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Pilot and testbed facilities: when the lab scale may not be enough

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Testbed and pilot facilities allow studies in real-world conditions—especially when scale matters. They often bring together universities and industry partners across borders, creating a space where collaboration thrives.

In this Viewpoint, we highlight some of the unique perks of the testbed approach, from helping graduates gain job-ready skills to supporting local businesses with practical platforms, and to provide insights for policy makers. The insights show why lab-only experiments sometimes just aren't enough.

Chemical pilot plant at the Technical University of Denmark: Jakob Kjøbsted Huusom and Helena Junicke

The pilot plant at the Department of Chemical and Biochemical Engineering at the Technical University of Denmark is a research and education facility, offering access to over 100 experimental setups commonly used in the chemical and biochemical industries. The aim of the facility is to bridge the gap between theory and practice in education and to realise and scale up novel process concepts towards industrial use.

Jakob Kjøbsted Huusom (left) and Helena Junicke (right).- Credit: Jakob Kjøbsted Huusom and Helena Junicke

The available equipment includes among others: reactors for organic and inorganic synthesis or fermentation, column separation units for distillation, absorption, ion exchange, and chromatography, extraction units for liquid-liquid and solid-liquid processes, filtration units with membranes and dead-end filters, various drying technologies, special equipment for illustrating specific process phenomena such as heat transfer, mixing, aeration, solid transport, cyclone separation, and cleaning in place.

The pilot plant is integral to engineering education, particularly in practical courses on reaction engineering and fermentation, as well as unit operations. It also serves as a minor experimental component in theoretical courses on process technology, process control, and good manufacturing practice. Over 200 students are annually working in the facilities as part of their coursework.

In the last four years, the department has implemented digital initiatives to significantly enhance the education and research output of the pilot plant facilities. Key initiatives include:

1. A Virtual Reality (VR) platform that enables students to prepare for pilot-scale experiments, boosting confidence and understanding before and during practical exercises.
2. A Supervisory Control and Data Acquisition (SCADA) system for experimental setups, offering an industrial-grade and engaging user interface for an improved learning experience.
3. Unified communication interfaces and automated SQL data acquisition, allowing students and researchers easy access to live and historical data for applications like data processing, model validation, process optimization, and digital twin development.

Examples of the VR and SCADA systems in action can be seen in this short video[1] and the VR setup for our crystallization process can be tested here[2].

The three initiatives were all initialized in 2021 based on funding by the Novo Nordisk Foundation and strategic PhD projects funded from the department. A review of the initial efforts was given in[3], and our developments have revealed some key learning points. We underestimated the time that Faculty and other researchers required to develop tailored solutions. We also underestimated how challenging maintenance can be. Finally, we underestimated the costs involved in what we perceived to be minor process changes. Overall, the initial strategy has however proven to be successful, and we have expanded both the SCADA and VR applications in number since then.

The state-of-the-art functions, such as SCADA-operated units via tablets and VR instructions, have generally increased students' motivation and engagement during practical exercises. This has led to higher user satisfaction, which can be seen as a return on the digitalization effort. The students tell us that the VR is fun preparation and helps them better understand what is expected from them. The VR component has been added to student preparation as a new didactic approach designed to supplement traditional written materials. This accommodates diverse learning styles and supports students at all levels. These VR tools have boosted students' confidence and independence, allowing teachers to dedicate more time to in-depth discussions rather than practical support.

The database and communication interfaces have enabled students to interact with real experimental data in theoretical courses or research-based project work, further enriching their education and enhancing their qualifications. It provides structured access to a vast amount of historical data for modelling applications, whether mechanistic, machine learning, or hybrid. It also offers design-build capabilities with real-time data integration in application development within a digital twin framework. Thus, the digitalization of our pilot plant has expanded the facility to become an Industry 4.0 development platform[4].

The core design of the digital infrastructure behind SCADA and database development has been focused on structuring the data information flow between individual components for real-time operation as well as data access and storage. This system allows all communication to run within our local network using authenticated access via OPC UA, MQTT, and HTTPS communication protocols. The live data from the processes is collected in the SCADA system and displayed in a web-based user interface. Through this interface, users can control the equipment and add additional metadata information. The IoT gateway then combines both the process data time-series and the metadata before sending it to the database on the Kubernetes server.

