainable-HPC: toward Digital Twin for active management of self-cooled data centers with Renewable Energy Sources and waste heat recovery

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***Abstract*— High-performance computing (HPC) data centers are key for advancing research and industry, but their high energy consumption and environmental impact pose critical sustainability challenges. Few HPC centers currently use renewable energy sources, particularly hydrogen-based storage, or integrate waste heat reuse. Recently, Digital Twins (DTs) are proving crucial for advancing sustainable HPC centers, enabling the integration of advanced monitoring and energy optimization with renewable energy sources. They simulate operations, predict maintenance needs, balance workloads, and support renewable integration for enhanced efficiency.**

**The paper first reviews current practices, focusing on the potential of DTs to improve HPC sustainability by dynamically managing resources and optimizing systems, including cooling, power distribution, and load balancing. Then, it illustrates the University of Turin's Sustainable HPC4AI (S-HPC4AI) project, which aims to develop a low impact HPC center to support Artificial Intelligence (AI) research across diverse scientific fields. The facility will feature renewable energy sources, advanced self-cooling, and waste heat recovery, setting a benchmark for energy-efficient, low-carbon HPC infrastructure. Central to the project is the integration of hydrogen and solar energy, with photovoltaic systems providing clean power and hydrogen fuel cells serving as reliable backup sources, reducing reliance on fossil fuels. Waste heat can be transformed into a productive resource for a local automated phenotyping system, reducing energy consumption and environmental impact on the overall. Furthermore, a DT will be developed, integrating BIM with sensors data about performance, resource usage and operating conditions, enabling real-time monitoring and predictive analytics for managing power, cooling, and energy resources. The potential and challenges of the S-HPC4AI model are discussed, suggesting possible solutions.**

***Keywords*— *Data center, HPC, DT, sustainability, efficiency, BIM, liquid cooling, hydrogen, RES, monitoring***

## I. INTRODUCTION

In recent years, data centers are increasing infrastructure due to the significant rise in the adoption of AI and Machine Learning (ML), and the consequent high performance computational requirements of workloads execution [1, 10]. Indeed, HPC data centers are the backbone of modern research and industry, enabling advancements in AI, scientific simulations, and big data analytics.

According to the literature, a DC can be defined as a physical space where computers, servers, IT components and storage devices work together in a network system [2]. With the increasing computational demand, its expected to evolve over time, improving in infrastructure, dimensions, equipment and technologies [3, 11]. Due to the complexity of this system, DC operators and designer, have to face several challenges, mainly dealing with temperature control, power usage and energy demands management, and physical space design [2].

Furthermore, focusing on the data centers needs and the recent overall government restrictions for the energy use, cooling system and energy management become key topics in the DC domains [4, 11]. Indeed, energy-consumption is one of the most significant issues and its high demand is expected to increase through time [4]. Consuming elements in DC can be identified in the system components, in the cooling system and in the power distribution network [5], amounting to the 90% of the DC energy comsumption [6]. A critical parameter lies in the Power Usage Effectiveness (PUE) ratio which considers the overhead power, relating the energy consumption of the IT equipment with the one entering the data center. [4,6,7]. In DCs, PUE values should state near the value of 1 but it usually has a value of 2, or 1.2 in the state of the art [4].

The operation of HPC data centers accounts for a substantial share of global electricity use and greenhouse gas emissions. Amid growing concerns about climate change and environmental degradation, the demand for more energy-efficient and sustainable HPC systems has never been more urgent. The DCs energy consumption leads them to be great CO2 emission producers, so new advances in technology exploitation to reduce CO2 emissions, energy cost and consumption should be pursued [6].

The challenge lies in balancing the need for high computational power with environmental responsibility. Current HPC facilities largely rely on fossil fuels, and very few integrate renewable energy sources, such as solar or hydrogen-based systems, or adopt innovative approaches like waste heat reuse to mitigate their environmental footprint. Moreover, advancement in Renewable Energy Sources (RES), enhances the environmental perspective, leading to the concept of Green Data Center (GDC), which integrates conventional power supply with RES solutions [8]. RES such as photovoltaic (PV) and hydrogen-based fuel cell systems (FCS), promise to improve the DC sustainability, thanks to the low costs and the clean energy production [6]. According to RES integration, it can be supplementary, supporting the main power system, or stand-alone, completely satisfying the energy demand. A third option includes the possibility of generating an exceeded amount of energy, but it is feasible only for small and simple DC [6]. However, usually RES can rarely supply all the energy demand, so the integration is the most adopted solution [8]. Besides the PUE, other parameters such as the Green Energy Coefficient (GEC), the Energy Reuse Factor (ERF), and the Carbon Usage Effectiveness (CUE) should be considered in the renewable energy adoption [6].

