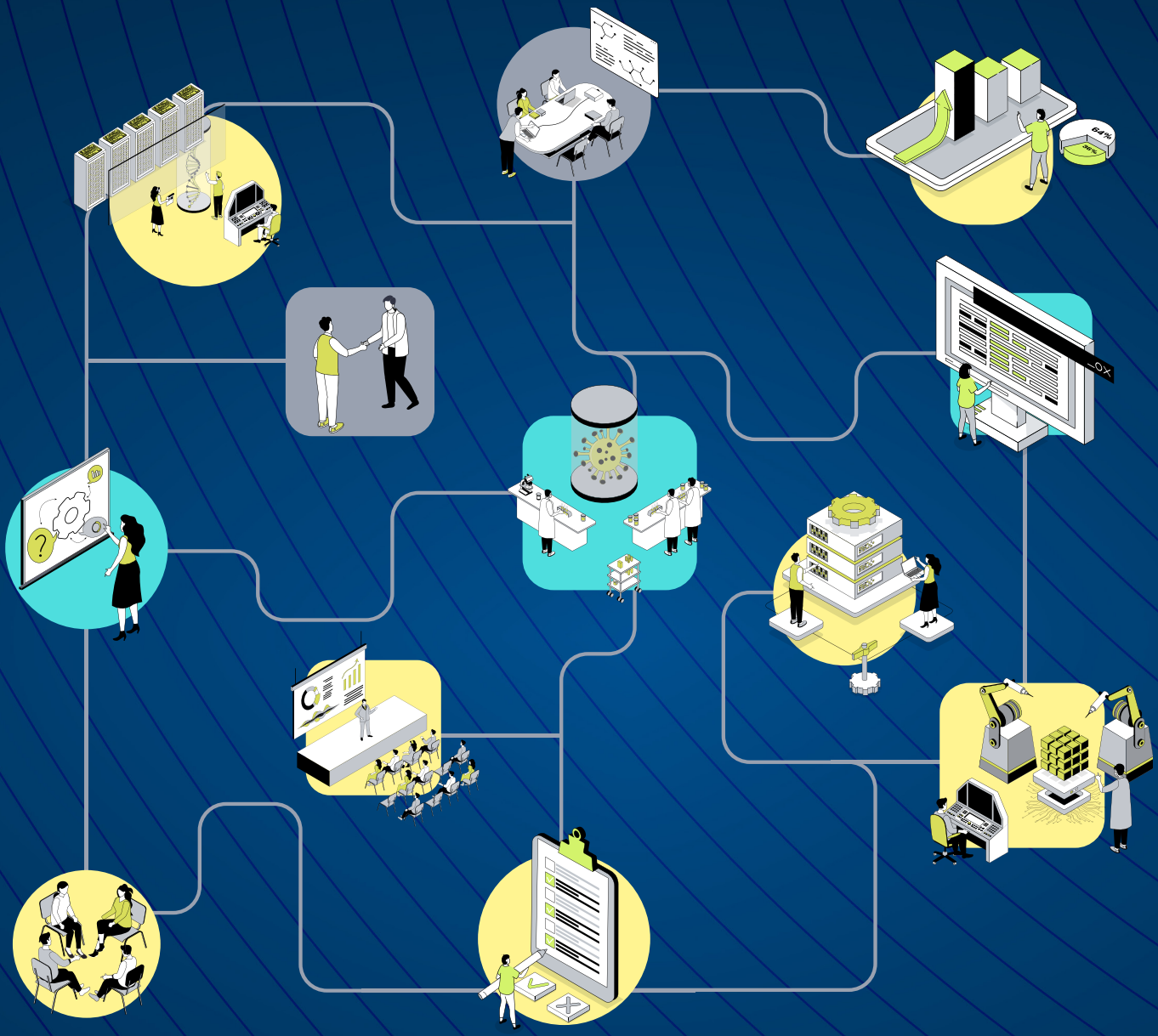

INNOVATION IN ACTION: A HANDBOOK FOR BUILDING PEOPLE-CENTRIC TESTBEDS

Version 1.0 – A Foundation for Collaborative Experimentation

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Contents

TABLE OF BOXES

Executive Summary

As emerging technologies continue to reshape sectors ranging from health to energy to public service delivery, governments and other actors are exploring ways to test, learn from, and responsibly scale new solutions. While these technologies hold promise, translating innovation into development outcomes involves navigating layers of uncertainty, institutional constraints, and evolving societal needs. Although interest in testbeds is growing globally, there remains limited practical guidance on how to design and implement them in ways that place people and development priorities at the center. This handbook—Version 1.0—is intended as a starting point to fill that gap, offering an initial framework for discussion and further refinement based on implementation insights and stakeholder feedback. It introduces people-centric testbeds as one approach to support evidence-based experimentation, stakeholder collaboration, and adaptive innovation governance.

People-centric testbeds are controlled experimental environments that support the testing, piloting, and assessment of emerging technologies under real-world conditions. They place people at the center of the design and implementation of innovation processes, encouraging inclusive engagement and fostering shared ownership. By generating insights that extend beyond technical performance, these testbeds contribute to a deeper understanding of the social, economic, and governance dimensions of innovation. Through principles of transparency, multistakeholder participation, and iterative learning, people-centric testbeds help ensure that technological experimentation aligns with local priorities, policy objectives, and the public interest.

This handbook is intended for a diverse group of users—including governments, community innovators, private sector partners and others—who are working to design, implement, or support testbeds in their respective contexts. It offers step-by-step guidance, adaptable frameworks, and practical insights drawn from global case studies, highlighting common challenges and enabling conditions. Designed with a focus on implementation, the handbook provides tools that can be applied and adjusted to suit a variety of institutional, regulatory, and development settings. Practitioners working in resource-constrained environments or complex policy ecosystems will find actionable resources to support context-specific planning, informed decision-making, and the localized execution of people-centric testbeds.

By consolidating global experiences and offering practical tools, this handbook aims to strengthen the capacity of government actors and others to experiment responsibly with emerging technologies. As an initial contribution to this emerging area of practice, this Version 1.0 is expected to evolve over time as additional insights, examples, and use cases emerge. Aligned with UNDP's broader mission to foster sustainable development, this resource contributes to building innovation systems that are not only technically sound but also socially responsive and grounded in development priorities.

Background

Rapid technological innovation is transforming the landscape of sustainable development globally. Emerging technologies—ranging from artificial intelligence (AI) to advanced manufacturing—hold the potential to accelerate progress towards sustainable development goals (SDGs). However, harnessing these opportunities requires a balanced approach that ensures technology solutions are inclusive and attuned to the needs of people and communities. A people-first approach that considers the local context, stakeholder collaboration, and appropriate governance is essential for harnessing the benefits of technological innovation while managing its risks responsibly.

Recognizing the potential of new technologies, countries are developing national strategies and investment plans to promote sustainable and socially responsible technologies. The frontier technology market, which includes technologies like AI, green hydrogen, and electric vehicles, could grow from $1.5 trillion to $9.5 trillion by 2030[1]. To harness these technologies for sustainable development, governments worldwide are prioritizing strategic investments and policy frameworks. For example, as of 2024, more than 60 countries have launched national AI strategies[2]. As these strategies move from design to implementation, governments are turning to experimental platforms that enable safe, real-world testing of technologies across sectors.

The integration of emerging technologies into society brings opportunities but also presents challenges for policymakers and stakeholders. Many regulatory systems were designed during an era of less rapid technological change and may not fully accommodate the needs of today's fast-evolving digital and innovation landscape. This can leave oversight gaps that expose communities—particularly first-time digital users or technology adopters—to risks such as exclusion, misinformation, or privacy concerns. It may also hamper innovation or lead to unintended consequences such as unequal access, regulatory uncertainty, or loss of public trust. To navigate these challenges, policymakers need regulatory approaches that are adaptive, inclusive, and responsive to evolving technological realities.

People-centric testbeds offer governments and stakeholders a structured yet flexible environment to engage with emerging technologies under real-world conditions. By enabling limited-scale trials in controlled settings, testbeds support iterative learning, allowing stakeholders to identify regulatory gaps, assess user experience, and refine solutions before broader deployment. This process enhances institutional readiness and strengthens the ability to make informed, timely, and adaptive decisions, especially in rapidly evolving or

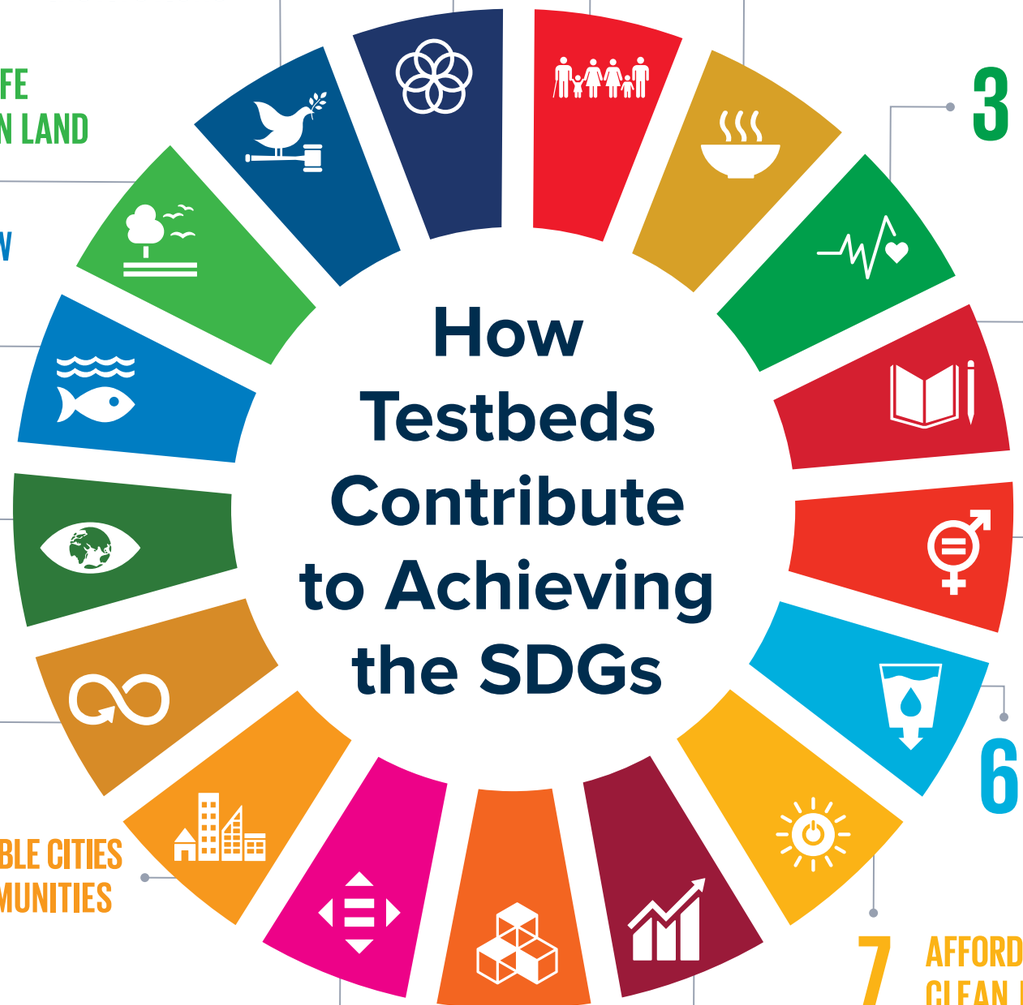
[1] UNCTAD, 2023, *Technology and Innovation Report 2023*: https://unctad.org/publication/technology-and-innovation-report-2023
[2] OECD, *AI Policy Observatory – Dashboards Overview:* https://oecd.ai/en/dashboards/overview (accessed 13 December 2024)

Testbeds help build dynamic innovation ecosystems that contribute to more inclusive and sustainable economic development.

uncertain environments. When grounded in a people-first approach, testbeds also facilitate the co-creation of policies and innovations that are socially responsive and locally relevant.

Lastly, people-centric testbeds can generate tangible economic benefits by creating jobs, developing workforce skills, and attracting investment in emerging technologies. As hubs of innovation and experimentation, they help cultivate specialized expertise aligned with the needs of fast-evolving industries. Testbeds can also act as catalysts for local economic activity, generating employment opportunities through operations, research, and maintenance, while drawing in investment and funding for the technologies under development. Moreover, by serving as launchpads for the commercialization of new solutions, they create opportunities for both startups and established firms to thrive. In doing so, testbeds help build dynamic innovation ecosystems that contribute to more inclusive and sustainable economic development.

How Testbeds Contribute to Achieving the SDGs



1 NO POVERTY

Testbeds can foster economic opportunities in underserved communities via access to technology and resources. By providing platforms for small businesses and inventors to create and test products, testbeds support job creation and income growth.

2 ZERO HUNGER

By enabling local farmers to experiment with and adopt such technologies as climate-resilient crops and advanced water management systems, testbeds can help ensure food security and resilience against climate variability.

3 GOOD HEALTH AND WELL-BEING

Some testbeds focus on integrating and validating community-specific health solutions, such as localized disease management programmes or community health training initiatives.

4 QUALITY EDUCATION

Through the sharing of knowledge, testbeds can help build technical skills and boost critical thinking and problem-solving capabilities among local communities while leveraging local talent and expertise.

5 GENDER EQUALITY

Testbeds support gender equality by providing female innovators with the resources and platforms needed to commercialize and scale their ventures, not only empowering them in the tech industry but also establishing powerful role models for future generations.

6 CLEAN WATER AND SANITATION

Environmental technology testbeds can develop and test water purification systems, smart water management solutions and IoT-based sanitation monitoring systems to ensure access to clean and safe water.

7 AFFORDABLE AND CLEAN ENERGY

Energy tech testbeds can evaluate renewable energy technologies, energy storage systems, smart grids and energy-efficient appliances to increase access to affordable and clean energy.

8 DECENT WORK AND ECONOMIC GROWTH

Testbeds can drive economic vitality, create high-quality jobs, foster entrepreneurship and stimulate economic growth and innovation by attracting investment and facilitating collaboration.

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Iterative testing and research promote inclusive and sustainable industrialization and allow local communities to drive technological innovation.

10 REDUCED INEQUALITIES

The testing of locally suited and relevant solutions that address the last-mile challenges of local communities can help reduce inequalities.

11 SUSTAINABLE CITIES AND COMMUNITIES

Urban testbeds foster sustainable cities by engaging communities in the development of solutions that address local needs. Through collaborative projects on waste management, public transportation, energy efficiency and similar topics, testbeds empower residents to help shape their urban environments.

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Testbeds can help make technology more responsible from the outset, tackling issues like e-waste and obsolescence.

13 CLIMATE ACTION

Climate tech testbeds can help combat climate change by testing carbon capture technologies, renewable energy innovations and climate modelling and monitoring systems.

14 LIFE BELOW WATER

Marine tech testbeds can develop and test technologies for ocean clean-up, sustainable fishing and marine biodiversity monitoring.

15 LIFE ON LAND

Environmental tech testbeds can test land management technologies, reforestation drones and biodiversity tracking systems to protect and restore terrestrial ecosystems.

16 PEACE, JUSTICE AND STRONG INSTITUTIONS

Testbeds can cultivate transparency, accountability and collaboration in technological development, helping shape innovative approaches and new ways of thinking within policy environments and ensuring that innovations serve the public good and uphold ethical standards.

17 PARTNERSHIPS FOR THE GOALS

Testbeds are an interdisciplinary and multi-stakeholder effort, requiring partnerships among governments, industry, academia and NGOs to develop and scale technological solutions aimed at achieving the SDGs.