The value in this setup has been manyfold. First and foremost, users experience an industrial-like environment and IT infrastructure. Additional benefits include the collection of a vast amount of data in our database, which can be used for modelling purposes[5–9]. Furthermore, the general setup using both the SCADA and IoT gateway for communication ensures that we can easily run experiments in a standardized mode for teaching purposes. However, we can also bypass the regular setup for operation and program-specific applications that use the real-time data. This could involve new control or optimization algorithms reading the process variables and computing values for actuators, which can be sent to the process. It could also involve research in dashboard design and operator support systems or learning algorithms re-training a model as new data becomes available[10].

These functionalities enabled by our digitalization efforts, coupled with the large representation of process technologies and our ability to openly share data, have led industry to express interest in collaboration based on our Industry 4.0 platform. There has been interest in how VR could assist in training personnel, in testing novel sensor technologies and showcasing how novel AI modelling techniques can be brought to practical applications in the process industry. Our facilities can therefore function as an asset for large research collaborations. Past surveys and reviews by our department have shown that industrial interest surpasses the current maturity in industry 4.0 concepts[11]. This motivates the need for such Industry 4.0 development platforms at universities.

Justin Searle (left) and Joanna Morgan (right). Credit: Justin Searle and Joanna Morgan

Active Building facility at Swansea University, UK: Joanna Morgan and Justin Searle

Established in 2011, SPECIFIC is an Innovation and Knowledge Centre, led by Swansea University, United Kingdom, with an array of industrial partners. Our work is focused on developing and testing low-carbon building technologies, to reduce the energy consumption of buildings and their overall carbon emissions, with the ultimate aim of helping organisations meet Net Zero Carbon (NZC) building targets.

In the UK, buildings are responsible for approximately 40% of energy consumption and 19% of greenhouse gas emissions[12]. Low-carbon technologies and materials have a critical role to play in reducing energy consumption and carbon emissions of buildings. However, it is often challenging to deploy new products on buildings, due to the complexities of construction projects and the inherent risks surrounding them. To assist companies in bringing low-carbon technologies to market, we have developed several demonstration buildings, which provide live testbeds for installing and gathering data on the performance of technologies.

The low-carbon building demonstrators developed at Swansea University are known as Active Buildings, which reflects the fact that their external envelopes (facades and roofs) are actively generating renewable electrical or thermal energy for use inside the building. The locally generated energy is managed through combining energy storage with smart control systems, to enable buildings to support the wider grid network by acting as "energy nodes". The aim is to ensure that we understand where the energy originates (solar, battery or grid) and where the energy ends up, (building services, exported, battery charge). Each circuit is metered to provide a complete picture of how and why the building is utilising energy, monitoring power and energy, as well as the impact of that energy on the environment, temperature, humidity, CO_2 levels etc. In 2019, six core principles for an Active Building were developed by the team at Swansea University to provide a robust description of the concept and facilitate the development of further Active Buildings, thereby contributing to an NZC built environment[13]. These principles are: 1. High-performance building fabric and use of passive design principles; 2. Energy efficient systems and performance monitoring; 3. On-site renewable energy generation; 4. Incorporation of energy storage; 5. Integration of electric vehicle charging; 6. Intelligent management of their interaction with the grid.

The first demonstration building constructed in 2014 was an off-grid garden office pod, which was self-sustainable through combining energy generation, energy storage and smart controls. The purpose of this project was to demonstrate the concept of energy generation, storage, use, and monitoring, on a real building at a small scale initially.

The second demonstration build in 2016 was a larger classroom building, which provided a teaching and meeting space on Swansea University's Bay Campus. It was constructed using a newly developed offsite panelised construction system, manufactured by a UK company, but not used on a building of this scale previously. Through this project, the company was able to gain knowledge and experience to aid and accelerate their product development, as well as create a case study to showcase to potential clients.

Third, a two-storey office building was constructed using modular construction and closer-to-market products. The purpose of this was to demonstrate that the Active Building concept was possible to achieve with current low-carbon technologies and existing supply chains.

The buildings have been heavily used since their construction, allowing us to collect a vast amount of data on their performance, optimize energy systems and trial different control philosophies. In addition, they serve as large testbeds for additional technology integration, which often requires existing infrastructure to support effective monitoring and feedback that would not be present in a normal building.

One of the main challenges encountered in the building demonstration programme was coordinating the integration of emerging technologies with well-established energy systems, particularly when dealing with the inertia of installers who are used to traditional technologies and start-up companies who are new to the construction industry. To overcome these required high levels of communication and scrutiny at all stages of the projects, from initial design through to construction, commissioning and operation. It was necessary for all parties to collaborate and adopt a "no-blame" culture, due to the uncertainties related to the performance of technologies.

