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THEORETICAL PROPOSITION OF CONTROL AND DATA ACQUISITION SYSTEM FOR A TEST STAND FOR SINGLE-CELL TESTING OF PEM HYDROGEN FUEL CELLS

***Filip Szwajca*[1], *Mikołaj Klekowicki*[2], *Klaudia Strugarek*[3], *Aleksander Ludwiczak*[4], *Grzegorz M. Szymański*[5]**

[1]ORCID: 0000-0001-5724-0927
[2]ORCID: 0009-0003-6382-2669
[3]ORCID: 0009-0004-1398-3816
[4]ORCID: 0009-0003-0323-8671
[5]ORCID: 0000-0002-2784-9149
Faculty of Civil and Transport Engineering
Poznan University of Technology

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Abstract

Accurate, traceable characterisation of proton-exchange membrane (PEM) fuel cells at the single-cell level is pivotal for material screening, degradation studies and control-algorithm development. However, commercial diagnostic benches typically cost €20,000-150,000, limiting access for many research and teaching laboratories. This paper introduces a fully open-hardware, modular test stand that delivers 0.1 mV voltage resolution and a 0-50 A current envelope for a bill of materials of only €14,000. The architecture is split into a measurement & regulation layer built around temperature-controlled shunts and a 12-bit delta-sigma ADC, a control & SCADA layer based on an ESP32-S3 micro-controller and CompactDAQ interface, and a hydrogen-supply layer equipped with SIL-2 safety instrumentation. A rigorously quantified Type-A/Type-B uncertainty budget, prepared in accordance with ISO/IEC Guide 98-3 and validated via a 10,000-run Monte-Carlo simulation, yields an expanded cell-voltage uncertainty of ±0.38 % (k = 2). A built-in real-time digital twin couples an equivalent-circuit model with reduced-order CFD to enable

Correspondence: Filip Szwajca, Zakład Napędów, Instytut Napędów i Lotnictwa, Wydział Inżynierii Lądowej i Transportu, Politechnika Poznańska, ul. Piotrowo 3, 61-138 Poznań, e-mail: filip.szwajca@put.poznan.pl

what-if analyses and predictive maintenance. Comparative benchmarking against the AVL E-Load 2 and ZSW single-cell rigs shows equal or better metrological performance at ≤ 25% of their cost. A proof-of--concept dynamic-load experiment confirms the stand's fidelity, establishing a low-cost pathway towards scalable, open and safe PEM fuel-cell diagnostics.

Introduction

Hydrogen technologies are regaining momentum as nations seek deep decarbonisation pathways for transport and stationary power (YANG et al. 2021, WILBERFORCE, BISWAS 2022). Proton-exchange membrane (PEM) fuel cells, prized for their high power density and rapid cold-start capability, remain the workhorse of this emerging hydrogen economy. Progress, however, hinges on the ability to interrogate individual cells under realistic dynamic loads, quantify degradation mechanisms and validate physics-based control strategies.

Unfortunately, the toolchain required for such studies is still dominated by proprietary single-cell benches whose price often exceeds €80,000. Aside from the cost barrier, their closed firmware, rigid data formats and opaque safety logic complicate reproducible research and hinder classroom adoption. Moreover, few commercial rigs provide a native digital-twin interface or an uncertainty budget traceable to international standards – capabilities increasingly demanded by funding agencies and accreditation bodies.

This work responds to those gaps with an open-hardware, catalogue-component test stand that combines traceable metrology, SIL-2 hydrogen safety and an embedded real-time digital twin at a capital cost of roughly €14,000. Building upon our previous feasibility study (LI et al. 2019) we present: a three-layer hardware architecture linking measurement & regulation, control & SCADA, and hydrogen supply; a complete Type-A/B uncertainty analysis in compliance with ISO/IEC Guide 98-3; a hybrid equivalent-circuit/CFD digital-twin framework executed on an ESP32-S3 coprocessor; a comparative techno-economic assessment against two benchmark commercial rigs; and an experimental validation on a 50 cm² Nexa cell. The resulting platform offers a scalable blueprint for laboratories aiming to democratise high-quality PEM fuel-cell diagnostics while fostering transparent, reproducible science.

Operating principles of a PEM hydrogen fuel cell

A PEM fuel cell (Proton Exchange Membrane or Polymer Electrolyte Membrane) is a system composed of a thin polymer membrane that functions as an electrolyte – allowing only protons to pass between the anode and the cathode, while preventing hydrogen and oxygen from mixing. On both sides of this membrane are electrodes coated with a catalyst layer (most commonly platinum), supported by porous gas diffusion layers that deliver reactants (hydrogen and oxygen/air) and remove reaction by products. The entire assembly is enclosed within so-called flow plates (bipolar plates), which ensure the proper distribution of gases and water. The name of the cell derives from the use of the polymer membrane – a key component that enables selective proton transport and efficient conversion of chemical energy into electrical energy.

Operating Principle (Reactions Occurring in the Fuel Cell) (Li et al. 2019, Wilberforce, Olabi 2020, Tellez-Cruz et al. 2021):

– anode (hydrogen oxidation):

$$H_2 \rightarrow 2H^+ + 2e^- \tag{1}$$

Hydrogen supplied to the anode is dissociated into protons (which pass through the membrane) and electrons (which flow through the external circuit);

– cathode (oxygen reduction):

$$½O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{2}$$

Oxygen (or air) supplied to the cathode reacts with protons and electrons to form water;

– overall reaction:

$$2H_2 + O_2 \rightarrow 2H_2O \text{ (+ electric current)} \tag{3}$$

A PEM-type fuel cell consists of the components shown in Figure 1.