Understanding People-Centric Testbeds

The concept of a testbed is broad, encompassing a range of formats and purposes tailored to specific research and development needs. While terms such as “living labs,” “sandboxes,” and “demonstrators” refer to distinct types of testing environments, they often overlap in purpose and practice. Each format sits at a different point along two dimensions: (i) the degree of environmental control (from laboratory conditions to real-world settings) and (ii) the stage of the innovation journey it supports (from idea generation through development, testing, implementation, and market entry). (See Figure 1) For example, a “living lab” emphasizes testing with real users in everyday settings, while a “sandbox” typically enables limited trials of new solutions in a controlled yet flexible regulatory environment. (see Box 1)

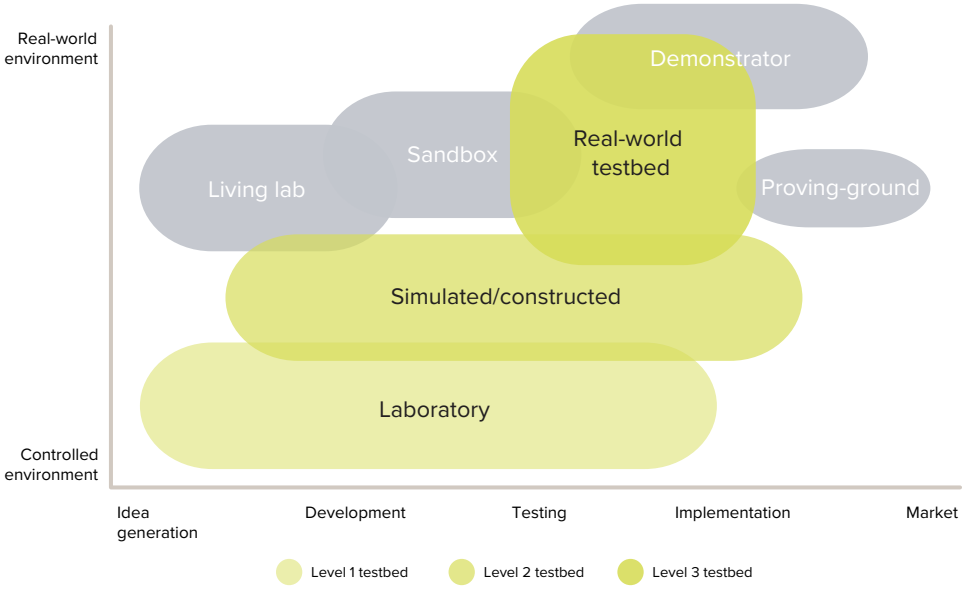


Figure 1: Typologies and Applications of Testbed Environments Across Development Phases[3]

For the purposes of this handbook, a testbed is defined as a collaborative and dynamic experimental environment in which new technologies, products, processes, or concepts are trialed, refined, validated, or refuted in partnership with relevant actors. These settings are designed to reflect real-world complexity, enabling practitioners to explore how innovations perform within existing infrastructures, institutional frameworks, and community contexts. Rather than assuming immediate scalability, testbeds create space for phased

[3] Arntzen, S., Wilcox, Z., Lee, N., Hadfield, C., & Rae, J., 2019. *Testing Innovation in the Real World: Real-world testbeds*. Nesta. https://www.nesta.org.uk/report/testing-innovation-real-world/

experimentation—surfacing usability issues, exploring regulatory or policy considerations, integrating user perspectives and feedback, and generating learning that can inform refinement. When rooted in local needs and shaped by those affected, such platforms help steer innovation efforts toward relevance, feasibility, and responsible adoption.

Key Characteristics of People-Centric Testbeds

People-centric testbeds are defined not only by their technical functions but also by the way they are designed, governed, and implemented. Several interrelated characteristics distinguish these testbeds from traditional innovation platforms.

First, these testbeds are built on the foundation of **human-centered design and interdisciplinary collaboration**. They bring together diverse stakeholders, including policymakers, local communities, engineers, designers, entrepreneurs, social scientists, NGOs, and ethicists—throughout the design and implementation process.

The integration of multiple perspectives also allows for a more holistic understanding of the potential impacts of technologies on people and their environments.

Secondly, people-centric testbeds embed **iterative feedback loops** into their processes. Structured, ongoing input from stakeholders—including community members and end-users—is systematically collected, reviewed, and used to inform ongoing development.

This feedback mechanism not only strengthens the relevance and effectiveness of technological solutions but also encourages inclusive participation and fosters a sense of shared ownership.

By continuously incorporating insights from real-world use, testbeds remain adaptable to shifting needs and priorities—increasing the likelihood of sustained acceptance, impact, and long-term viability.

Moreover, **ethical and transparent practices** are central to the operation of people-centric testbeds. Given the sensitive nature of data and technologies involved, these platforms prioritize the establishment of ethical frameworks, particularly around data privacy and security.

Clear data usage policies and strong security measures are adopted to protect user information and uphold user trust.

Open communication about technology development processes and data usage helps build stakeholder confidence and supports the responsible and inclusive adoption of innovations across different community contexts.

In developing countries, human-centric testing environments offer opportunities to adapt innovation to local realities. Many technologies originate in contexts that may not reflect local conditions, where assumptions about infrastructure, user behavior, or resource availability often do not reflect local realities. These platforms allow for early-stage adaptation—accounting for factors such as energy reliability, service delivery limitations, climatic variation, or logistical constraints—so that solutions are more likely to be both practical and impactful. By anchoring innovation in real-world conditions, these environments enhance relevance, usability, and long-term uptake. (see Box 4)

Box 1: Types of Testbeds

Testbeds come in a variety of formats, each tailored to meet different needs. Their nature, scope, scale and focus differ depending on the specific research and development goals they aim to achieve. Below are some common types of testbeds.

Technology-specific testbeds: These are designed to test and evaluate specific technologies and innovations within a certain domain—such as energy systems, network equipment and advanced manufacturing processes—or use case such as using 5G to operate drones in search-and-rescue scenarios. They often mimic real-world operational conditions to ensure that the technologies are robust, efficient, and ready for deployment. For example, the Carbon Capture and Utilization Translational Testbed in Singapore is designed to accelerate the adoption of emerging technologies aimed at capturing and converting carbon dioxide into valuable products such as fuels, chemicals and materials. It tests innovative carbon capture and utilization solutions in real-world conditions, enabling researchers and industry stakeholders to validate and scale technologies that address pressing sustainability challenges.

Virtual or simulation-based testbeds: These testbeds leverage simulation tools, data models and computational resources to emulate real-world scenarios, providing a controlled, cost-effective and scalable platform for experimentation. This type of testbed is particularly useful for scenarios that are difficult or expensive to create physically. For instance, the Institute of Electrical and Electronics Engineers (IEEE) Testbed for 5G and 6G Technologies is a virtual platform designed to foster the development and testing of next-generation wireless technologies. It allows researchers and developers to simulate and evaluate the performance of 5G and 6G applications to address technical challenges and optimize network performance before real-world deployment.

Open-source testbeds: Built around the principle of open-source collaboration, these testbeds allow innovators to contribute to and benefit from shared resources, tools and data. These platforms are common in software development, robotics, IoT, and wireless systems, where diverse input accelerates iterative testing. An example is the NIST Open-Source Wireless Testbed, launched by the U.S. National Institute of Standards and Technology (NIST). This government-backed testbed combines software-defined radios, high-performance servers, and both virtual and physical network components to support experimentation with open-access Radio Access Networks (O-RAN), emerging protocols, and applications—such as AI-driven network control—across physical and emulated networks. Through its open-source design, the platform lowers barriers for R&D, promotes shared learning, and supports the development of standard-aligned innovations in wireless technology.

Regulatory sandboxes: These frameworks are set up by regulatory bodies to allow startups and other innovators to conduct live experiments in a controlled environment under a regulator's supervision. The primary aim is to test new products, services or business models without immediately incurring regulatory consequences. This set-up is especially beneficial in industries that are heavily regulated, such as finance, health care and telecommunications. By limiting the scale and scope of testing, sandboxes help identify potential regulatory issues early while minimizing associated risks. Depending on the outcomes, sandbox initiatives can lead to updated regulations, the introduction of new rules, regulatory approval or licensing of the innovation, or the discontinuation of products that fail to meet necessary standards.

For example, the Bank of Thailand has established a regulatory sandbox that provides a controlled environment for testing financial technology innovations. It allows financial institutions, technology providers, and startups to trial new products, services, and business models under real-world conditions while being closely supervised by regulators. The sandbox supports a wide range of initiatives, including digital payments, blockchain-based applications, and the use of artificial intelligence in financial services. Notable projects tested within the sandbox include peer-to-peer lending platforms, biometric authentication systems, and next-generation digital payment solutions.

Additional relevant materials can be found in the Practical Resources for Testbed Development and Implementation section, which offers further guidance, tools, and references to support the design and execution of testbeds.

The success and impact of testbeds rely on the active participation and collaboration of diverse stakeholders.

Stakeholders Involved in People-Centric Testbeds

The success and impact of testbeds rely on the active participation and collaboration of diverse stakeholders. This section outlines the key stakeholders involved in testbeds and highlights how their roles and contributions drive the effective development, deployment, and scaling of new technologies.

Government Stakeholders

Government agencies—including line Ministries, regulators, and local authorities—often play a central role in setting up and supporting testbed initiatives. In addition to regulatory functions, they may provide funding, policy direction, and coordination across stakeholders. Governments help create the conditions for innovation by shaping legal and institutional frameworks that guide safety, accountability, and responsible use. As public sector actors, they are positioned to align testing activities with national priorities and ensure that innovation efforts support broader development objectives.

Example: Estonia's Digital Testbed Framework[4], launched in 2021 by the national government, offers an innovative model for public-sector-led experimentation. It provides startups, scale-ups, and global innovators with access to Estonia's digital government technology stack, enabling them to test applications—ranging from AI tools for education and health to chatbot interfaces for parliamentary services—within a live public-sector environment. In exchange, participants contribute their solutions back into an open-source repository, fostering a shared ecosystem of public value. This initiative exemplifies how a government can actively facilitate responsible innovation: it reduces barriers to entry, accelerates public-sector learning, and creates collaborative pathways between public institutions and innovators.

Knowledge Institutions

Universities, research institutes, and other academic organizations contribute technical knowledge and research capacity to testbed initiatives. They support experimentation by applying scientific methods to evaluate emerging technologies in real-world conditions. In addition to generating evidence and insights that may inform policy and practice, they help share findings with a wider community of stakeholders, including government and industry. These institutions also support training and capacity development, helping to equip future professionals with the skills needed to engage with evolving technologies. In doing so, they strengthen the foundation for ongoing learning and collaboration beyond individual testbed projects.

[4] e-Estonia, 2023, *Estonia's Digital Testbed Framework: Join Our Country-Sized Hackathon*: https://e-estonia.com/estonias-digital-testbed-framework-join-our-country-sized-hackathon/

Example: The COSMOS (Cloud enhanced Open Software defined Mobile wireless testbed for city-Scale deployment)[5] testbed demonstrates the role universities play in driving innovation and research in real-world settings. Spearheaded by Columbia University, City College of New York and Rutgers University, this testbed provides a platform for cutting-edge research in wireless communications and networking. These academic institutions are fundamental in developing the testbed's infrastructure and research agenda and facilitating a diverse range of experiments. The collaboration helps ensure that the testbed is equipped with state-of-the-art technologies and methodologies, promoting a rich environment for experimentation and discovery in urban communication networks.

Innovators contribute to testbeds by introducing new ideas, tools, and approaches for addressing development challenges.

Technology Developers and Startups

Innovators contribute to testbeds by introducing new ideas, tools, and approaches for addressing development challenges. Their flexibility and responsiveness align well with the iterative nature of testing environments. By engaging in testbed activities, they can trial their innovations in applied settings that reflect operational, regulatory, or community-specific dynamics. These engagements help innovators refine usability, performance, and relevance based on direct stakeholder feedback. Participation also offers opportunities to build networks, attract investment, and better understand market pathways, supporting the growth and scaling of their solutions. In this way, testbeds serve as practical entry points for technology providers to adapt and strengthen their innovations before broader adoption.

Example: In Japan, the Shibuya Startup Support initiative launched a Testbed City[6] program in Tokyo's Shibuya district. This urban platform allows startups to test and refine technologies with a focus on social impact and urban development, leveraging their innovative capabilities and agility to rapidly test and adapt technologies in real-world settings. Shibuya City also offers its local infrastructure for product and concept testing and operates a pool of local volunteers for product testing, with more than 2,300 residents registered. This collaboration accelerates the development of new solutions and integrates these technologies into the fabric of city life, enhancing urban liveability and technological integration.

Industry Partners

Industry partners help infuse testbeds with resources, expertise, and market insights that support the development and adaptation of new technologies. Their understanding of consumer trends and industry standards can help align testing efforts with practical use cases and potential demand. Established firms, in particular, play a role during the validation stage by providing feedback that

[5] Raychaudhuri, D., Seskar, I., Zussman, G., Korakis, T., Kilper, D., Chen, T., Gutterman, C., 2020, *Challenge: COSMOS: A city-scale programmable testbed for experimentation with advanced wireless*, In Proceedings of the 26th Annual International Conference on Mobile Computing and Networking (pp. 1–13). London United Kingdom: ACM: https://doi.org/10.1145/3372224.3380891
[6] Shibuya Startup Support, 2023, *Testbed City*: https://shibuya-startup-support.jp/testbed-city

informs improvements in design, functionality, and scalability. In some cases, they also act as connectors—linking testbeds to broader industry ecosystems, including supply chains, certification pathways, and distribution networks. Such engagement can help innovations move beyond testing into broader adoption and use.

Example: The telecommunications company Digicel Fiji, a subsidiary of the Australian company Telstra, has partnered with local authorities to establish the first 5G testbed in Fiji.[7] Through its Xtreme Fibre Network, Digicel has conducted official 5G testing to evaluate and optimize network performance, supporting the deployment of high-speed Internet and next-generation technologies. The testbed also enables the trial of applications that depend on fast, reliable data transmission, such as IoT, smart infrastructure, and digital services.[8] Digicel's involvement extends beyond infrastructure development to encompass collaboration with local stakeholders and government bodies to ensure the network meets the country's specific digital landscape and economic goals.

Civic and Community Associations

By participating in testing activities, communities offer insights that shape the development and adjustment of solutions.

End users, local communities, NGOs and civic organizations help ensure that technological innovations are effective and aligned with the needs and contexts of the people they aim to serve. Their involvement brings in perspectives that may otherwise be overlooked, helping ensure that new technologies are relevant, accessible, and usable within specific contexts. By participating in testing activities, communities offer insights that shape the development and adjustment of solutions. Their contributions help refine functionality, improve cultural and contextual fit, and build acceptance among potential users (see Box 2). NGOs and civic groups can also facilitate engagement by mobilizing participation, building trust, and advocating for approaches that prioritize equity, inclusion, and broader social value.

Example: In the project UrbanTestbeds.JR,[9] facilitated by the Interreg Baltic Sea Region programme, youth contribute to shaping sustainable urban environments alongside public authorities and other stakeholders. The project engages youth in co-designing urban testbeds focused on sustainability and climate action, combining AI and data-driven storytelling to make climate plans more accessible and participatory. Through workshops and collaborative design sprints, young participants contribute to the planning and implementation of urban testbeds on sustainability and climate mitigation. Their insights and feedback help produce innovative solutions that resonate with their needs and expectations for a sustainable future. This enhances the capacities of youth to influence local policies and practices while fostering a resilient community able to address environmental challenges.