Another challenge was ensuring that design intentions were translated into effective installations. Often, particularly when dealing with unestablished systems, it is easy for design intentions to be lost or misinterpreted as projects progress. At all times, it was necessary to ensure all parties were fully aware of the anticipated outcome of the project, in that the goal was to operate as an NZC building.

Finally, once the buildings were complete, the collection and monitoring of data was crucial to enable the energy systems to be assessed robustly. Data monitoring is critical to measure the performance of systems, find and rectify faults swiftly and optimise energy performance.

One of the most valuable lessons learnt through the building demonstration programme, particularly for NZC buildings, is the importance of robust installation and commissioning of equipment. Without strong collaboration and scrutiny, it was found that this is often where the biggest issues in the energy performance of buildings stem from.

The success of innovative designs or novel solutions during early stages of development, requires strong collaboration and clear common goals during the project inception and delivery. Many of the barriers to the installation and integration of new technologies can be overcome, providing there is an open and honest review during the development of the design and installation process. This is where technology demonstration projects are vital as the 'friendly, knowledgeable' client can work with the supply chain to mitigate risks and support with monitoring and honest feedback, thus maximising the opportunity for success and learning from issues that do arise. The construction sector is fragmented, and the often-complex supply chains serve to dilute or pass on responsibility. Demonstration projects can often reduce the potential for blame and encourage honesty during development, and this drives improvement and chances for success and shared learning.

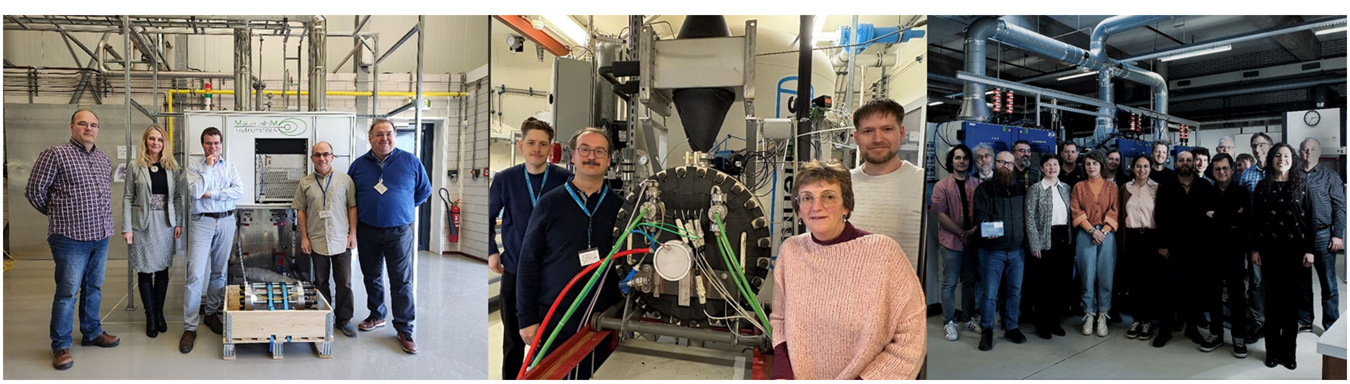
Testing facilities for hydrogen and battery technologies at the European Commission's Joint Research Centre: Darina Blagoeva, Thomas Malkow, Aurelien Pitois, and Andreas Pfrang

The testing facilities for hydrogen and battery technologies at the European Commission's Joint Research Centre (JRC) Petten site in the Netherlands provides policymakers and industry with independent assessment of hydrogen and battery technologies under simulated operating conditions[14]. The JRC Petten site includes among others the Electrolyser Testing Facility (ELTEST), High-Pressure Gas Testing Facility (GASTEF) and Battery Energy Storage Testing Facility (BESTEST).

The ELTEST facility (shown left) evaluates both low-temperature water electrolysis and high-temperature steam electrolysis, with a strong emphasis on performance and durability. This includes accelerated stress testing to measure endurance and performance decline. ELTEST is equipped to handle both low- and high-temperature applications, supporting power outputs ranging from a few hundred watts up to 84 kW for fuel cells and up to 30 kW for water electrolyser stack evaluation. The latter capability is made possible by the establishment of a new facility specifically designed for low-temperature electrolysis, scheduled to begin operation in 2026. It will enable the evaluation of electrolyser stacks with capacities up to 30 kW, as well as facilitate investigations into safety and environmental issues, such as the release of perfluoroalkyl and polyfluoroalkyl substances (PFAS) into wastewater potentially discharged by electrolysers.