Recently, DTs have emerged as transformative technology in this context. A DT is a digital replica of a physical system that continuously collects real-time data to simulate, monitor, and optimize the system's performance with a bidirectional link between the physical world and the virtual model. So, a DT for DC (DTDC) should provide a virtual replica of the physical environment in both structure and behaviour, enabling predictive activities, supporting the decision-making process for data center optimization. DT potential lies in representing a complex system as the DC in a virtual environment. [2,3], enabling scenario-based simulations and real-time monitoring. Data centers components usually feature communication interfaces providing real time data exchange [3] enabling the connection to the physical DC in a bidirectional information exchange [1]. For HPC centers, DTs offer a promising solution to address sustainability challenges. They enable real-time monitoring of resource usage, predictive analytics for energy management, and seamless integration of renewable energy sources, thereby enhancing efficiency and reducing emissions. Moreover, thanks to the dynamics of technology, the DT can be exploited for energy consumption simulation aimed at introducing saving strategies [5], supported by IoT and sensing devices, useful for data center's monitoring and management [3].

The paper explores the potential of DTs in sustainable HPC practices, focusing on the University of Turin's S-HPC4AI project, which aims to develop a low-impact HPC center, leveraging RES and advanced cooling systems. By integrating DTs with cutting-edge energy solutions, the S-HPC4AI project can set a benchmark for future energy-efficient, low-carbon HPC infrastructures.

## II. CURRENT PRACTICES IN SUSTAINABLE HPC

### A. *Energy Savings Strategies*

DC energy-saving strategies can be supported by AI enabling an automated, scalable and adaptable data control approach [5].

According to [6] energy saving strategies can be pursued by three different approaches:

- Traditional: focusing on air flows optimization strategies and cooling system empowerment with possible issues in complex DC.
- AI based: deep learning algorithms can be exploited to identify high consumption events and teach the system to adapt consequently. As a result, resources usage can be optimized and consumption lowered, with possible issues in the training phases.
- Supported by DT: a DT can be created to measure PUE, generate statistics on DC performance, state and consumption, enabling automation in mitigation strategies and DC intelligent management.

### B. *Data Center Cooling System*

The 40% of the DC energy consumption is usually demanded by the cooling system [7] which is key to ensure DC operations at the right temperature, and guarantee correct heat dissipation [1,4,5]. Indeed, activities on cooling efficiency improvement and redundancy reduction should be pursued [5, 13]. Furthermore, DCs can change over time due to the advancement of technologies and the need for new components, so the infrastructure and the cooling system need to be modular and flexible [4]. [4] identifies two types of cooling systems: related to air conditioning, controlling ventilation and air flow, or exploiting fluid-jacket contact. In the HPC4AI project [9], the first commercial prototype of evaporative two-phase cooling was applied for a high-power density GPU-enabled server, which can dissipate up to 1000W per socket. This two-phase cooling is more efficient than state-of-the-art liquid cooling, and uses green dielectric gas which prevents damage when a pipe breaks. So, pipes work at low pressure and can be thin and cheap.

### C. *Renewable Energy in HPC*

Despite the environmental challenges posed by HPC centers, only a limited number have adopted renewable energy solutions. Solar panels, wind turbines, and hydrogen fuel cells are technically viable options, but their implementation in HPC is constrained by factors such as energy intermittency, storage costs, and infrastructure limitations. A notable example of renewable energy adoption in HPC is represented using solar energy at the National Renewable Energy Laboratory (NREL) in the United States which operates a solar-powered data center, demonstrating effective integration of renewable energy, though its fixed design limits scalability and flexibility [14]. Similarly, Iceland's geothermal-powered HPC facilities showcase the potential of localized, renewable energy resources but remain constrained by geographical availability [15]. However, these cases remain exceptions rather than the standard and most HPC facilities still rely on grid electricity, predominantly sourced from fossil fuels. This dependence highlights the urgent need to overcome technical, economic, and policy barriers to integrate renewable energy sources more effectively into HPC operations. Several initiatives have explored sustainable solutions for high-performance computing (HPC).