[7] Srikapardhi, 2023, *Digicel Fiji Officially Launches 5G Testing*: https://telecomtalk.info/digicel-fiji-first-telco-officially-5g-testing/702673/
[8] Srikapardhi, 2023, *Digicel Fiji Completes First Phase of Xtreme Fibre Network in Suva*: https://telecomtalk.info/digicel-fiji-completes-firstphase-xtreme-fibre-network/770277/
[9] Interreg Baltic, 2023, *UrbanTestbeds.JR*: https://interreg-baltic.eu/project/urbantestbeds-jr/

Box 2: SWIFT Testbed: Advancing Weather Forecasting Capabilities in Africa

Overview

The Science for Weather Information and Forecasting Techniques (SWIFT) testbed is a collaborative initiative that brings together expertise from the University of Leeds, the University of Reading, and various African meteorological agencies. Key partners include the Kenya Meteorological Department, the Nigerian and Ghana Meteorological Agencies, and the Agence Nationale de l'Aviation Civile et de la Météorologie (ANACIM) in Dakar, each working closely with their respective local universities. The project was conceived to address the need for enhanced weather forecasting capabilities across West and East Africa, recognizing the key role that accurate weather predictions play in supporting agriculture, public health, and disaster management in the region. Subsequent testbeds involving the weather services of South Africa, Zambia, and Mozambique have extended the SWIFT model across Southern Africa under the WISER-EWSA project. The testbed's core approach combines advanced research with operational forecasting in a quasi-operational setting, effectively bridging academic research and practical application.

Implementation and Feasibility

The implementation of the SWIFT testbed prioritized both technical excellence and practical applicability. It began with extensive pre-testbed workshops that served to identify specific needs and challenges within the target regions. These initial assessments informed the development of forecasting tools through a collaborative process involving project managers, researchers and forecasters. The technical infrastructure was designed to integrate advanced meteorological technology with existing local systems, ensuring compatibility and sustainability. A comprehensive training programme was established to build local capacity, while multilingual dissemination strategies were developed to ensure the widespread accessibility of weather information across diverse communities.

Community Approach

The SWIFT testbed stands out for its strong co-production approach, which brought together diverse sources of knowledge—including scientists, meteorologists, farmers, and community members—and placed community engagement at the core of its process. The aim was to ensure that the resulting forecasting tools were not only scientifically rigorous but also tailored to the specific needs and contexts of local users. This approach created a space for ongoing feedback and refinement, making the tools more usable and relevant in real-world settings.

Source: Fletcher, J. K., and Coauthors, 2023: Tropical Africa's First Testbed for High-Impact Weather Forecasting and Nowcasting. Bull. Amer. Meteor. Soc., 104, E1409–E1425, https://doi.org/10.1175/BAMS-D-21-0156

Structured meetings and consultation sessions were held with representatives from sectors such as agriculture, health, and disaster response, allowing different user groups to contribute to the design and implementation of forecast services. This participatory model also extended to the evaluation process, where end users were actively involved in assessing and improving the tools. The use of local languages and audio formats for weather communications further emphasized the project's commitment to inclusive information delivery. Importantly, the collaborative work between weather services and communities has been formalized into a set of Standard Operating Procedures (SOPs), providing a shared reference for ongoing service delivery and co-management.

The project prioritizes the development of local capabilities through comprehensive training programmes aimed at building sustainable meteorological expertise. These programmes are designed to enhance the understanding and operational skills of local forecasters and users, focusing on both the technical intricacies and the practical applications of advanced forecasting products, as defined by the SOP. A key component is the transformation of complex meteorological data into understandable and actionable information tailored to meet the needs of non-expert users. Daily classes clarify technical concepts and facilitate hands-on experience, ensuring that all participants can effectively interpret and apply weather forecasts.

To embed this expertise within local institutions, the testbed emphasizes the institutionalization of knowledge. In Senegal, for example, specific training initiatives have been implemented to ensure that knowledge remains within local institutions, thus sustaining the forecasting capabilities independently of the testbed's direct involvement. These efforts not only foster a deeper understanding and acceptance of meteorological products but also promote continuity and resilience in weather forecasting practices across the regions served by the SWIFT testbed.

Impact

The SWIFT testbed has generated notable and measurable outcomes across its areas of implementation. It has contributed to improvements in the accuracy and reliability of weather forecasts while making them more accessible to a wide range of users through innovative communication channels. Local meteorological agencies have also experienced capacity strengthening through targeted knowledge transfer and hands-on training initiatives. Importantly, the services introduced during the testbed phase have continued beyond the project's initial implementation period, indicating sustained institutional uptake and ongoing relevance.

Impact-based forecasting focuses on predicting the impacts of weather events rather than just providing meteorological data. Forecasts are communicated in terms of expected impacts rather than technical meteorological data. This approach helps users understand what the weather means for them and what actions they should take. For instance, instead of generic rainfall measurements such as "20 mm of rain", the forecasts might advise something like this: "The rain is expected to cause flooding in low-lying areas. Take precautions to protect your property."

The integration of scientific expertise with local insights has resulted in more contextually relevant forecasting products, leading to higher rates of user acceptance and adoption through fostering a sense of ownership. These improvements have translated into tangible benefits for various sectors, from agricultural planning to disaster preparedness.

Lessons Learned

The implementation of the SWIFT testbed has yielded valuable insights that can inform future similar initiatives. A fundamental lesson is the importance of integrating local knowledge with scientific expertise, creating a synergy that enhances the effectiveness of weather forecasting systems. The project has demonstrated the value of sustained stakeholder engagement throughout the development process, ensuring that forecasting products remain relevant and useful. The necessity of adapting technology to local contexts and needs has emerged as a crucial factor in successful implementation. The project also highlights the vital role of capacity-building in ensuring long-term sustainability and underscores the effectiveness of multiformat communication strategies in reaching diverse audiences. These lessons constitute a valuable knowledge base for future weather forecasting initiatives in developing regions.

How to Design and Implement People-Centric Testbeds

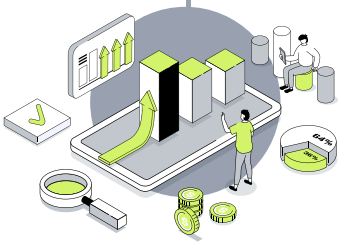
Phase 1: Objective Definition and Scope Determination

Defining Purpose and Scope:

Testbeds require a clear value proposition, realistic expectations, and defined boundaries. They assess how emerging technologies interact with regulations, infrastructure, and local conditions, ensuring solutions are sustainable and socially acceptable.

Scope Determination:

The scope includes technological, geographical, operational, and resource aspects. It ensures alignment with objectives, efficient resource use, and actionable outcomes.



Feasibility Study and Compliance:

Feasibility studies evaluate technical, economic, institutional, and regulatory readiness. They ensure the testbed's viability, align expectations, and address compliance with applicable regulations and evolving regulations.

This phase is where the rationale and added value of a testbed are shaped.

The starting point for any testbed is a clear definition of its purpose and boundaries. Testbeds are not an end in themselves; they are strategic tools to explore what works, inform policymaking, and manage uncertainty in areas where on-the-ground evidence is limited or where new technologies and approaches are outpacing existing systems. At their core, these platforms are designed to help governments and stakeholders engage with specific challenges—such as outdated regulations, unclear institutional mandates, or uncertain public impacts—through structured experimentation and iterative learning. This phase is where the rationale and added value of a testbed are shaped. It involves defining the problem, setting realistic expectations, and outlining the scope of technologies or interventions under consideration.

Early consideration of people-first principles can strengthen the relevance and responsiveness of the testbed. Engagement with stakeholders—including policymakers, regulators, service providers, end users, and civic actors—ensures the initiative is grounded in real-world priorities and reflects the lived experiences of those it aims to serve. This inclusive approach increases the likelihood that the outcomes will be both usable and sustainable in the intended setting.

Additional relevant materials can be found in the Practical Resources for Testbed Development and Implementation section, which offers further guidance, tools, and references to support the design and execution of testbeds.

1.1 Identify Key Issues and Objectives

Anchoring a testbed around a clear value proposition helps clarify its purpose and ensures that its outcomes are relevant to stakeholders. In many cases, testbeds are initiated to **support regulatory exploration or inform evolving policy frameworks**. As emerging technologies often operate beyond the scope of existing rules, these platforms create an opportunity to assess how innovations interact with current legal, institutional, or ethical systems. By replicating practical use cases or operational settings, testbed environments can help surface gaps in regulation, test adherence to safety and accountability standards, and generate insights for future policymaking. For instance, several governments have developed experimental platforms for quantum communication to examine issues related to data integrity, infrastructure security, and compliance—helping align these emerging systems with national policies before large-scale rollout.

In many contexts, particularly in developing countries, testbeds can assess whether **new or externally developed technologies** are appropriate for local conditions. Technologies designed elsewhere may not account for environmental, cultural, or infrastructure-specific factors. Testbeds enable stakeholders to evaluate technologies in specific conditions, reducing the risk of misaligned solutions and improving long-term sustainability. This is particularly useful in sectors such as energy, health, or mobility, where misfit technologies can result in service disruptions, safety risks, or wasted investment. For example, battery technologies developed abroad may perform reliably in their original context but degrade rapidly—or even fail—when exposed to high temperatures, humidity, or other environmental stresses commonly found in many regions. A localized testbed approach also allows for co-development with communities, ensuring that solutions are not only technically effective but also socially acceptable and relevant.

Defining the scope is especially important to help prioritize efforts, optimize resource use, and ensure the testbed remains focused and actionable.

In settings exploring **cross-border testing or pilot initiatives**, testbeds can be a platform for responsible and context-sensitive engagement. By setting clear protocols, ensuring regulatory oversight, and embedding public accountability, they enable foreign innovators to trial their technologies while aligning with local priorities and safeguards. This reduces friction in approval processes, builds mutual trust, and supports more inclusive and adaptive forms of innovation exchange. For instance, overseas developers of clean energy or water purification systems may use a government-supported testbed to refine their solutions for local infrastructure or climate conditions, working closely with public authorities to meet compliance requirements and respond to community needs.

Finally, **clearly defining the decision a testbed is meant to inform** helps ensure that its design, scope, and outcomes remain relevant and actionable**.** Whether the aim is to guide regulatory reform, support procurement processes, or assess readiness for scaling or investment, linking testbed activities to a specific decision point enables stakeholders to align objectives, tailor evaluation methods, and generate insights that are timely and usable. This clarity also helps determine the appropriate level of integration—whether the testbed is intended to inform local service improvements, national policy development, or commercial deployment.

1.2 Scope Determination

Defining the scope of a testbed helps ensure that its design and operation are strategically aligned with its objectives and context . A well-articulated scope outlines the technologies to be tested, the geographical and operational boundaries, and the resources required for effective implementation. This clarity helps stakeholders manage expectations, allocate resources efficiently, and ensure that the testbed delivers relevant and measurable outcomes. Clearly defining the scope is especially important to help prioritize efforts, optimize resource use, and ensure the testbed remains focused and actionable. Scope determination should be carried out in a participatory manner, with all relevant stakeholders involved, to ensure that the result is beneficial for all.

The **technological scope** refers to the specific innovations, systems, or processes to be tested, refined, or demonstrated. Clearly defining this scope is essential for ensuring that the testbed remains strategically focused and capable of generating actionable insights. The technological scope should reflect no t only local development priorities but also broader trends in science and technology. Depending on the context, testbeds might be used to evaluate emerging fields such as AI for climate modelling, advanced sensors for environmental monitoring, or bioengineered materials for construction. In other cases, the focus may be on adapting existing technologies—such as digital twins for infrastructure planning or interoperable platforms for cross-border data exchange—to new use cases.

The **geographical scope** defines the physical location and geographical extent of the testbed. This includes evaluating how the environment may support or constrain the technologies being tested. For instance, coastal regions may be suitable for piloting ocean-based renewable energy solutions, while remote rural areas might provide appropriate conditions for testing beyond-visual-line-of-sight drone technologies. In addition to physical characteristics, understanding the socio-economic context—such as demographics, economic activities and cultural factors—can influence how technologies are adopted and scaled within the area.

Early planning for resource efficiency and sustainability can support the long-term operation of the testbed and reduce dependency on external inputs.

The **operational scope** outlines how the testbed will be implemented and managed throughout its lifecycle. This includes defining its timeline, development phases, and testing stages, along with future scalability plans. Clear milestones and key performance indicators (KPIs) should be established to facilitate continuous monitoring and evaluation. These indicators should be tailored to the specific objectives of the testbed, ensuring they accurately measure progress and impact. Additionally, identifying potential risks and creating contingency plans will help the testbed managers and stakeholders navigate challenge s effectively, helping ensure smooth operation from inception to decommissioning.

Determining the **resource scope** involves identifying the physical, human, and financial resources needed to support the testbed. This includes securing infrastructure, acquiring specialized tools and equipment, assembling expert teams, and ensuring sufficient funding. Importantly, building an effective testbed does not always require extensive new infrastructure or large-scale facilities. Repurposing existing spaces and leveraging available assets can make testbed implementation more feasible and cost-effective. Early planning for resource efficiency and sustainability can support the long-term operation of the testbed and reduce dependency on external inputs.

1.3 Feasibility Study and Compliance

The feasibility study process ensures that the proposed testbed can realistically achieve its intended goals within the defined parameters. This includes evaluating whether the necessary technical, economic, institutional, and regulatory conditions are in place to support implementation. A well-conducted feasibility study also helps align expectations among stakeholders and informs any necessary design adjustments before launch.

The **technical evaluation** focuses on whether the proposed technologies and infrastructure can effectively support the testbed's intended goals. This involves reviewing the compatibility of selected technologies, the readiness of supporting infrastructure, and the capacity of available resources to meet operational demands. Ensuring that the technical setup is feasible reduces the risk of disruptions during the development and implementation phases. Equally important is analyzing the **economic viability** of the testbed, including a thorough review of projected costs, funding sources and long-term financial sustainability. Understanding potential cost implications and identifying funding gaps early allows stakeholders to explore financing options, partnerships or cost-saving measures to maintain steady operations without compromising quality or impact.

Institutional feasibility involves evaluating infrastructure readiness, staffing requirements, supply chain dependencies, and compliance with regulatory standards. Careful planning around these elements ensures the testbed can operate efficiently within the set timelines and resources. Furthermore, all testbed activities should comply with **applicable regulations**, including those related to environmental protection, safety, and relevant industry standards. In cases where regulations are evolving, the testbed may serve as a platform to explore and refine appropriate norms and procedures. This can help clarify legal responsibilities, support future policy development, and ensure that testing activities remain aligned with broader compliance expectations.

Box 3: CSIR Energy Storage Testbed in South Africa

Overview

The Indoor Energy Storage Testbed at South Africa's Council for Scientific and Industrial Research (CSIR) is designed to assess the performance, safety, and reliability of lithium-ion batteries. It conducts tests on key parameters such as storage capacity, life cycle, and depth of discharge—providing developers and importers with data essential for optimizing battery technologies and preparing them for market entry. These services support the country's broader energy transition by improving the availability and quality of battery storage solutions for renewable energy systems.

The testbed contributes to building industry capacity. It enables small and medium-sized enterprises, manufacturers, and importers—who may otherwise lack access to such facilities—to evaluate their products under standardized conditions. Insights gained through testing can also inform more sustainable practices, including battery repurposing and recycling, contributing to a circular economy.

Established under the World Bank's Energy Storage Partnership and supported by a long-standing collaboration between the South African and Flemish governments, the testbed also benefits from the involvement of the Vlaamse Instelling voor Technologisch Onderzoek (VITO). Its work has helped shape national standards for lithium-ion batteries in partnership with the South African Bureau of Standards and continues to address key technical and regulatory gaps in South Africa's growing energy storage market.

Feasibility and Implementation

The implementation of the CSIR Energy Storage Testbed began with a comprehensive feasibility study that identified gaps in local industry capabilities, technical expertise and regulatory frameworks. This study highlighted the need for significant infrastructure upgrades to accommodate new, high-demand battery testing equipment. The Chroma 17020 battery tester and the 1,000-litre climate chamber required a robust electrical and cooling system to handle the increased power requirements and thermal output and ensure safe and effective operation within the testbed.