The JRC also plays a leading role in establishing harmonised testing protocols for low- and high-temperature electrolysis, working in close collaboration with a working group of experts convened under the umbrella of the Clean Hydrogen Joint Undertaking[15]. The protocols provide a foundation for the standardisation of electrolysers, and the ELTEST facility will be utilised to experimentally validate the published testing protocols, ensuring their practical application and effectiveness. A validation exercise, planned for 2026-2027 and organised by the JRC, will subject the recently published Accelerated Stress Testing protocols[16] to a Round Robin validation, requiring participation from multiple partners.

The High-Pressure Gas Testing Facility (GASTEF) (centre figure) is used for experimental assessment of the safety and performance of systems and components under pressurised hydrogen and for pre-normative research[17]. The GASTEF facility consists of a half-buried concrete bunker connected to gas bundles in a gas storage area and is complemented by a control room in an adjacent building. The bunker hosts an 88 MPa compressor, a hydrogen pre-cooling system, a



ELTEST team (left), GASTEF team (centre) and BESTEST team (right). Credit: European Commission's Joint Research Centre safety pressure vessel and a sleeve, which contains the sample. Pressure cycles with hydrogen can be performed from 2 MPa up to 85 MPa. The facility allows for measurement of temperature and pressure of the flowing hydrogen, temperature at different locations of the sample, permeation/ leakage of hydrogen, and surface strains induced on the sample from the gas pressure.

Over the past 15 years, JRC has conducted experimental research on innovative high-pressure hydrogen storage systems on board vehicles. Commercial hydrogen vehicle tanks have undergone a series of tests, including permeation measurements, hydrogen filling-emptying cycles, and rapid filling experiments, to evaluate their mechanical and thermal performance over the vehicle's lifespan. The results have contributed to the development of the UNECE Global Technical Regulation on Hydrogen and Fuel Cell Vehicle Safety (GTR No. 13)[18] and the risk assessment of hydrogen refuelling in vehicles.

The GASTEF facility is expanding its scope to include the testing of hydrogen pipeline sections, with the aim of facilitating the development of a comprehensive hydrogen infrastructure in the European Union. As the expansion of hydrogen transmission infrastructure is expected to rely on repurposed natural gas pipelines, supplemented by new constructions, the JRC is utilising the GASTEF facility to conduct real-scale studies on the feasibility of converting existing natural gas pipelines for hydrogen transport.

The GASTEF facility will be utilised to test hydrogen pipeline sections sealed at both ends, thus mimicking gas cylinders. The fatigue and permeation behaviours of these pipeline sections will be tested similarly to the on-board storage tanks[19]. The facility will conduct dynamic tests, including accelerated ageing under high hydrogen pressures and frequent cycle testing, as well as monitoring of crack growth, all on full-scale pipeline sections. The findings will be shared with relevant European and international standardisation bodies, such as CEN JTC6 and ISO TC197, to inform the development of hydrogen technology standards. Standardising methods to verify and validate the safety of hydrogen infrastructure is crucial for gaining market acceptance and ensuring the seamless integration of hydrogen technologies into the global energy landscape.

The Battery Testing Facility (BESTEST) (right figure) aims at analysing performance and degradation thereof. Battery cells and modules are charged and discharged under normal, but varying, environmental operating conditions. Three Bidirectional Battery Testers offer the possibility for testing up to 96 cells in parallel (out of which 44 are equipped for Electrochemical Impedance Spectroscopy, EIS). These cell testers offer current ranges up to 25 A, while higher currents can still be arranged by coupling multiple channels and are complemented by potentiostats for lower and a module tester for higher currents, above 100 A. Performance testing is carried out under controlled temperature and, if required, also under controlled humidity. The laboratory also allows for cell preparation, pre- and post-test battery cell tear-down and post-mortem diagnosis.

The BESTEST facility contributes to the development of policies related to batteries. A key example of such policy is the Batteries Regulation[20], which aims at rendering batteries a sustainable industrial product by considering and introducing requirements for the whole battery life cycle. While the Batteries Regulation has been in force since August 2023, some of the mandatory requirements and related procedures are being developed and will become mandatory in the coming years. JRC supports the development of harmonised standards[21], e.g., on performance and durability[22], as well as safety requirements.

The testing facilities at the JRC Petten site offer Open Access under Horizon Europe and Ceric-Eric eligibility criteria. The facilities can be used by industry and other organisations, as well as within the Open Innovation Test Bed initiative on electrolysis: Cleanhypro[23]. Moreover, under specific circumstances, the JRC can provide in-kind contributions to EU-funded projects by participating in various capacities, such as joining the Advisory Board, acting as an associated partner, or signing a Collaboration Agreement with project consortia.

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Competing interests

The authors declare no competing interests.