### *D. Waste Heat Reuse in HPC Centers*

Another underutilized opportunity for sustainable HPC practices is the reuse of waste heat. HPC systems generate significant amounts of heat during operation, often requiring energy-intensive cooling systems to maintain optimal temperatures. Instead of discarding this heat, it can be repurposed for applications such as district heating, greenhouse farming, or industrial processes.

For instance, the Lefdal Mine Data Center in Norway channels waste heat to nearby industries, significantly improving energy efficiency. However, the implementation of heat reuse systems requires careful planning, robust infrastructure, and coordination with external stakeholders, which can complicate their adoption.

### *E. Role of Digital Twins in Resource Optimization*

Digital Twins have proven instrumental in addressing the limitations of traditional energy management [5] in HPC. There are several applications of DTDCs that enable operators:

- Monitor and forecast energy consumption, enabling real-time mitigations operation, thanks to bidirectional communication protocols (Athavale 2024).
- Predict maintenance needs and prevent system failures (Zhu 2024), Athavale 2024).
- Optimize workload distribution to minimize energy use. Indeed, DC performance evaluation and optimization scenario simulation can also be performed, both with the thermal control and cooling strategies implementation. (Athavale 2024)
- Facilitate the seamless integration of renewable energy sources.

Moreover, the implementation of AI systems enables real-time data analysis and elaboration for past insight and future predictions. The application of ML algorithms can provide empowered analysis and predictions based on real-time data, according to the granularity of the measurement timestamp. [1]. These capabilities not only enhance the efficiency of HPC centers but also reduce their carbon footprint, making DTs a cornerstone of sustainable HPC practices.

In this context, some challenges can be identified in data, technologies and tools interoperability, while the DT construction can result in difficult information exchange definition, data granularity representation and DT user interaction [1].

Opportunities can be highlighted in the field of predictive scenarios for proactive maintenance, energy management and cooling systems improvement. Moreover, the use of a digital replica for scenario-based simulation can reduce costs and resources on testing related to implementation strategies, services verification, and DC conditions monitoring [1].

## III. A CASE STUDY: THE S-HPC4AI PROJECT

The Sustainable High-Performance Center for Artificial Intelligence (S-HPC4AI) project is an innovative initiative led by the University of Turin to address the environmental challenges associated with HPC and AI. The project aims to establish a next-generation laboratory designed to minimize the ecological footprint of AI applications across diverse fields, including biological sciences, food production, chemistry, bioinformatics, socioeconomics, and medicine. This ambitious effort aligns with the global sustainability goals, focusing on developing energy-efficient and environmentally conscious computational infrastructures.

At the heart of this initiative there is the construction of an advanced data center at the new science campus in Grugliasco, a municipality located in the west of Turin. This facility will serve as a hub for testing innovative technologies, including experimental cooling methods to optimize energy use, recover and reuse heat generated by computing systems, integrating RES with robust storage mechanisms [13]. The data center aims to achieve operational efficiency and focuses on modularity to enable configuration flexibility, and scalability to meet evolving technological demands.

Building upon the successful HPC4AI [9], the S-HPC4AI laboratory will explore cutting-edge methods and solutions up to pre-commercial development stages. This continuity leverages the existing expertise and infrastructure while introducing new dimensions, such as the full digitalization using Building Information Modeling (BIM) and DT technologies [12]. These tools can be exploited to enhance the precision and efficiency of data center management and operations, ensuring a holistic approach to sustainability.

The project prioritizes reducing the carbon footprint of HPC systems through various strategies. One key focus is maximizing the efficiency of cooling systems, incorporating advanced techniques like two-phase and adsorption cooling, which rival the performance of current state-of-the-art direct liquid cooling systems. Additionally, the data center aims to repurpose waste heat for agricultural and food-related applications, showcasing a commitment to circular energy use. Hydrogen-based energy storage systems will also be tested as a sustainable solution for ensuring operational continuity.

Another critical component of the project is the modular design of the data center. The facility will use low-carbon construction materials and feature flexible, independent modules that can be expanded, reduced, or reconfigured based on specific requirements. Each module will operate as a self-contained computing island, accommodating different power, cooling, and security needs while maintaining overall system efficiency and reliability. The modular infrastructure will also allow for experimentation with new technologies without disrupting the performance or safety of other modules.