The study also evaluated the regulatory environment to identify any gaps in existing policies that govern energy storage technologies. This led to active collaborations with regulatory bodies to establish updated standards and safety regulations tailored to the advanced technologies being tested.

An economic analysis was conducted to assess the potential impacts of integrating new energy

CSIR, 2023, *Energy Storage Testbed Factsheet:* https://www.csir.co.za/sites/default/files/Documents/CSIR%27s%20Energy%20Storage%20Testbed%20factsheet.pdf

storage technologies, considering cost benefits and stakeholders' return on investment. This analysis helped validate the economic viability of the testbed and its alignment with industry and market expectations.

The integration of these detailed assessments helped ensure that the CSIR Energy Storage Testbed was not only technically prepared but also compliant with the highest safety standards and regulatory requirements, setting a benchmark for future energy storage initiatives.

The implementation process then incorporated rigorous safety protocols and regulatory compliance measures to mitigate potential fire hazards. This included the development of comprehensive fire safety measures, emergency response plans and regular safety drills to prepare for any incidents.

Community Approach

The testbed's community engagement strategy focuses on fostering collaboration among academic institutions, industry partners and local enterprises. The facility maintains strong relationships with small and medium-sized enterprises, providing crucial testing services and technical support to enable local businesses to evaluate and improve their energy storage solutions. Knowledge-sharing initiatives and training programmes form a central component of the testbed's operations, helping to build local technical expertise and industry capacity. Regular engagement with regulatory bodies ensures that the facility's work continues to align with and inform industry standards development.

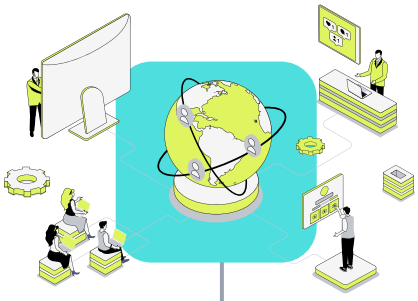
Impact

The CSIR Energy Storage Testbed has generated substantial impacts across multiple dimensions of the energy storage sector in South Africa. The facility has played a pivotal role in developing comprehensive standards for lithium-ion batteries, filling a gap in the local industry. Through its support of small and medium enterprises, the testbed has contributed to the growth and development of the local battery industry, enhancing market knowledge and technical expertise. The facility's testing capabilities have enabled local manufacturers and importers to validate their products, leading to improved quality and reliability in the market. These achievements collectively strengthen the country's position in the global energy storage landscape.

Lessons Learned

The implementation and operation of the CSIR Energy Storage Testbed yields valuable insights for similar initiatives. The project underscores the importance of international partnerships in facilitating technology transfer and knowledge exchange while demonstrating the value of comprehensive safety and operational protocols in technical facilities. The experience highlights the role of local capacity-building in ensuring long-term sustainability and independence. The phased implementation approach adopted by the project has proven effective in managing complexity and ensuring steady progress. Furthermore, the testbed's experience emphasizes the importance of maintaining strong alignment with regulatory frameworks while pushing boundaries.

Phase 2: Stakeholder Engagement and Partnership Formation



Identify Key Stakeholders:

Stakeholder mapping identifies and categorizes actors based on influence and interest, enabling tailored engagement strategies. Stakeholder influence and interests can vary significantly across testbed domains.

Form Strategic Partnerships:

Strategic partnerships are essential for addressing challenges like funding and infrastructure, especially in developing countries.

Partner selection should be guided by clear criteria, including the ability to contribute resources. The selection should align with testbed goals and values.

Once potential partners are identified, the next step is to negotiate and clearly define the roles and contributions of each party.

Clear and well-documented agreements help ensure alignment, accountability, and collaboration. These agreements address resource allocation, intellectual property, and dispute resolution, ensuring smooth coordination and long-term success.

Effective testbed implementation depends on early and sustained engagement with a broad spectrum of actors. Strong partnerships help ensure that the testbed benefits from a wide range of expertise, resources, and perspectives, ultimately increasing its effectiveness and impact. Engaging relevant stakeholders early in the process also fosters a sense of ownership, aligns interests, and encourages shared responsibility in achieving the testbed's goals. This phase involves identifying relevant actors and establishing collaborative frameworks that enable co-design, resource sharing, and open communication throughout the testbed lifecycle. Co-creation with stakeholders can increase the usability and legitimacy of the results, while reducing the risk of fragmented efforts or misaligned incentives.

In developing countries, strategic partnerships can help address constraints related to funding, infrastructure, and technical capacity that may otherwise limit the scope or impact of a testbed. Collaborating with national and international partners facilitates access for local actors to technical expertise, funding,

Initial partners—often government entities, industry players, or research institutions—are often engaged early to help shape the testbed's direction and scope.

and infrastructure. Such partnerships also offer opportunities for knowledge exchange, institutional development, and the co-design of solutions that reflect local needs and conditions. When anchored in national priorities and designed to distribute benefits fairly, these collaborations can support the growth of more inclusive and sustainable innovation ecosystems.

2.1 Identify Key Stakeholders

This step involves systematically identifying and mapping the individuals, groups, and institutions that influence, contribute to, or are affected by the testbed. An inclusive approach is important—one that actively considers individuals and communities that may be underrepresented, including women, youth, persons with disabilities, and minority populations. The process should go beyond listing stakeholders to include an understanding of their roles, interests, and expectations. This helps inform how different groups can engage meaningfully and ensures that a broad range of perspectives is reflected in the design and operation of the testbed.

Stakeholder mapping typically categorizes actors according to their level of influence and degree of interest. Those with high influence—such as government agencies, regulators, or major industry actors—may require structured engagement through formal agreements or advisory roles. Conversely, actors with lower influence but high interest—such as community groups or end users—may be engaged through participatory methods such as co-design workshops, focus groups, or public consultations. Tailoring engagement strategies based on this mapping can help ensure that different perspectives are incorporated and that support is built across constituencies.

Stakeholder influence and interests can vary significantly across testbed domains. For instance, in a smart mobility testbed, actors may include public agencies responsible for transport regulation, technology developers, transit operators, and daily commuters. Recognizing these different roles allows testbed organizers to tailor engagement approaches—such as aligning with transport policies, coordinating with private-sector partners on technical trials, and gathering user feedback from commuters. These differentiated strategies can help ensure that the perspectives of each group are acknowledged and integrated throughout the process.

A similar diversity of roles can exist in the context of a renewable energy testbed. Public energy agencies and regulatory institutions may guide the overall policy environment and ensure alignment with national development goals. Industry participants—including hardware manufacturers or energy providers—may contribute technologies or implementation support. Academic institutions can assist with testing protocols, data collection, and the interpretation of results. Meanwhile, local communities—particularly those in underserved areas—can offer practical insights about day-to-day feasibility, such as affordability, reliability, or user experience (see Box 3).

Additional relevant materials can be found in the Practical Resources for Testbed Development and Implementation section, which offers further guidance, tools, and references to support the design and execution of testbeds.

Transparent discussions at this stage help set realistic expectations, support mutual understanding, and reduce the likelihood of conflicts during implementation.

2.2 Form Strategic Partnerships

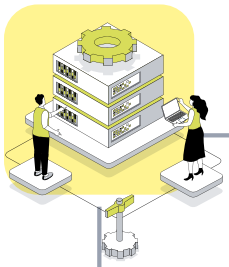
Building on the stakeholder mapping process, the next step is to establish partnerships that turn shared interests into concrete collaboration. Initial partners—often government entities, industry players, or research institutions—are often engaged early to help shape the testbed's direction and scope. In addition to national actors, international partners—such as development agencies, global research institutions, multinational companies, and investors—can contribute technologies, funding , and comparative knowledge that supports the adaptation of innovations. (See Box 4) As the testbed evolves, new partnerships may be needed to address emerging priorities, bring in specialized expertise, or support scale-up efforts. A flexible and iterative approach to partnership development ensures that the initiative remains responsive and well-resourced throughout its lifecycle.

Partner selection should be guided by clear criteria, including the ability to contribute resources—such as technology, finan cing, domain expertise, access to under-represented communities, or deep knowledge of local socio-economic contexts—and alignment with the testbed's goals and values. Each collaboration should be designed to add value—whether through technical input, operational support, or expanded reach—and should be grounded in a shared commitment to the success and integrity of the testbed.

Once potential partners are identified, the next step is to **negotiate and clearly define the roles and contributions** of each party. This process involves clarifying what each party will contribute—such as funding, hardware, specialized knowledge, or access to networks—and what benefits they may expect in return, such as data access, learning opportunities, or brand visibility. Transparent discussions at this stage help set realistic expectations, support mutual understanding, and reduce the likelihood of conflicts during implementation.

Clear and well-documented agreements help ensure alignment, accountability, and collaboration. These agreements should define the partnership's scope and objectives, detailing how contributions support the testbed's goals in such areas as technology development or deployment. Roles, responsibilities, and resource allocation should be clearly outlined to prevent overlaps and ensure efficiency. In addition, provisions should be included on intellectual property management—clarifying ownership, usage rights, and conditions for data sharing or publication—as well as procedures for resolving disputes and terminating the partnership if needed. Such frameworks help promote accountability, support collaborative work, and enable smoother long-term coordination.

Phase 3: Design and Infrastructure Development

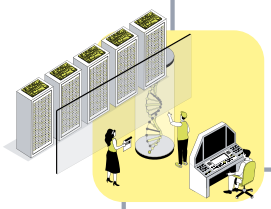


Site Selection and Architectural Design

- Site selection
- People-centric designs
- Sustainability strategies
- Architectural design
- Safety protocols

Technology Integration

- Interoperability and System Integration
- Connectivity infrastructure
- Data Infrastructure and Management Efficient
- Cybersecurity and Vulnerability Management



Infrastructure Planning for Virtual Testbeds

- Advanced Simulation Capabilities
- Global Accessibility and Collaboration

Hybrid Testbeds: Combining On-Site and Cloud Resources

- Staged Testing for Risk Mitigation
- Digital Twin Technology

Spaces and systems should be designed to support diverse technologies and to accommodate adjustments as priorities or requirements change.

With clear objectives defined, scope determined, and partnerships in place, the next step involves designing the testbed and establishing the infrastructure required to support its activities. This phase translates planning into operational systems that enable testing, iteration, and collaborative innovation. In addition to meeting technical and functional needs, the design should reflect a people-centered approach—ensuring that the testbed remains relevant and responsive to the needs of communities and stakeholders involved. Effective infrastructure planning benefits from modular and adaptable layouts that can evolve over time. Spaces and systems should be designed to support diverse technologies and to accommodate adjustments as priorities or requirements change.

Designing context-appropriate testbeds is especially important. This may involve repurposing existing facilities, working within available resource constraints, and aligning infrastructure development with local planning systems. For instance, a renewable energy testbed might make use of an underutilized public building to pilot off-grid solar technologies, integrating locally sourced materials and workforce training into the setup. Rather than constructing new sites, the initiative can focus on adapting what is available to test the feasibility of energy solutions under local environmental and grid conditions.

3.1 Site Selection and Architectural Design

Site selection lays the groundwork for all subsequent development activities. The chosen location should be accessible and conducive to the specific types of trials planned—taking into account factors such as environmental conditions, availability of infrastructure (e.g., energy supply and connectivity), regulatory and permitting considerations, local security, and the socio-economic context of the surrounding community. For example, a smart agriculture testbed could benefit from being situated in peri-urban or rural areas where proximity to farms allows direct field testing under varying soil and weather conditions. Proximity to key stakeholders—such as universities, tech companies and research institutions—can help facilitate collaboration and leverage external expertise. Moreover, assessing how the testbed location interacts with the local community can help promote inclusion, minimize disruption, and ensure that the testbed generates shared value.

Once the site is selected, **architectural design** plays a central role in supporting the testbed's long-term functionality and adaptability. The layout should reflect the practical needs of the technologies and experiments being planned, while also allowing flexibility as those needs evolve. Taking a modular approach can enable spaces to be reconfigured, expanded, or adapted over time, supporting iterative innovation and minimizing the need for major structural changes. For example, a modular laboratory equipped with movable partitions and adaptable connectivity could accommodate different use cases—such as shifting from testing environmental sensors to piloting drones—without requiring significant renovation or new infrastructure investment.

People-centric testbeds foster local ownership, encourage community participation, and build trust through integration into the surrounding environment and remaining accessible to all stakeholders. This integration can be achieved via **dedicated spaces for public engagement**—such as demonstration areas, training facilities, and collaborative workspaces—where community members can interact with technologies, share feedback, and co-create solutions. To ensure equitable access, architectural design should account for the needs of all stakeholders, particularly marginalized or

Adopting circular economy principles can further support sustainable operations.

underserved groups. This includes incorporating universal design principles—ramps, elevators, and wayfinding systems, for example—as well as features that promote digital inclusion, such as multilingual user interfaces and assistive technologies.

Establishing appropriate **safety protocols** and ensuring **regulatory compliance** is part of testbed development, particularly when working with high-risk or emerging technologies. This requires the design and implementation of safety procedures that reflect the specific risks posed by the technologies being tested. For instance, testbeds involving high-voltage systems, chemical processing, or autonomous robotics may need to integrate safeguards such as containment systems, emergency stop mechanisms, or automated shutdown protocols. These measures help prevent accidents and manage potential hazards effectively.

Sustainability considerations help ensure the prioritization of resource efficiency and environmental responsibility throughout the project's life cycle. This involves integrating green infrastructure—such as energy-efficient building designs, renewable energy sources such as solar and wind, and the use of sustainable materials—in construction and end-of-life planning. Resource optimization also is important, with systems for water conservation, waste reduction, and energy efficiency playing central roles. For example, installing rooftop solar panels combined with passive cooling systems can reduce energy demand from conventional power sources while enhancing environmental performance. Adopting circular economy principles can further support sustainable operations—by designing systems that enable reuse, recycling, and minimal waste generation. This can be particularly useful during the transition or decommissioning phases of a testbed, helping minimize long-term environmental impact.

In resource-constrained settings, sustainability strategies can also focus on reducing reliance on imported or hard-to-maintain components. For instance, prioritizing locally available materials and technologies—such as regionally manufactured building supplies or open-source hardware—can lower costs, simplify maintenance, and strengthen local supply chains. Affordable and scalable solutions, such as mobile or modular testbeds, are particularly valuable, as they are cost-effective, easy to deploy and adaptable to evolving needs.

Additional relevant materials can be found in the Practical Resources for Testbed Development and Implementation section, which offers further guidance, tools, and references to support the design and execution of testbeds.

Box 4: Strategic Site Selection for the Atmospheric Research Testbed in Central India

Overview

The Atmospheric Research Testbed in Central India (ART-CI) is an initiative of the Indian Institute of Tropical Meteorology (IITM), operating under the Ministry of Earth Sciences. Established to deepen scientific understanding of monsoon convection and regional climate dynamics, the ART-CI plays a key role in advancing atmospheric science in South Asia. The testbed provides a highly controlled and data-rich environment to study the interactions between atmospheric variables and monsoon behavior, contributing to more accurate weather forecasts and long-term climate models.

Image source: Tropmet, 2023, *Atmospheric Research Testbed in Central India (ART-CI)*: https://www.tropmet.res.in/32-project_details

Rationale for Site Selection

The testbed is located in Silkheda, in the Sehore district of Madhya Pradesh, approximately 50 kilometers northwest of Bhopal, India. The site was selected based on a combination of geographic and environmental considerations that make it particularly suitable for atmospheric research.

Geographically, Silkheda lies along the path of major rain-bearing synoptic systems that originate from the Bay of Bengal, offering a strategic vantage point for observing the development and progression of monsoon systems. Its location in central India provides an ideal setting for studying the dynamic processes that shape regional rainfall patterns and broader monsoonal behavior. Environmentally, the site benefits from relatively low levels of anthropogenic pollution, which is critical for collecting clean and uncontaminated meteorological data. This natural advantage enhances the accuracy and reliability of atmospheric measurements, enabling more precise analysis of cloud formation, precipitation mechanisms, and chemical interactions in the atmosphere.

Following the selection of this strategic site, ART-CI was equipped with a wide range of advanced instruments. These include ground-based radars, radiometers, GPS sondes, automatic weather stations, and in situ sensors that provide continuous monitoring of key atmospheric variables such as soil moisture, radiation, wind patterns, cloud microphysics, and aerosol concentrations. This comprehensive infrastructure supports long-term research efforts to better understand monsoon variability, improve forecasting models, and inform regional climate resilience strategies

Vision and Future Development

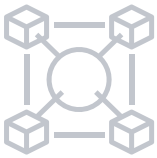
Not only is the testbed a facility for current research, but it also envisioned as a growing hub for atmospheric science. The plan includes phased expansions for further capability enhancement. Each phase aims to add new instruments and technologies that will allow more detailed studies of the interactions between the land and the atmosphere in the core monsoon zone. This strategic development ensures that the testbed remains at the cutting edge of atmospheric research, providing valuable insights that can inform both science and policy for better management of monsoon impacts.

Phased Development and Future Prospects

The establishment of the ART-CI in central India is being carried out in phases, with each stage aimed at incrementally enhancing the testbed's capabilities. The initial phase already has set the groundwork for what is to become a pivotal facility for atmospheric research in India. Future plans include expanding the range of instruments and possibly extending the geographical coverage of the testbed to provide even more detailed insights into the monsoon systems affecting the region.

This strategic site selection and phased development approach not only underscores the importance of geographical and environmental factors in research testbeds but also highlights the commitment to developing a deep understanding of crucial atmospheric processes that affect millions of people in India and beyond.

The Indian Express, 2024, Explained: What is India's Atmospheric Testbed in Bhopal and Why it Matters: https://indianexpress.com/article/explained/explained-climate/india-atmospheric-testbed-bhopal-significance-9215690/



To support seamless operations and knowledge exchange, testbeds should be designed with interoperability in mind.

3.2 Technology Integration

The integration of technologies is a fundamental component in the design and operation of many testbeds, especially those that rely on complex data management, real-time communication, and interconnected systems. However, the level and complexity of technological infrastructure required can vary widely based on the testbed's objectives, scale, and available resources. Some technology-intensive testbeds—such as those focused on autonomous mobility or digital healthcare—may require advanced infrastructure, including high-speed connectivity, secure data platforms, and automated monitoring systems. These components enable the processing of complex data flows, support real-time feedback loops, and facilitate interoperability across connected systems.

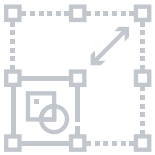
In contrast, smaller-scale or low-tech testbeds may rely on simpler, cost-effective solutions that are specifically tailored to their context. For example, an urban air quality testbed may deploy low-cost environmental sensors and mobile data collection units to monitor pollution hotspots in densely populated neighborhoods. These tools can help communities and local authorities track air quality trends, identify pollution sources, and test policy interventions such as traffic restrictions or green buffers. These affordable and easy-to-maintain technologies can deliver relevant improvements in productivity without requiring complex infrastructure. Whether deploying cutting-edge systems or cost-effective tools, the integration process should be guided by the testbed's purpose, the needs of its stakeholders, and its capacity to adapt and scale over time.

Interoperability and System Integration

To support seamless operations and knowledge exchange, testbeds should be designed with interoperability in mind. This allows diverse technologies, systems, and platforms to work together without disruption, enabling a cohesive environment for experimentation and evaluation. Interoperability not only facilitates technical compatibility but also enhances collaboration across sectors, helping stakeholders jointly develop, test, and refine integrated solutions. This is particularly relevant when technologies intersect across domains—such as energy, mobility, and health—where dynamic, multi-system integration is often required.

At the core of interoperability is the ability of hardware, software, and communication networks to interact effectively. This requires the adoption of open standards, standardized communication protocols, and flexible application interfaces (APIs) to ensure systems can connect and exchange data regardless of vendor or origin. For example, in a healthcare testbed, interoperability may involve linking wearable sensors, patient record systems, and diagnostic algorithms to enable real-time data flow and coordinated clinical responses.

Open-source technologies can offer additional benefits in this context, providing adaptable and transparent options that are particularly useful in settings with limited resources. By reducing dependency on proprietary systems, they enable easier customization and wider participation from local developers and innovators. To support long-term sustainability and adaptability, testbeds should also consider future-proofing their integration strategy. This includes designing for modular upgrades, enabling backward compatibility, and accommodating emerging standards. Regular reviews of system compatibility and collaborative development of integration roadmaps with partners can help keep the testbed responsive to technological shifts and stakeholder needs.



As experiments evolve and data volumes grow, network systems may need to scale up to maintain performance.

Connectivity Infrastructure

Reliable connectivity can be an important consideration for many testbeds, particularly those that rely on continuous data exchange or remote operations. High-speed, stable networks enable real-time monitoring, remote experiment management, and collaboration across geographic locations. This helps ensure that data remains accessible, supports timely decision-making, and facilitates integrated analysis. However, in settings with limited digital infrastructure, testbeds can adopt low-cost and context-appropriate connectivity strategies. For instance, in remote scientific research testbeds, offline data collection tools such as ruggedized data loggers or portable storage devices can capture experimental data for later analysis when connectivity is restored.

In testbeds focused on disaster response and humanitarian technology, temporary communication solutions such as pop-up networks—through portable satellite internet or mobile network hotspots—can enable the rapid deployment of emergency communication and data-sharing systems in hard-to-reach areas. Moreover, to ensure long-term viability, testbed planners should assess the scalability and security of connectivity infrastructure from the outset. As experiments evolve and data volumes grow, network systems may need to scale up to maintain performance.

With the growing use of digital technologies, an increasing number of testbeds focus on communications, wireless systems, and emerging networked solutions such as 5G, IoT, and autonomous mobility. For these testbeds, access to radio spectrum can be a practical consideration. Allocating dedicated or shared spectrum—whether for short-range devices, experimental wireless networks, or satellite-ground communications—can help enable safe, interference-free testing and reliable connectivity. In many cases, testbeds may benefit from temporary or experimental licenses granted by national regulatory authorities, which permit controlled use of frequency bands under defined conditions. Early engagement with regulators is therefore important to clarify procedures, assess compatibility with existing users, and ensure compliance.

Data Infrastructure and Management

Efficient data infrastructure and management underpin many technology-focused testbeds (see Box 1), supporting the collection, storage, analysis, and secure sharing of data generated during testing and experimentation. This data can serve as a feedback mechanism that allows teams to assess performance, refine technologies, and adjust implementation processes in real time. These insights support the iterative development of solutions that are more effective, adaptable, and relevant to the testbed's specific context. Beyond technical learning, testbed data—when systematically analyzed—can inform operational improvements, regulatory adjustments, and public policy, particularly in contexts where there is limited existing data on emerging technologies.

Technology-focused testbeds—especially those working with real-time or sensor-based inputs—often generate large volumes of data. Managing this data effectively requires scalable, secure, and context-appropriate storage solutions. Cloud-based systems can provide flexible and cost-efficient options, particularly for testbeds that may scale over time. However, in sectors where data sensitivity is a concern—such as health, finance, or biotechnology—on-premises servers or hybrid cloud models may be preferred to meet local data protection requirements and compliance standards. For instance, fintech-focused testbeds require encryption, access controls, and multi-layered cybersecurity to protect transaction data and user privacy.

An effective cybersecurity strategy should also include clear incident response procedures to guide actions in the event of a breach or technical failure.

Real-time data processing capabilities can improve responsiveness and support more timely decision-making within testbeds. Combining edge computing with centralized cloud systems enables the rapid processing of data near its source, which can reduce latency and support applications where immediate responses are required. This is particularly relevant in testbeds for autonomous systems, industrial automation, or space technologies, where even brief delays can affect functionality or safety. In parallel, the use of advanced analytics tools, including AI and machine learning, can support pattern recognition, predictive analysis, and continuous refinement, particularly when working with large, complex, or unstructured datasets.

In low-resource settings, data infrastructure and management can face additional constraints, such as limited digital infrastructure, inconsistent internet connectivity, or limited capacity to establish and enforce data governance frameworks. For example, the absence of clear rules on data ownership, sharing, privacy, and security. In these contexts, testbeds can offer a valuable platform to pilot context-appropriate data solutions—such as lightweight, decentralized systems or offline data collection tools—that can function in resource-constrained environments. Importantly, testbeds also can contribute to longer-term capacity development by strengthening local skills in data management, cybersecurity, and analytics. This helps ensure that data-driven innovations are not only technically viable but also sustainable and locally embedded.

Cybersecurity and Vulnerability Management

As testbeds increasingly rely on digital technologies and handle sensitive data, cybersecurity and vulnerability management become important for protecting infrastructure, maintaining research integrity, and ensuring responsible data handling. Establishing a cybersecurity framework helps reduce exposure to threats and safeguards both systems and data. This includes implementing layered security controls such as firewalls, intrusion detection systems, and encryption of data in transit and at rest. Security protocols should align with internationally recognized standards such as the ISO/IEC 27001 for information security management and applicable national cybersecurity frameworks.

Testbeds should also implement proactive vulnerability management to identify and reduce exposure to digital risks. Regular vulnerability assessments, penetration testing, and system monitoring can help detect issues early and prevent disruptions. Structured patch management processes—used to apply timely software and firmware updates—can further minimize risks. For instance, in an industrial automation testbed, failure to patch outdated control systems could expose operations to malware or service interruptions. An effective cybersecurity strategy should also include clear incident response procedures to guide actions in the event of a breach or technical failure. This includes defining roles and responsibilities, outlining steps for containment and recovery, and establishing communication protocols with relevant stakeholders.

Since many cybersecurity breaches originate from human error—such as falling for phishing scams or poor password practices—ongoing awareness and training programs are important. These should cover secure system use, threat recognition, safe data handling, and password management. Building a culture of digital security across staff and partners reinforces shared responsibility and strengthens the overall resilience of the testbed. Additional measures may include segmenting networks, limiting user access based on roles, and integrating cybersecurity considerations from the initial design phase to ensure security is embedded, not added later.

Digital connectivity supports more inclusive and equitable participation, allowing global experts to contribute insights, share tools, and co-develop solutions in real time.

3.3. Infrastructure Planning for Virtual Testbeds

Virtual testbeds are fully digital environments that support simulation, testing, and analysis without the physical constraints of traditional testbeds (see Box 1). These platforms offer several advantages, including cost-effectiveness, scalability, and broader accessibility. While some of the same principles discussed earlier—such as modular design, scalability, and inclusive access—also apply, the digital nature of virtual testbeds introduces distinct considerations and opportunities. In particular, the use of cloud-native architecture plays a central role in enabling flexibility, on-demand resource allocation, and remote collaboration. This section focuses on the specific infrastructure needs of virtual testbeds, with emphasis on their reliance on cloud-based platforms and digital integration tools.

Advanced Simulation Capabilities

One of the main benefits of virtual testbeds is their ability to support high-fidelity simulations that reproduce complex real-world systems in controlled digital environments. These simulations allow researchers and developers to model, test, and refine technologies in scenarios that may be too expensive, unsafe, or logistically difficult to recreate in physical settings. By capturing intricate processes and interactions, virtual testbeds provide a way to conduct context-specific experimentation while minimizing physical risk and resource expenditure.

For instance, a flood simulation model can project how rising water levels in urban areas might disrupt transport networks, strain drainage systems, or affect infrastructure such as hospitals and power stations. These insights can support more targeted emergency planning, infrastructure reinforcement, and evacuation strategies. Similarly, in seismically active regions, virtual models can assess the structural resilience of buildings and bridges under different earthquake intensities, informing decisions on retrofitting and regulatory standards.

Global Accessibility and Collaboration

Virtual testbeds can expand the reach of collaboration by enabling remote access for researchers, innovators, and stakeholders across regions and disciplines. Unlike physical testbeds, which are often bound by location-specific infrastructure and on-site requirements, virtual platforms overcome geographic and logistical barriers. This digital connectivity supports more inclusive and equitable participation, allowing global experts to contribute insights, share tools, and co-develop solutions in real time. Such accessibility is particularly valuable for stakeholders in developing countries, offering entry points to advanced computational capabilities and global collaboration networks that might otherwise remain inaccessible. This, in turn, helps reduce capacity disparities and enables more context-aware innovation.

For instance, virtual testbeds in climate science can connect researchers across continents to collaboratively simulate climate change impacts and test adaptation strategies. These platforms allow scientists in climate-vulnerable regions to engage with advanced modeling tools and datasets, enabling them to design more targeted interventions informed by both local conditions and international knowledge. Similarly, virtual environments can support coordinated disaster preparedness by enabling simulations of joint emergency response across borders—such as during tsunamis, wildfires, or disease outbreaks. By simulating joint response efforts between neighboring countries, virtual platforms help align emergency protocols, improve resource sharing, and strengthen collective resilience.

By enabling physical systems to interface with virtual models in real time, hybrid testbeds can support more diverse use cases and enhance the accuracy and scope of experimentation.

3.4 Hybrid Testbeds: Combining On-Site and Cloud Resources

Hybrid testbeds combine physical infrastructure with cloud-based virtual environments, offering a flexible approach to experimentation and innovation. This integrated model allows teams to conduct on-site testing while accessing cloud-based tools for simulation, data processing, and analytics. By enabling physical systems to interface with virtual models in real time, hybrid testbeds can support more diverse use cases and enhance the accuracy and scope of experimentation. These platforms are particularly useful when testing technologies that require both real-world interaction and advanced computational capabilities. For instance, autonomous vehicle systems can be tested in physical environments while simultaneously running virtual simulations to assess performance under varied traffic and weather conditions. This approach can help identify technical and contextual risks early in the development cycle.

Staged Testing for Risk Mitigation

One of the advantages of hybrid testbeds is their ability to support a staged testing process, which systematically reduces risks by validating technologies in controlled virtual environments before advancing to physical deployment. This sequential approach allows developers to identify and address potential failures early in the development cycle, minimizing costly setbacks and ensuring safer, more reliable innovations. By first leveraging virtual simulations to test concepts, systems, and processes, stakeholders can refine technologies and mitigate operational risks before transitioning to real-world trials.

For example, in the development of autonomous vehicles, initial testing often takes place in virtual environments to simulate complex traffic scenarios, hazardous weather conditions, or emergency responses. These simulations help assess how navigation algorithms and sensor systems behave under varying conditions, without exposing people or equipment to unnecessary risk. Once the system performs consistently in virtual trials, it can be tested in controlled physical environments to validate its real-world functionality. This layered process helps manage risk and supports smoother transitions from concept to deployment.

Digital Twin Technology

Digital twin technology enables real-time simulation and analysis by creating a dynamic digital representation of a physical object, process, or system. This virtual model is continuously updated through data streams from its physical counterpart, allowing for ongoing monitoring, diagnostics, and performance evaluation. The integration of digital twins into testbeds provides opportunities to assess how systems behave under different scenarios, anticipate operational issues, and evaluate the impact of various design or policy choices.

For example, a digital twin of a water distribution network can simulate flow dynamics, pressure variations, and leak scenarios across the system. This enables utility operators to detect inefficiencies, plan preventive maintenance, and evaluate how infrastructure upgrades or demand shifts may affect service delivery. Such simulations also support contingency planning by modelling responses to droughts, pipe failures, or contamination events—allowing for better-informed, risk-aware management of essential services.