The data center will meet Tier-III certification standards, ensuring redundancy of energy and heat distribution systems. This design guarantees almost uninterrupted operations, even during maintenance or partial system shutdowns, thus enhancing its suitability for mission-critical applications and ensuring reliability and security.

Another crucial aspect relates to the modularity and high reconfigurability of the new S-HPC4AI. At this aim, the power will be distributed via crossbars in the ceiling, with maximum flexibility in the rack PDUs connection. It will host 16 racks each equipped with PDUs monitoring the lad at the phase level, and servers are connected to balance out the load.

The project also addresses the emerging challenges of confidential computing in AI systems that increasingly operate in distributed environments, such as energy-efficient edge and mobile networks. Ensuring data privacy, system security, and decision-making autonomy is crucial in these contexts. The S-HPC4AI laboratory will experiment with solutions to enhance these aspects, focusing on applications that demand minimal energy consumption while maintaining robust performance.

The S-HPC4AI project represents a bold step toward achieving sustainable high-performance computing. By combining innovative technologies, modular design principles, and a commitment to reducing ecological impact, the initiative sets a new benchmark for environmentally conscious computing infrastructure. It also underscores the importance of collaboration between academia, industry, and policymakers in driving transformative advancements in the field.

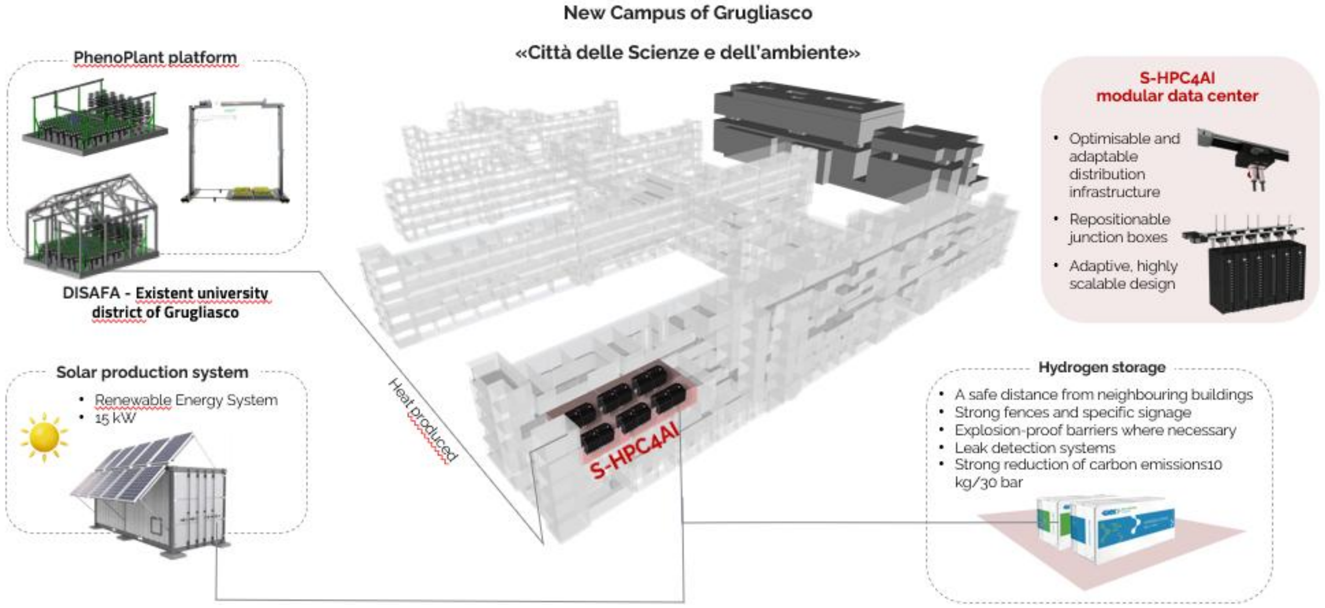

Figure 1 – Layout of the positioning and operation plan of the new S-HPC4AI in the BIM model of the building on the new campus of Grugliasco

Focusing more specifically on the solutions and technologies to be implemented in the new data center, three primary strategies can be highlighted: using RES, reusing waste heat generated by the data center, and advanced energy storage systems. Regarding the energy supply, it is a crucial point to the project as it represents a growing concern due to the increasing global demand for energy, driven by the widespread adoption of cloud and AI solutions by companies and institutions. The new S-HPC4AI will be located in a building on the new Grugliasco campus (Figure 1) and it will occupy approximately 300-400 sqms, structured as follows and as shown in Figure 2:

- Space A: rack space of approximately 200 m², air-conditioned and acoustically insulated main area, prepared to accommodate 16-20 reconfigurable racks of 10-40 kW. Installation of floating floors for cabling and cooling ducts.
- Space B: Space of approximately 50 sqm for UPS batteries, separate and ventilated, complying with safety regulations for the containment of high-performance batteries.
- Space C: Welcome center of about 40-50 sqm, access area with physical separation from the technical area to improve security and access control.
- Space D: Staging area of approximately 40-50 sq m separating Space C from Spaces A and B
- Space E: Meeting/training area of approximately 60 sq m, soundproofed room seating 20, with audiovisual systems, suitable for educational activities and presentations.

The energy supply through renewable sources will be ensured by a solar power generation system with a capacity of approximately 15 kW. This photovoltaic system will serve as the primary RES for the facility, providing a steady supply of clean energy while reducing dependence on non-renewable power sources. To address fluctuations in solar energy production, the system will be integrated with advanced energy storage technologies, ensuring uninterrupted operational continuity even during periods of reduced sunlight or increased energy demand. The decision to implement this solar energy system reflects the project's commitment to environmental sustainability, as it directly contributes to reducing the DC overall carbon footprint. Additionally, it underscores the importance of promoting energy self-sufficiency as a key principle in designing modern HPC facilities.

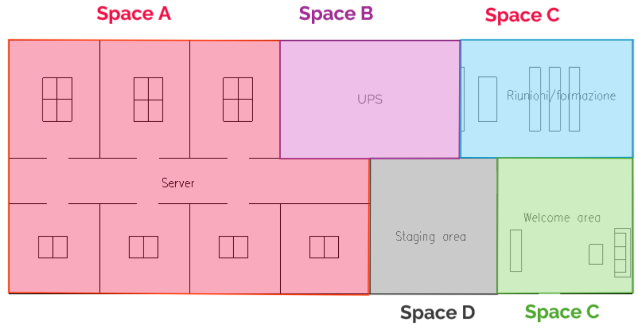

Figure 2 – approximate outline of the spaces of the new S-HPC4AI

A particularly innovative feature of the project involves recovering and reusing heat generated by the data center's computational systems. This waste heat will be redirected to experimental greenhouses (Figure 1) as part of the **PhenoPlant** initiative led by the Department of Agricultural, Forestry and Food Sciences (DISAFA) at the University of Turin. PhenoPlant is dedicated to studying and optimizing plant growth under controlled environmental conditions, representing an ideal application for recovered thermal energy. Advanced heat pumps will be installed to facilitate the collection, transfer, and repurpose of this energy, enabling the greenhouses to maintain optimal conditions for plant growth while minimizing external energy input. A crucial point is the connection between the data center and the greenhouse through pre-insulated pipes for heat transport, such as PEX or steel pipes with polyurethane insulation. It is also planned to install HDPE ducts to protect fiber optic cables to connect the DC’s IT system and the Phenotyping platform. This approach addresses energy efficiency and highlights the potential for creating synergies between digital technologies and agricultural practices. By integrating waste heat recovery into the data center’s design, the project contributes to a circular economy model, where resources are reused, and energy waste is minimized. This collaboration also showcases the versatility of HPC infrastructures in supporting interdisciplinary research. Repurposing waste heat not only improves the overall energy efficiency of the data center but also minimizes its environmental impact, setting a precedent for sustainable HPC practices.

Another key technological advancement of the project lies in the low pressure hydrogen-based storage (approximately 7 kg of hydrogen stored at 30 bar, 90 KW/h of stored energy), without the need for a hydrogen compression unit, to optimize and reduce safety constraints (Figure 1). It is designed with a storage capacity supplemented by an electrolyzer for hydrogen production and a 10 kW fuel cell for energy conversion. This setup ensures efficient energy generation, storage, and utilization, making it a cornerstone of the facility’s energy management strategy, and provides a sustainable and reliable energy backup for the data center in case of long power interruptions. Shorter interruptions are faced by UPS powering. In accordance with current safety regulations, the hydrogen storage infrastructure will be located in a protected area that complies with safety distances from other facilities, as per fire regulations and specifications for hydrogen storage, situated safely from surrounding buildings and equipped with explosion-proof barriers in critical locations to ensure safety. Moreover, the system will include state-of-the-art hydrogen leakage detection mechanisms to identify potential risks in real-time, alongside dedicated fencing and warning signage to restrict access and ensure compliance with safety protocols. These measures are crucial to maintaining operational security while showcasing hydrogen technology as a viable component of next-generation energy systems. This activity, along with those of monitoring and optimising the performance and consumption of the new S-HPC4AI, will be enhanced by the exploitation of a DT, developed starting from the DC's BIM model. It will be supported by the installation of IoT sensor networks and actuators that allow real-time intervention when deviations from the expected behaviour, failures or anomalies occur.