Box 5: Innovating Data Center Efficiency in the Tropics Through Physical and Digital Integration

Overview

The Sustainable Tropical Data Centre Testbed in Singapore is an innovative research facility dedicated to enhancing the sustainability and efficiency of data centers operating in tropical climates. Jointly led by the National University of Singapore and Nanyang Technological University, this testbed is strategically designed to address the unique challenges posed by the country's hot and humid environment. The initiative not only aims to reduce the substantial energy consumption typically associated with cooling data centers but also strives to advance cooling technologies that can be adopted globally in similar climates.

The rationale for the testbed's development was multifaceted, addressing both environmental sustainability and economic efficiency concerns. The country's position as a global data center hub made it an ideal location for developing and testing innovative cooling solutions that could be applied across similar climate zones worldwide. The project aims to demonstrate that significant improvements in energy efficiency are achievable through the integration of advanced cooling technologies and smart management systems.

Feasibility and Implementation

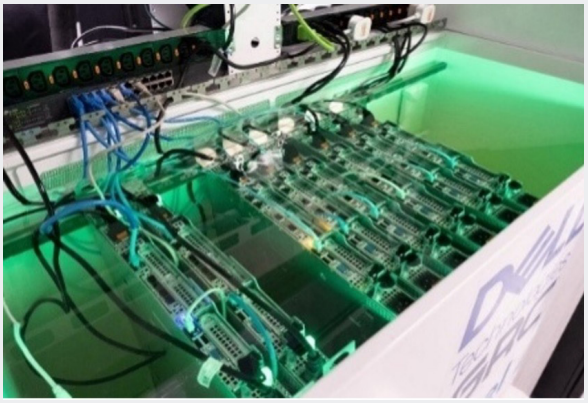
The testbed is endowed with sophisticated infrastructure and technology tailored for evaluating data center cooling solutions in tropical environments. Located at the National University of Singapore, the facility features a suite of systems designed for detailed analysis and optimization of energy efficiency and sustainability in data center operations:

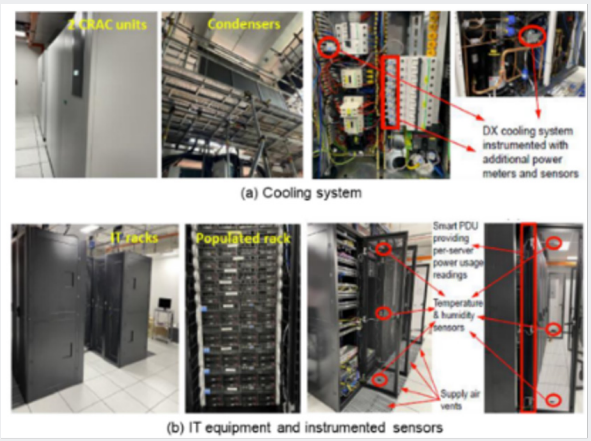
Advanced cooling systems: A key feature of the testbed is its array of cooling technologies adapted to handle the high humidity and ambient temperatures characteristic of tropical regions. Liquid cooling, advanced evaporative cooling systems and other cutting-edge solutions are tested for their efficiency and effectiveness in real-world scenarios.

Integrated renewable energy solutions: The testbed focuses on energy-efficient infrastructure to minimize the carbon footprint of data centre operations, including renewable energy sources (such as solar panels) and energy recovery systems that help reduce overall energy consumption.

High-tech monitoring and evaluation systems: Sophisticated monitoring tools continuously measure the performance of installed cooling systems under various operational conditions. These systems allow researchers to track the performance of cooling technologies in real time and adjust the testing variables to simulate different environmental conditions.

A sophisticated digital twin serves as a virtual counterpart to the physical testbed and provides a dynamic platform for simulation, analysis and optimization:





National University of Singapore, 2024, *Singapore Tropical Data Centre Testbed (STDCT):* https://cde.nus.edu.sg/stdct/

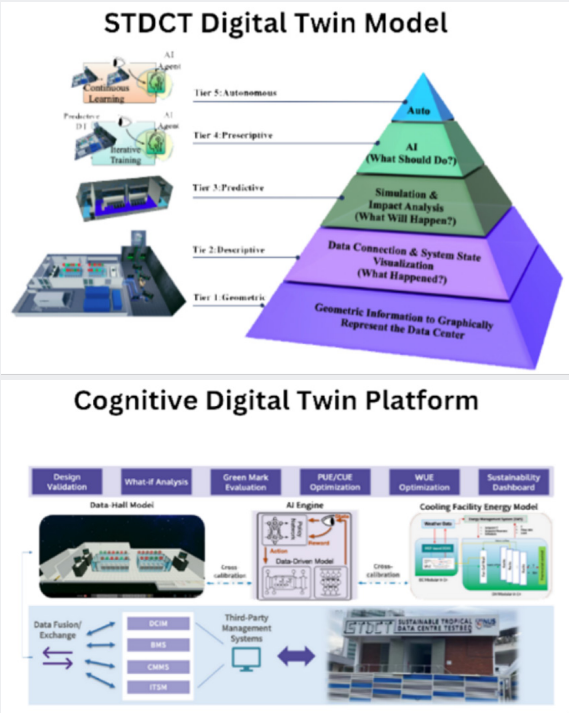
Real-time simulation and analysis: The digital twin technology allows researchers to create accurate, real-time simulations of the physical testbed, including detailed modelling of the data centre's cooling systems, energy consumption and operational dynamics under various climatic conditions. By mirroring the actual operations

within the virtual environment, the digital twin enables detailed scenario analysis without the need to manipulate the physical components directly.

Predictive maintenance and optimization: Using the digital twin, researchers can predict outcomes based on different variables, helping them foresee potential system failures or inefficiencies before they occur. This not only enhances the reliability of operations but also optimizes performance by allowing for adjustments in cooling strategies and energy use to be tested before they are applied in reality.

Facilitating innovation and experimentation: The digital twin extends the testbed's capabilities beyond physical experimentation. It provides a safe and cost-effective environment for testing hypotheses, validating new cooling technologies and refining operational strategies. This virtual testing ground reduces the time and resources spent on physical trials and improves the overall sustainability of data center operations.

Training and education: The digital twin also serves as an educational tool for students and trainees, offering hands-on experience in data center management and operations. This immersive learning environment helps prepare the next generation of engineers and technicians with the skills needed to manage advanced and sustainable data centers.



National University of Singapore, 2024, *Singapore Tropical Data Centre Testbed (STDCT):* https://cde.nus.edu.sg/stdct/

Community Approach

The testbed established itself as a central hub for data center innovation, fostering collaboration among industry partners, academic researchers and technology providers. The facility's open innovation approach encourages industry players to test and validate new cooling technologies within its controlled environment. Regular workshops and technical seminars gather stakeholders from across the industry to share insights and best practices.

The testbed is a valuable educational resource, providing hands-on training opportunities for students and professionals in data center operations and management. The digital twin technology particularly enhances these educational initiatives by offering a risk-free environment for learning and experimentation. The facility also maintains strong partnerships with industry associations and professional bodies, contributing to the development of standards and best practices for tropical data center operations.

Impact

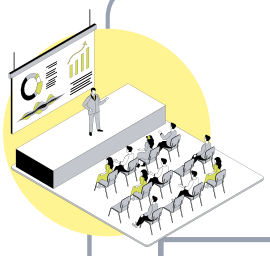
The testbed has advanced sustainable data center operations in tropical regions. It has demonstrated that substantial energy savings are achievable through optimized cooling strategies and innovative technologies, with some tested solutions showing potential energy savings of up to 40 percent compared to conventional cooling systems. These findings have influenced data center design and operational practices across Southeast Asia and other tropical regions.

The testbed's research has contributed to the development of new industry standards for data center sustainability in tropical environments. The facility's integrated approach to physical and digital infrastructure has established a new paradigm for data center testing and optimization, influencing how future facilities are designed and operated. The success of the digital twin implementation has demonstrated the value of virtual simulation in reducing operational risks and optimizing performance.

Phase 4: Operation and Management

Governance and Operational Frameworks

A strong governance structure ensures clear stakeholder roles, decision-making processes, and accountability, fostering collaboration among government agencies, private companies, academic institutions, and communities. Standard Operating Procedures (SOPs) are essential for efficient, safe, and consistent operations, adapting to evolving technologies and priorities.



Resource and Asset Management:

1. **Effective resource management** involves strategic planning, diversified funding sources, and revenue-generating models to ensure financial stability and operational sustainability.
2. **Revenue-generating approaches** to support ongoing operations. These could include charging for specialized services such as equipment usage, technical validation, technology certification, or training programs.
3. **Human resource management** focuses on recruiting skilled professionals, fostering collaboration, and providing ongoing professional development to adapt to emerging priorities.
4. **Ongoing professional development:** Partnerships with academic institutions and innovation hubs can enhance workforce capacity.
5. **Infrastructure maintenance**, both physical and digital, is critical for reliability and long-term functionality.

Risk Management and Mitigation

Testbeds face various risks—operational, financial, technological, and security—that can impact their effectiveness and credibility. Effective risk management involves identifying and assessing these risks to plan proactive mitigation strategies.

Mitigation strategies include contingency protocols to ensure continuity, emergency power supplies, fail-safe systems, and supplier diversification.

People-centered management approaches can enhance the relevance and inclusiveness of the testbed over time.

This phase focuses on ensuring that the testbed functions effectively, delivers intended outcomes, and adapts to changing conditions over time. An adaptive operational framework includes clear governance structures, routine monitoring and evaluation, risk management measures, and ongoing stakeholder engagement. These elements help maintain operational efficiency, ensure responsible use of resources, and support learning and adaptation as technologies and local contexts evolve. People-centered management approaches can enhance the relevance and inclusiveness of the testbed over time. This includes regular engagement with community members, transparent feedback mechanisms, and decision-making processes that involve a broad range of stakeholders—especially those from local communities and underrepresented groups. By institutionalizing inclusive participation and continuous learning, the testbed is more likely to stay grounded in real-world needs and support equitable outcomes.

4.1 Governance and Operational Frameworks

A well-developed governance structure helps support the operation, coordination, and continued relevance of a testbed. As outlined in Section 2.2, stakeholder roles and responsibilities should be clearly defined from the outset to promote shared accountability and facilitate smooth collaboration. An appropriate governance framework describes decision-making processes, clarifies lines of authority, and sets expectations for each participating stakeholder—including government agencies, private-sector actors, academic institutions, and community representatives. Such clarity can contribute to transparent operations, timely coordination, and a more inclusive approach to testbed management.

For instance, in a telecommunications testbed exploring next-generation wireless technologies, an established governance structure can guide collaboration between partners while ensuring compliance with national regulations and international standards. Public agencies may oversee spectrum management, data privacy, and cybersecurity compliance in line with strategic policy objectives. Technology companies may contribute by designing and testing network infrastructure and services. Academic institutions may focus on experimental research, modeling use cases, and examining the societal implications of deployment. In parallel, local businesses and end users can offer feedback on reliability, affordability, and usability, helping ensure that the testbed addresses both technical performance and social relevance.

Establishing a reliable operational framework for a testbed begins with the creation of comprehensive standard operating procedures (SOPs) that guide every aspect of day-to-day operations. (see Box 2) These SOPs serve as the backbone of the testbed, ensuring that activities are conducted efficiently, safely, and consistently. They cover a wide range of functions, from routine maintenance and equipment calibration to emergency response protocols. To maintain operational efficiency, SOPs should streamline workflows and incorporate automation where feasible to reduce redundancy and enhance productivity. They should be clearly documented and easily accessible to all personnel, with regular training sessions to ensure compliance. Importantly, SOPs should be treated as living documents—regularly reviewed and adjusted to reflect evolving technologies, shifting priorities, and lessons learned from practice.

For example, in a marine energy testbed focused on testing wave energy converters, detailed SOPs are crucial for managing the complex and high-

A diverse funding portfolio can reduce reliance on a single funding stream and strengthen the testbed's ability to weather fluctuations in support.

risk marine environment. These procedures cover protocols for the safe deployment and retrieval of wave energy converters, guidelines for operating heavy maritime equipment, and real-time monitoring of environmental impacts on marine ecosystems. Maintenance schedules are designed to account for harsh ocean conditions, including corrosion and biofouling, while safety protocols outline step-by-step actions for handling severe weather disruptions or equipment failures at sea, among other emergencies. Additionally, SOPs would establish coordination procedures between offshore and onshore teams to ensure seamless communication during testing operations.

4.2 Resource and Asset Management

Sound resource management requires deliberate planning and allocation to sustain operations, maintain infrastructure, and adapt to changing needs. A robust approach to managing resources and assets helps testbeds remain resilient, scale appropriately, and pursue innovation in line with their objectives. In contexts with limited resources, this becomes particularly important. Strategic use of available assets—such as sharing equipment, repurposing existing facilities, or sourcing materials locally—can help reduce costs and improve relevance to the surrounding community. Diversifying funding sources can also enhance financial stability and provide access to technical expertise (see Box 4).

Securing long-term financial viability requires more than basic funding—it required a adaptive **financial strategy** that evolves alongside the testbed's operational and strategic direction. This includes aligning budget allocations with immediate operational priorities while also supporting long-term growth and capacity building. A diverse funding portfolio—drawing from public sources, private-sector contributions, philanthropic initiatives, and grant mechanisms—can reduce reliance on a single funding stream and strengthen the testbed's ability to weather fluctuations in support.

In addition to external sources, testbeds may consider **revenue-generating approaches** to support ongoing operations. These could include charging for specialized services such as equipment usage, technical validation, technology certification, or training programs. Such models can help offset operational costs while reinforcing the testbed's role as a valued resource for local innovators, researchers, or enterprises. In some cases, intellectual property generated through testing and experimentation may be licensed to external parties for further development or commercialization, offering a potential revenue stream for the testbed or its hosting institution. By integrating these service-based offerings into their operational model, testbeds can enhance their long-term financial viability while also contributing to broader ecosystem development.

The ability of a testbed to remain operational and evolve over time depends largely on the capacity, expertise, and commitment of its people. **Human resource management** ensures that the necessary skills and leadership are in place to support complex testing environments, manage partnerships, and adapt to emerging priorities. Developing a capable workforce begins with recruiting individuals who offer both technical expertise and cross-functional

Additional relevant materials can be found in the Practical Resources for Testbed Development and Implementation section, which offers further guidance, tools, and references to support the design and execution of testbeds.

Retaining talent is as important as attracting it. Sustaining operations and preserving institutional knowledge over time requires intentional strategies to foster staff motivation and well-being.

competencies. These may include knowledge in areas such as technology development, systems integration, project coordination, regulatory frameworks, or community engagement. In addition to technical skills, hiring practices should place emphasis on collaborative mindsets, adaptability, and practical problem-solving—traits particularly valuable in multidisciplinary and fast-changing testbed settings.

Ongoing professional development is also important. Providing structured opportunities for staff to engage with emerging technologies, sectoral trends, and applied research enhances the testbed's ability to remain responsive and relevant. This may include technical upskilling, leadership development, or cross-sector exchanges that facilitate learning across different innovation domains. Retaining talent is as important as attracting it. Sustaining operations and preserving institutional knowledge over time requires intentional strategies to foster staff motivation and well-being. These could include clear career development pathways, inclusive workplace practices, and regular opportunities for feedback and recognition.

In many developing countries, attracting and retaining skilled professionals can pose challenges. To address this, testbeds may adopt context-appropriate and forward-looking approaches to workforce development. Partnerships with academic institutions, public agencies, and regional innovation hubs can offer additional human resource support through student placements, secondments, or shared training programs. These collaborations not only help build capacity but also strengthen the testbed's connections within the broader innovation ecosystem. Moreover, testbeds can strengthen local capabilities by embedding training and knowledge transfer into their operational models. This may include hosting on-site fellowships, apprenticeships, or collaboration with vocational programs to provide practical experience and build long-term capacity.

Regular infrastructure maintenance supports the continued functioning, reliability, and relevance of a testbed. For physical infrastructure, this includes routine inspections, timely repairs, and the replacement of equipment that is no longer performing as intended, all of which help reduce the risk of disruptions and ensure continued operations. Preventive measures—such as scheduled servicing and diagnostics—can help maintain system stability and extend asset lifespan. For digital infrastructure, maintenance involves ongoing software updates, cybersecurity enhancements, and scaling of computational resources to meet emerging demands. This includes patching vulnerabilities, optimizing performance, and integrating updated tools or platforms that enable advanced testing.

4.3 Risk Management and Mitigation

Testbeds may face a diverse array of risks—spanning operational, financial, technological, and security dimensions—that can undermine their effectiveness, continuity, or credibility. A proactive approach to risk management begins with the structured identification and assessment of these risks, allowing testbeds to anticipate potential disruptions and plan accordingly. Operational risks—such as equipment failure, staffing limitations, or delays in service delivery—can be addressed through routine maintenance, contingency planning, and redundant systems. Financial risks—including volatile funding streams, cost overruns, or delayed disbursements—require robust budgeting practices, conservative forecasting, and a diversified financial base to strengthen resilience. Technological and cybersecurity threats—such as outdated software, data leaks,

To complement technical and operational safeguards, testbeds should also integrate reputational and ethical risk management into their overall framework.

or unauthorized access—should be continuously monitored and managed through timely system updates, infrastructure safeguards, and capacity-building initiatives, including staff training on digital scams and risk protocols.

Once risks are assessed, testbeds should formulate context-appropriate mitigation strategies aimed at preserving operational continuity and stakeholder confidence. This includes establishing clear contingency protocols to maintain essential functions, minimize disruptions, and ensure regulatory compliance. Examples might include maintaining emergency power supplies, implementing fail-safe systems for mission-critical data, or developing relationships with multiple suppliers to reduce dependency on any single source. Periodic scenario planning, tabletop exercises, and simulated stress tests can also enhance the readiness of testbed teams to respond swiftly and cohesively in high-pressure situations. These practices not only prepare personnel to manage emergencies but also reveal system-level weaknesses that can be addressed in advance.

To complement technical and operational safeguards, testbeds should also integrate reputational and ethical risk management into their overall framework. This includes adhering to national and international regulations related to privacy, data use, environmental standards, and the ethical treatment of participants in trials or studies. Establishing internal oversight mechanisms, such as data governance committees or ethics review boards, can help ensure compliance and build stakeholder trust. In highly sensitive domains—such as healthcare, energy, or public infrastructure—public communication strategies may also be useful to manage misinformation and foster transparency. Maintaining open communication channels—such as dedicated websites, public dashboards, newsletters, or stakeholder briefings—can help testbeds engage communities, funders, and regulatory authorities, reduce misunderstandings, and reinforce transparency and accountability.

Box 6: Soma Lab: Pioneering Hydrogen Innovation and Community Engagement

Overview

In 2018, IHI Corporation, in collaboration with Soma City and Fukushima Prefecture, established the Soma IHI Green Energy Center (SIGC) to drive regional revitalization through innovative energy solutions. Located in Soma City, which was severely affected by the Great East Japan Earthquake in 2011, the SIGC is a smart community project that aims to promote the local production and consumption of solar power. In September 2020, the Soma Lab, a research facility for renewable energy-derived hydrogen utilization, was opened within the SIGC. The lab promotes carbon recycling research to utilize CO_2-free hydrogen produced by using surplus renewable electricity.

The Soma Lab fosters community engagement and regional revitalization by serving as a hub for open innovation in hydrogen utilization technologies. Designed to attract researchers and innovators from around the world, the lab facilitates the development and market launch of hydrogen technologies, thereby contributing to the realization of a hydrogen economy in Fukushima. The influx of global researchers to Soma City not only accelerates technological advancements but also enhances cultural and intellectual exchanges, strengthening the region's profile as a centre for innovation.

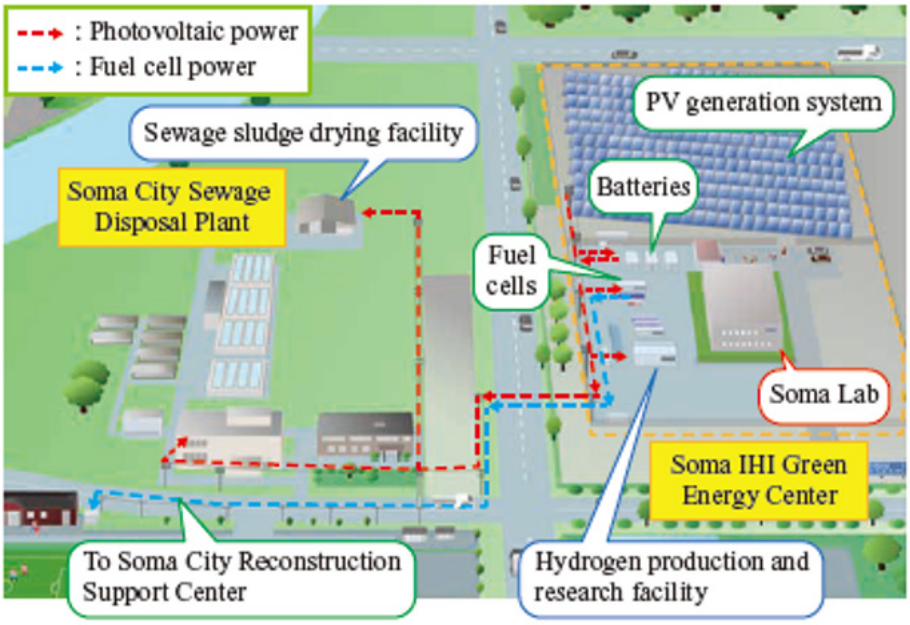
Feasibility and Implementation

The facility's physical infrastructure includes advanced hydrogen production and utilization systems, including a green hydrogen and CO_2 methanation system. The implementation plan carefully considered safety requirements for hydrogen handling while maintaining an open, welcoming environment for community engagement.

The technical infrastructure was developed to support both research activities and practical demonstrations of hydrogen technology applications. This included the installation of hydrogen production facilities powered by surplus renewable electricity, testing facilities for various hydrogen applications, and demonstration units for public education and engagement.

Community Approach

A key feature of the Soma Lab is its dedicated community space, which is strategically designed to encourage interaction and



IHI Corporation, 2024, *Soma Lab: Creating New Value Through Hydrogen Technology and Regional Collaboration:* https://www.ihi.co.jp/en/technology/techinfo/contents_no/1199390_13586.html

collaboration among researchers from diverse fields. This space, overlooking a photovoltaic generation system, presents the work of the SIGC to visitors and facilitates discussions on future energy concepts. Additionally, the lab's conference room is used for community-oriented activities, such as experiential learning programmes for children. Developed in collaboration with Soma City, these programmes aim to deepen the understanding of science and energy—particularly hydrogen—among the younger generation.

The Soma Lab also is actively involved in community events such as the Children's Science Festival, where interactive demonstrations, including hydrogen-powered go-karts, are used to engage children and spark their interest in the hydrogen economy. Furthermore, the lab contributes directly to local transportation initiatives by supplying e-methane, produced through its green hydrogen and CO_2 methanation system, to power the country's first e-methane vehicles for Soma City's community bus service. This initiative not only supports the local production and consumption of solar energy but also underscores the lab's commitment to regional development and sustainability.

Impact

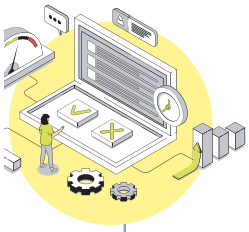
The Soma Lab has achieved significant impacts in both technical innovation and community revitalization. The facility has successfully attracted international researchers and collaborators, establishing Soma City as a recognized center for hydrogen technology innovation. The practical implementation of hydrogen technologies, particularly in local transportation, has demonstrated the feasibility of hydrogen-based solutions in everyday applications.

The lab's community engagement initiatives have successfully increased public understanding and acceptance of hydrogen technologies while contributing to the region's educational resources. The facility has played a crucial role in the area's economic recovery by attracting investment and creating high-skilled employment opportunities in the renewable energy space .

Lessons Learned

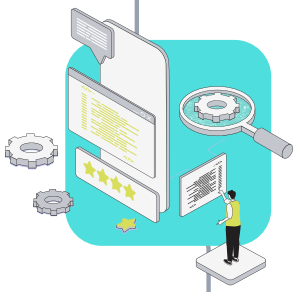
The success of Soma Lab's community engagement approach demonstrates how scientific research facilities can effectively contribute to regional revitalization while advancing technological innovation. The experience has highlighted the importance of demonstrating practical applications of research outcomes in building community support and understanding. The success of initiatives like the e-methane-powered community bus service shows how research facilities can contribute directly to community infrastructure while advancing research objectives.

Phase 5: Monitoring, Evaluation and Iterative Improvement



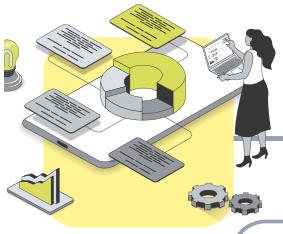
Monitoring and Evaluation Framework

A well-structured M&E framework helps testbeds assess progress, ensure accountability, and support evidence-based adjustments. It involves defining relevant metrics tailored to the testbed's goals.



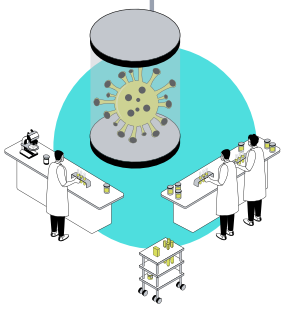
Feedback Integration and Iterative Improvement

Regular stakeholder feedback through surveys, interviews, and workshops helps testbeds adapt to changing contexts and address real-world needs. An adaptive management approach allows dynamic adjustments to strategies, processes, and objectives based on feedback and M&E findings.



Reporting and Knowledge-Sharing

Transparent reporting and consistent knowledge-sharing foster accountability, collaboration, and informed decision-making. Reporting formats vary based on audience needs, such as progress reports, dashboards, or open-access portals. Knowledge-sharing through technical papers, case studies, and global platforms helps reduce duplication and supports peer learning.



Scaling, Replication, and Exit Strategies

Scaling and replication strategies focus on adapting successful testbed models across diverse contexts. Temporary testbeds validate innovations within a limited timeframe, while scalable testbeds serve as reference models for broader adoption. Exit planning ensures innovations transition into markets, policies, or standards, maintaining their value post-project.

Ongoing monitoring and evaluation allow testbeds to assess progress against clearly defined goals and adapt to changing circumstances. By tracking key performance indicators (KPIs), resource use, stakeholder engagement, and policy alignment, testbeds can make informed decisions to adjust strategies, improve performance, and maintain relevance over time. This process supports transparency, accountability, and evidence-informed management.

Testbeds should establish feedback loops that draw on performance metrics, stakeholder input, and lessons learned from previous cycles.

Iterative improvement is central to this phase. Rather than treating evaluation as a one-time activity, testbeds should establish feedback loops that draw on performance metrics, stakeholder input, and lessons learned from previous cycles. These insights can be used to refine protocols, update tools, improve user experiences, and realign priorities where needed. This approach is particularly valuable when testbeds are addressing complex or rapidly evolving challenges—such as climate resilience, health innovation, or digital governance—that require ongoing learning and adaptive responses.

5.1 Establishing a Monitoring and Evaluation Framework

A well-structured monitoring and evaluation (M&E) framework enables testbeds to assess progress, ensure accountability, and support evidence-based adjustments over time. To translate testbed objectives into **actionable performance insights**, it is important to define relevant metrics or indicators that align with the testbed's goals and context, as highlighted in the *section 1.1 Identify Key Issues and Objectives*. These performance measures—whether in the form of Key Performance Indicators (KPIs), outcome indicators, or qualitative benchmarks—can vary significantly depending on the nature of the testbed, the technologies being tested, and the sectoral or societal priorities it aims to address. For instance, a testbed focused on regulatory innovation might prioritize indicators related to policy uptake or procedural efficiency, while one centred on technological experimentation might track throughput, validation rates, or technical reliability.

A comprehensive set of indicators should capture **multiple dimensions of performance**, such as operational effectiveness, environmental sustainability, social inclusion, and economic value. Operational metrics assess system uptime, testing cycles completed, or responsiveness to technical failures. Social indicators examine levels of stakeholder engagement, inclusivity of participation, or responsiveness to community feedback. Environmental metrics measure emissions reduction, energy usage, or resource efficiency. By tailoring these indicators to the testbed's unique mandate, teams can generate insights that support ongoing learning and facilitate evidence-based decision-making.

Moreover, baselines and benchmarking practices can help contextualize progress and performance. Baseline data provide a starting point against which future results can be measured, while benchmarking allows testbeds to compare their performance against industry standards, similar projects, or global best practices. For example, the Sustainable Tropical Data Centre Testbed (STDCT) in Singapore (see Box 6) illustrates how an M&E framework can drive results. Since its launch in 2021, the testbed has tracked progress against time-bound KPIs tailored to tropical conditions. By mid-2024, it aimed to achieve a 40% reduction in energy use, a 30–40% cut in water consumption, and a 40% decrease in CO_2 emissions—potentially lowering emissions to less than 0.54 million tons per year. The testbed also targets a Power Usage Effectiveness (PUE)[10] of less than 1.2, outperforming Singapore's current standard of 1.3 and the global average of 1.5.[11] These measurable, data-driven targets show how continuous performance tracking can help testbeds achieve ambitious sustainability goals while optimizing their technical operations.

[10] PUE value of 1.0 signifies optimal power usage efficiency.
[11] National University of Singapore, 2023, November 29, *Testbed for cooling tech in tropical data centres launched at NUS*: https://cde.nus.edu.sg/news-detail/tropical-climate-data-centre-testbed-launched-at-nus/

At the technical level, M&E results can help refine test protocols, update performance benchmarks, or adjust experimental variables to better reflect real-world conditions.

5.2 Feedback Integration and Iterative Improvement

Regular stakeholder feedback enables testbeds to evolve effectively, remain responsive to changing contexts, and address real-world needs. Structured feedback mechanisms—such as surveys, interviews, focus groups, or interactive workshops—help maintain an ongoing dialogue with stakeholders, including end users, researchers, industry partners, and local communities. These interactions can provide insights into user experiences, uncover operational or design-related issues, and identify emerging priorities that may not have been initially anticipated.

To transform this valuable feedback into actionable change, testbeds can embrace an adaptive management approach that allows testbeds to adjust their strategies, processes, and objectives dynamically and respond swiftly to new information or shifting circumstances. This approach empowers managers to promptly address unexpected technical challenges, refine stakeholder engagement tactics, or reallocate resources as conditions evolve. For instance, feedback from end users might reveal previously unidentified barriers to technology adoption—such as language, access, or maintenance concerns—which could inform refinements that improve usability and relevance in the local context.

Moreover, the iterative improvement is also supported by findings from M&E efforts, which generate evidence on what works, what does not, and why. These insights can be applied across multiple levels of testbed operations. At the operational level, M&E findings may highlight inefficiencies in workflows—such as delays in data processing, resource bottlenecks, or coordination gaps between stakeholders—prompting process redesign or the adoption of digital tools to improve coordination and turnaround times. At the technical level, M&E results can help refine test protocols, update performance benchmarks, or adjust experimental variables to better reflect real-world conditions. This iterative process ensures that testing methodologies evolve alongside user feedback, environmental factors, or policy shifts.

5.3 Reporting and Knowledge-Sharing

Transparent reporting and consistent knowledge-sharing support accountability, foster collaboration, and enable broader uptake of insights. Providing regular updates on testbed progress, challenges, and outcomes helps maintain stakeholder trust and encourages continued engagement. Reporting can take different formats depending on the audience and purpose—such as progress reports for funders, performance dashboards for internal teams, summary briefs for policymakers, or open-access portals that share real-time data and outcomes with the public.