By combining RES, waste heat recovery, and hydrogen storage, the S-HPC4AI exemplifies an innovative approach to sustainable high-performance computing with low environmental impact, potential great resources optimization through circular economy strategies. It establishes a model for future data centers aiming to balance high performance with reduced ecological impact. The project embodies a forward-looking vision where cutting-edge technology, sustainability, and interdisciplinary collaboration converge to address some of the most pressing challenges in energy and computational science today.

## IV. DIGITAL TWIN FOR SUSTAINABLE HPC

As mentioned, the S-HPC4AI project aims also to develop a DT of the DC for real-time monitoring and optimization of its operations. It aims to ensure optimal internal conditions and energy performance, avoiding overheating and malfunctioning, and preventing dangerous situations or resources waste.

The first step concerns the consolidation of all the necessary data and information into a virtual replica, facilitating effective management. At this aim, the BIM model of the DC will be developed and data about indoor conditions will be verified against real-time data. The digital model will serve as a critical tool for simulating the energy performance of the system, including the DC’s interaction with the building and the indoor conditions where the servers are housed. Controlling the heat generated by the DC is crucial to maintain optimal temperature and humidity levels for the electrical equipment while efficiently removing excess heat to promote energy savings. In the modeling process, key activities should emphasize precise dimensioning, thermal zoning, and alignment with real-world conditions to ensure reliability.

The DT will exploit BIM integrated with sensor data to create a comprehensive digital representation of the facility. Analytical interactive dashboards will also be developed to provide a user-friendly interface for monitoring, with alerts in case of anomalies or failures and emergencies. This enables operators to easily monitor key performance indicators, such as energy consumption, cooling efficiency, and resource utilization, in real time. It also facilitates predictive analytics, enabling proactive maintenance and dynamic system adjustments to optimize performance.

The DT for S-HPC4AI offers several advanced features, in:

- Energy Management: dynamic allocation of power resources to balance workloads and minimize energy use.
- Cooling Optimization: real-time adjustments to cooling systems based on operational conditions and performance data.
- Renewable Integration: Seamless integration of solar and hydrogen-based energy sources to ensure uninterrupted operation.

These functionalities not only enhance the efficiency of the S-HPC4AI facility but also demonstrate the transformative potential of DTs in sustainable HPC practices.

Despite its potential, the implementation of sustainable HPC practices faces significant challenges. One of the primary obstacles is the high upfront cost associated with deploying renewable energy systems and waste heat recovery infrastructure, which can be financially prohibitive for many organizations. Additionally, the technical complexities involved in integrating DT technology with existing data center operations pose a barrier, as it requires advanced expertise and seamless interoperability between legacy and modern systems. Another critical issue is the limited availability of skilled personnel capable of managing and maintaining advanced energy systems, which can hinder the effective adoption of sustainable practices.

To address these challenges, the S-HPC4AI project emphasizes the importance of leveraging public-private partnerships to secure funding for renewable energy initiatives, enabling wider adoption of sustainable energy solutions. Furthermore, the project advocates significant investment in workforce training programs to cultivate the expertise necessary for implementing and managing sustainable HPC systems effectively. Furthermore, it would be valuable to focus on the development of standardized protocols that facilitate the integration of DT technology and streamline sustainability monitoring processes, currently absent. These strategies collectively aim to mitigate the challenges and pave the way for scalable and efficient sustainable HPC practices.

## V. COMPARISON WITH EXISTING SOLUTIONS

HPC facilities across the globe are exploring sustainable practices, and comparing initiatives helps highlight the distinctive advantages of the S-HPC4AI project. For instance, the National Renewable Energy Laboratory (NREL) in the United States operates a solar-powered data center that effectively utilizes renewable energy. This facility demonstrates the feasibility of integrating solar energy into HPC operations, but its design lacks modularity, which limits scalability and flexibility for adapting to future technological advancements [14]. On the other hand, Iceland has leveraged its abundant geothermal energy resources to power HPC centers, creating a model of sustainable energy usage. However, this approach is geographically constrained and may not be easily replicated in regions without access to similar geothermal resources [15].

In contrast, the S-HPC4AI project introduces an innovative combination of hydrogen-based energy storage and DT technology, providing a uniquely scalable and adaptable solution. The integration of hydrogen storage ensures a reliable backup power supply while reducing dependence on fossil fuels. Furthermore, the use of DTs enhances operational efficiency by enabling real-time monitoring, predictive analytics, and seamless integration of renewable energy sources. These capabilities position S-HPC4AI as a benchmark for future HPC facilities aiming to achieve both sustainability and high performance [1].

Additionally, the modular design enables its infrastructure to evolve alongside technological advancements. Unlike the fixed setups of NREL’s and Iceland’s centers, the modularity of S-HPC4AI allows for experimentation with cutting-edge technologies without disrupting ongoing operations. This flexibility not only ensures long-term relevance but also reduces the overall lifecycle cost of the data center. The project focuses on combining multiple sustainability strategies: solar energy, hydrogen storage, and DT-driven optimization, and provides a holistic approach to achieving energy efficiency while minimizing environmental impact.

By comparing these initiatives, it becomes evident that S-HPC4AI can set a new standard for sustainable HPC design. While other facilities have made strides in integrating renewable energy, the comprehensive and adaptable approach of S-HPC4AI addresses a wider range of challenges, offering a model that can be implemented in diverse geographical and technological contexts. The lessons learned from this benchmarking process underscore the importance of innovation and adaptability in the pursuit of sustainable high-performance computing solutions.

## VI. CONCLUSION AND FUTURE DIRECTIONS

The S-HPC4AI project represents a significant evolution in the design and operation of sustainable HPC centers. By integrating renewable energy sources, such as hydrogen-based storage and photovoltaic systems, alongside advanced cooling mechanisms, waste heat recovery, and DT technology, the project demonstrates the feasibility of achieving high computational performance with a substantially reduced environmental footprint. These innovations directly address the pressing challenges of excessive energy consumption and carbon emissions, setting a new benchmark for sustainable HPC infrastructure.

The transformative potential of DT technology within the S-HPC4AI framework is particularly notable. With capabilities such as real-time monitoring, predictive analytics, and optimization, DTs enable unprecedented levels of operational efficiency and sustainability. These features not only facilitate the seamless integration of renewable energy sources but also enhance the reliability and resilience of the data center. Furthermore, the project’s emphasis on modularity and adaptability allows for the continuous incorporation of emerging technologies, ensuring its long-term relevance and cost-effectiveness.

Compared to other initiatives, such as the solar-powered data center at the National Renewable Energy Laboratory (NREL) and Iceland’s geothermal-powered HPC facilities, S-HPC4AI offers a more comprehensive and flexible solution. While NREL’s center effectively integrates renewable energy, it lacks the modularity required for scalable adaptation. Similarly, Iceland’s geothermal approach is geographically limited, making it less universally applicable. In contrast, S-HPC4AI’s innovative combination of hydrogen storage and DT technology addresses these limitations, offering a replicable model that balances sustainability with high performance.

Despite its advancements, the widespread adoption of such sustainable practices requires overcoming significant barriers, including high initial costs, technical complexities, and a shortage of skilled personnel. Future research must focus on reducing the costs of renewable energy technologies, developing standardized protocols for DT integration, and expanding workforce training programs to ensure successful implementation. Additionally, exploring next-generation technologies, such as quantum computing and AI-driven energy management systems, could further enhance the sustainability of HPC operations.

S-HPC4AI’s commitment to circular economy principles, exemplified by waste heat recovery for agricultural applications, highlights the broader societal impact of sustainable HPC solutions. By repurposing excess heat and optimizing resource use, the project fosters interdisciplinary collaboration and extends the benefits of HPC technologies beyond computing.

In conclusion, the S-HPC4AI project serves as a model for the future of sustainable high-performance computing. By embracing innovation, adaptability, and collaboration, it paves the way for HPC centers worldwide to achieve greater energy efficiency, reduced environmental impact, and enhanced operational resilience. The project underscores the critical role of advanced technologies, such as DTs and renewable energy integration, in driving sustainable HPC practices.

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