Knowledge-sharing allows lessons learned from testbed activities to inform others working in similar or related areas. Documenting practical experiences—including implementation processes, technical adjustments, and stakeholder engagement methods—can support peer learning, reduce duplication of effort, and contribute to more informed decision-making. These insights may be shared through technical papers, case studies, policy briefs, conference presentations, or participation in global learning platforms and practitioner networks.

For testbeds operating in developing countries, structured reporting and documentation can also help mobilize support and share locally grounded

Sharing results in accessible, evidence-based formats can contribute to national policy discussions, attract international collaboration, and support future funding opportunities.

approaches with wider audiences. Sharing results in accessible, evidence-based formats can contribute to national policy discussions, attract international collaboration, and support future funding opportunities. Experiences from resource-constrained environments—such as how local supply chains were integrated or how inclusive engagement was ensured—may also inform other initiatives facing similar conditions.

5.4 Scaling, Replication, and Exit Strategies

Testbeds may vary significantly in their scope, duration, and long-term objectives. Some are time-bound initiatives established to explore specific innovations or policy ideas within a clearly defined context. Once their goals are achieved, these testbeds are either dismantled or integrated into broader systems. Others are designed from the outset to support ongoing innovation, inform broader policy agendas, and enable replication across multiple geographies or sectors.

Temporary, single-use testbeds are often deployed to validate targeted innovations within a limited timeframe. For instance, the Tokyo 2020 Olympic Hydrogen Testbed[12] was set up to demonstrate hydrogen-powered energy systems in the Olympic Village. Following the Games, most of the infrastructure was decommissioned, although selected components were integrated into Japan's longer-term hydrogen strategy. This approach allows governments or project teams to assess feasibility in a controlled environment without committing to sustained operations.

By contrast, other testbeds serve as platforms for scalable innovation and replication. A smart city testbed piloted in one municipality, for example, may test integrated solutions such as digital payment systems, real-time transit data, or connected public infrastructure. Once proven effective, these models can be adapted and applied in other cities or regions—especially when accompanied by clear documentation, capacity-building efforts, and enabling policy frameworks. In these cases, the testbed functions as a reference model that informs wider adoption and institutional learning.

To effectively scale innovations and replicate successful models, testbeds should develop scaling strategies that support adaptation across varying contexts. This includes creating adaptable toolkits, flexible implementation frameworks, and knowledge-transfer mechanisms that allow others to draw from tested experiences. For instance, energy-efficiency innovations tested in urban settings may need careful adaptation—such as redesigning equipment or adjusting processes—to match local infrastructure conditions, resource constraints, and community preferences in rural or peri-urban areas. This customization ensures that testbed solutions remain relevant, practical, and beneficial across diverse environments.

An important yet often overlooked component of scaling is deliberate exit and transition planning. Such planning outlines clear pathways for tested innovations to move beyond the testbed environment into broader market contexts, public policies, or sectoral standards. This process may involve identifying private-sector partners to support commercialization, collaborating with policymakers to integrate outcomes into existing regulations or public service delivery models, or aligning innovations with national strategies and

[12] International Olympic Committee, 2021, July 17, *At Tokyo 2020, hydrogen shows promise of a carbon-free future*: https://olympics.com/ioc/news/at-tokyo-2020-hydrogen-shows-promise-of-a-carbon-free-future

Clear transition pathways help maintain continuity and ensure that testbed-generated knowledge and solutions continue to contribute value after the project ends.

development priorities. Clear transition pathways help maintain continuity and ensure that testbed-generated knowledge and solutions continue to contribute value after the project ends.

In some developing countries, infrastructure limitations, constrained budgets, and fragmented service delivery systems can significantly hinder the ability to maintain or expand pilot initiatives beyond their initial testing phase. These challenges often result in pilots that remain isolated, unable to transition into fully integrated or self-sustaining solutions. To overcome these barriers, stakeholders can take a proactive, systems-oriented approach. This includes establishing strong institutional partnerships at an early stage—across public agencies, academic institutions, and civil society—to ensure cross-sector alignment and shared responsibility for scaling. Aligning pilot objectives with national development plans or sectoral strategies helps increase policy relevance and the likelihood of long-term adoption. Equally important is investing in local capacity-building through training, mentorship, and embedded knowledge-transfer practices, so that government partners and communities are equipped to lead implementation after the pilot ends.

Success Factors and Lessons for Developing People-Centric Testbeds

1. Clear Objectives Aligned with Community Priorities

Testbeds benefit from having a clearly defined set of objectives that reflect the needs and priorities of the communities they engage. Early engagement with relevant stakeholders can help ensure that tested innovations are context-sensitive, socially appropriate, and focused on addressing tangible challenges. This alignment also supports trust-building and enhances long-term value for users and beneficiaries.

2. Inclusive Collaboration and Structured Partnerships

The active involvement of diverse partners—including public institutions, private sector entities, academic bodies, and civil society—can strengthen a testbed's design and implementation. Clearly defined roles, transparent coordination mechanisms, and mutually agreed objectives help foster stable and productive partnerships. In particular, collaborations that bridge sectors can enhance access to resources, technical capabilities, and policy support.

3. Pragmatic Resource Planning and Operational Flexibility

Effective resource planning contributes to both the stability and responsiveness of testbed operations. Financial, technical, and human resources can be deployed more effectively when managed with flexibility and an eye toward evolving needs. Where resources are limited, strategies such as modular implementation, leveraging shared infrastructure, or tapping into local capabilities may offer more sustainable pathways forward.

4. Continuous Monitoring and Iterative Adjustment

Monitoring and evaluation frameworks allow testbeds to track progress, assess results, and adapt operations over time. The use of performance data and stakeholder feedback can support timely adjustments to design, improve implementation, and maintain alignment with changing priorities. Testbeds that incorporate learning and reflection into their management processes are often better positioned to remain relevant in dynamic environments.

5. Knowledge-Sharing and Capacity Development

Disseminating findings, lessons, and methodologies can extend the influence of a testbed beyond its original scope. Sharing knowledge—whether through publications, events, or digital platforms—enables others to learn from the experience and apply insights in new settings. At the same time, investing in local capacity—through training, mentoring, or embedded learning—can help build long-term institutional strength and retain expertise within the ecosystem after the testbed concludes.

Practical Resources for Testbed Development and Implementation

1. Designing People-Centric and Inclusive Testbeds

- **Using Human-Centred Design** – UNICEF
  A practical guide illustrating how user-centered design methodologies can be applied to co-create technology and public services effectively.
  https://www.sbcguidance.org/create/using-human-centred-design
- **A Framework for National Dialogues on Frontier Technologies** – UNDP
  Offers guidance for organizing inclusive consultations to integrate community perspectives into technology governance.
  https://www.undp.org/acceleratorlabs/publications/framework-frontier-tech

2. Strategic Planning and Innovation Management

- **The United Nations Innovation Toolkit (S.P.A.C.E.)** – UN Innovation Network
  Helps institutions structure innovation efforts using a proven five-part framework.
  https://www.uninnovation.network/innovation-toolkit
- **How to Build a Regulatory Sandbox: A Practical Guide for Policy Makers** – CGAP / World Bank
  Detailed guidance for designing and managing regulatory sandboxes for tech experimentation.
  https://www.cgap.org/research/publication/how-to-build-regulatory-sandbox-practical-guide-for-policy-makers

3. Stakeholder Engagement and Partnerships

- **Public-Private Dialogue (PPD) Stakeholder Mapping Toolkit** – World Bank
  Provides tools for identifying, mapping, and engaging diverse stakeholders.
  https://documents1.worldbank.org/curated/en/842721467995900796/pdf/106395-WP-PUBLIC-PPD-Stakeholder-Mapping-Toolkit-2016.pdf
- **Five-Step Approach to Stakeholder Engagement** – BSR
  Offers a structured methodology for identifying, engaging, and sustaining stakeholder participation.
  https://www.bsr.org/en/reports/bsrs-five-step-approach-to-stakeholder-engagement

4. Risk, Safety, and Environmental Considerations

- **Environmental, Health and Safety General Guidelines** – World Bank
  Sets out baseline EHS standards to ensure sustainable and safe project implementation.
  https://documents1.worldbank.org/curated/en/157871484635724258/pdf/112110-WP-Final-General-EHS-Guidelines.pdf
- **Guidelines for the Testing of Chemicals** – OECD
  International guidelines for chemical testing to support responsible innovation in fields such as biotech.
  https://www.oecd.org/en/topics/sub-issues/testing-of-chemicals/test-guidelines.html
- **Guidance on Developing Safety Performance Indicators for Industry** – OECD
  Helps testbed managers evaluate safety metrics in industrial or high-risk innovation contexts.
  https://www.oecd.org/en/publications/guidance-on-developing-safety-performance-indicators-for-industry_9789264221741-en.html

5. Data Privacy, Ethics, and Cybersecurity

- **Data Privacy, Ethics and Protection: Guidance Note on Big Data for Achievement of the 2030 Agenda**– UN Global Pulse
  Offers principles and frameworks for managing data ethically in development contexts.
  https://unsdg.un.org/sites/default/files/UNDG_BigData_final_web.pdf
- **Principles on Personal Data Protection and Privacy** – UN SCEB
  A UN-wide framework for safeguarding personal data in digital projects.
  https://unsceb.org/principles-personal-data-protection-and-privacy-listing
- **ISO/IEC 27001:2022 Information Security Management Systems** – ISO
  An international standard for information security and risk management.
  https://www.iso.org/standard/27001
- **Global Cybersecurity Index (GCI)** – ITU
  A global benchmark to assess cybersecurity readiness and regulatory maturity.
  https://www.itu.int/en/ITU-D/Cybersecurity/pages/global-cybersecurity-index.aspx
- **Internet of Things (IoT) Cyber Security Guide** – IMDA Singapore
  Outlining security best practices for deploying IoT systems securely.
  https://www.imda.gov.sg/-/media/imda/files/regulation-licensing-and-consultations/ict-standards/telecommunication-standards/reference-spec/imda-iot-cyber-security-guide.pdf

6. Infrastructure and Asset Management

- **Managing Infrastructure Assets for Sustainable Development** – UN DESA
  Provides a guidance on how governments and agencies can manage infrastructure assets sustainably from planning through to lifecycle maintenance.
  https://desapublications.un.org/publications/managing-infrastructure-assets-sustainable-development-handbook-local-and-national

Glossary

5G: The fifth generation of wireless technology, 5G offers faster speeds, lower latency and greater capacity than previous generations. It enables advanced applications such as real time communication, Internet of things (IoT) and enhanced mobile broadband.

6G: The upcoming sixth generation of wireless technology, 6G is anticipated to provide even faster speeds, lower latency and greater capacity than 5G. It is expected to support advanced technologies such as AI-driven communications, holographic connectivity and ultrarealistic simulations, further transforming industries and digital experiences.

Advanced Encryption Standard (AES): A widely used encryption algorithm that secures data through symmetric key cryptography. Known for its speed and strong security, AES is utilized in applications such as wireless communication, file encryption and secure data transmission.

Application Programming Interface (API): An application programming interface is a set of rules and protocols that allow software applications to communicate and interact with each other. APIs enable the seamless integration of functionalities, the exchange of data and the creation of interoperable systems across platforms.

Artificial Intelligence (AI): Artificial intelligence refers to the capability of machines to simulate human intelligence, enabling them to perform tasks such as learning, reasoning and decision-making. It is used in applications such as predictive analytics, natural language processing and autonomous systems.

Calibration: The process of adjusting and verifying the accuracy of a device or system by comparing it against a standard reference, calibration ensures that measurements are precise, reliable and consistent with established benchmarks.

Cloud Computing: Cloud computing offers on-demand and scalable computing resources over the Internet. It allows users to use space or capabilities not available on their personal machines.

Data Integration: Data integration is the process of combining data from multiple sources into a unified, accurate and up-to-date data set.

Digital Twin: A digital twin is a virtual representation of a physical object, process or system that is continuously updated with real time data. Digital twins enable simulation, monitoring and analysis to optimize performance, predict issues and support decision-making.

Edge Computing: Edge computing is a distributed computing model in which data are processed and computations performed closer to the data's source, reducing latency and improving data privacy and security.

Electric Vehicle (EV): An electric vehicle is powered entirely or partially by electricity that is stored in batteries or obtained from an external source.

End User: An end user is an individual or group who ultimately uses or benefits from a product, service or system and whose needs and feedback are central to the design and implementation process.

Feedback Loop: A feedback loop is a process in which information from past actions or outcomes is used to adjust future actions, ensuring continuous improvement and adaptation in response to real-world conditions and stakeholder input.

Firewall: A firewall is a security system that monitors and controls incoming and outgoing network traffic based on predetermined security policies.

Green Hydrogen: Green hydrogen is hydrogen produced through the process of electrolysis powered by renewable energy sources, such as solar or wind.

Heating, Ventilation and Air Conditioning (HVAC): A heating, ventilation and air conditioning system is designed to regulate indoor temperature, humidity and air quality for comfort and efficiency.

High-Performance Computing (HPC): High-performance computing refers to the use of supercomputers and specialized computing resources to perform complex calculations at high speeds. HPC is essential for processing large data sets, running simulations and solving advanced scientific and engineering problems.

Intrusion Detection System (IDS): An intrusion detection system is a network security tool that monitors network or system activities for suspicious behaviour or policy violations, alerting administrators to potential threats or breaches.

Internet of Things (IoT): The Internet of things is a network of interconnected physical devices embedded with sensors, software and other technologies that enable them to collect, exchange and act on data.

Key Performance Indicator (KPI): A key performance indicator is a measurable value used to assess the effectiveness of an organization, project or process in achieving specific objectives.

Memorandum of Understanding (MoU): A memorandum of understanding is a document outlining the general terms and understanding between two or more parties and detailing their roles, responsibilities and intentions.

Multifactor Authentication (MFA): Multifactor authentication is a security process that verifies a user's identity through two or more authentication methods, such as a password, a smartphone-generated code or biometric data.

Project Charter: A project charter is a formal document that outlines the objectives, scope, stakeholders and overall framework of a project. It serves as a foundational reference for all participants, defining roles, responsibilities and goals to ensure alignment and guide project execution.

Role-Based Access Control (RBAC): Role-based access control is a security mechanism that restricts system access based on a user's role within an organization.

Secure Sockets Layer/Transport Layer Security (SSL/TLS): Cryptographic protocols that provide secure communication over a network by encrypting the data transmitted between systems. Transport Layer Security, the successor to Secure Sockets Layer, ensures data integrity, confidentiality and authentication, making it essential for securing websites, emails and other online services.

Security Information and Event Management System: A security information and event management (SIEM) helps organizations detect, analyse and address potential security threats and vulnerabilities before they can harm business operations.

SMART: An acronym for setting specific, measurable, achievable, relevant and time-bound goals. The SMART framework is used to ensure that objectives are clearly defined and realistic; it helps improve focus, motivation and the likelihood of successful outcomes.

Smart Grid: A smart grid is an advanced electrical grid that uses digital technology to monitor, manage and optimize the distribution of electricity.

Standard Operating Procedures (SOPs): Standard operating procedures are step-by-step directions created to help employees handle routine tasks.

Software-Defined Networking (SDN): Software-defined networking is an approach to network management that enables the dynamic and programmatically efficient configuration of network resources.

Technology Readiness Level (TRL): The standardized technology readiness level framework is used to assess the maturity of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the project's progress, ranging from basic research (TRL 1) to full-scale deployment (TRL 9).

Technology Scalability: Technology scalability refers to the ability of a technology, system or software to handle an increasing amount of work, users or data without a significant decrease in performance or a need for major modifications.

Virtual Private Network (VPN): A virtual private network is a protected Internet connection that disguises traffic by redirecting it through a special remote server operated by a VPN host.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