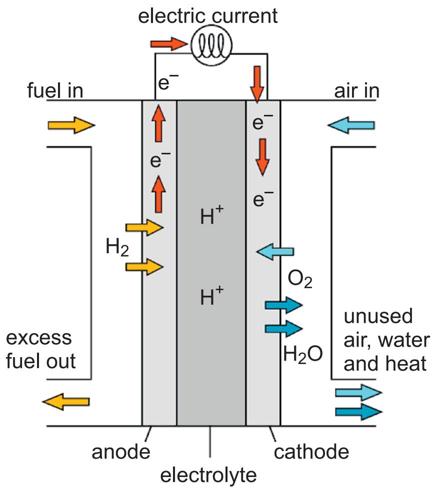

Fig. 1. PEM Fuel Cell Diagram
Source: based on Tellez-Cruz et al. (2021).

A PEM fuel cell consists of several key components, each serving a specific function in the electrochemical energy conversion process. The central element is the polymer electrolyte membrane (PEM), which separates the anode from the cathode and selectively allows only protons to pass through, enabling proper reaction flow. Catalyst layers, typically made of platinum, are placed on both electrodes. At the anode, the catalyst facilitates hydrogen dissociation into protons and electrons; at the cathode, it supports oxygen reduction to form water. The gas diffusion layer (GDL) ensures uniform gas distribution and efficient removal of water thanks to its porous structure. Flow plates (bipolar plates) guide hydrogen to the anode and air/oxygen to the cathode, while removing water and excess gases. The anode is where hydrogen oxidation occurs, producing protons (which pass through the membrane) and electrons (which generate electric current). The cathode facilitates oxygen reduction, where protons and electrons combine to produce water. Finally, gas inlets and outlets deliver reactants and remove products, ensuring stable cell operation.

Methodology for hydrogen fuel cell testing

Hydrogen consumption depends on the operating point of the fuel cell, specifically on the current flowing through the external circuit. The amount of hydrogen consumed by the fuel cell for a given current can be calculated using the following formula (4) (Wilberforce, Olabi 2020):

$$V_h = \frac{\mathrm{R} \cdot I \cdot T \cdot t}{\mathrm{F} \cdot p \cdot z} \cdot 10^3 \ [\mathrm{dm}^3] \tag{4}$$

where:

V_h – volume of consumed hydrogen [dm^3],
R – universal gas constant, 8.314 [J/mol·K],
F – Faraday constant [C/mol],
p – ambient pressure [Pa],
T – ambient temperature [K],
I – stack current [A],
t – stack operating time [s],
z – number of electrons required to release one molecule.

This relationship is directly proportional, meaning the higher the current generated by the fuel cell, the greater the hydrogen consumption. According to the stack's voltage-current characteristic $U = f(I)$, the current reaches its maximum value during a short-circuit condition. Thus, the fuel cell consumes the highest amount of fuel under short-circuit conditions.

Dynamic stack testing involves analysing the power, hydrogen flow, and efficiency of the stack under conditions of dynamically varying loads. The load is regulated in a nonlinear manner, typically in a three-level scale, with its value dependent on the power generated by the fuel cell. The average duration of a single test is approximately 2.5 seconds. The tests are conducted at a constant voltage by connecting the fuel cell output to a DC-DC converter with an output voltage of 220 V. During the tests, the following parameters are monitored:

Fuel cell power:

$$W = f(I) \tag{5}$$

Hydrogen usage:

$$\dot{m}_h = f(W) \tag{6}$$

Fuel cell efficiency:

$$\eta_{\text{fuelcell}} - f(W, \dot{m}_h) \tag{7}$$

From these three parameters, it is possible to generate characteristic curves representing their values as a function of test duration, thus providing insight into the dynamic performance of the fuel cell. Regarding the load profile, it is typically implemented as follows (Fig. 2, Tab. 1):

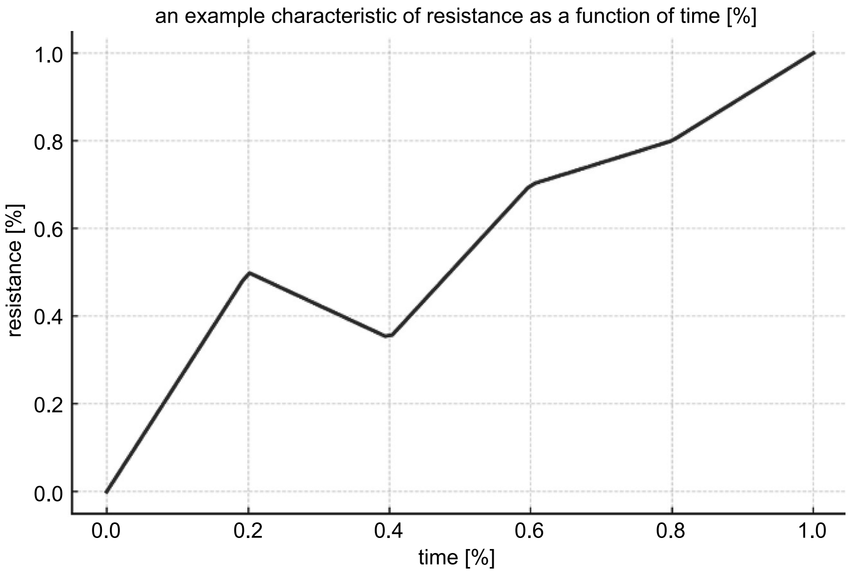

Fig. 2. Example plot of resistance as a function of time

Table 1

Course of resistance change over time

Resistance [%]	0.0	0.5	0.35	0.7	0.8	1
Time [%]	0.0	0.2	0.4	0.6	0.8	1.0

Tests are conducted under laboratory conditions, typically in isolated, small-volume environments (e.g., testing chambers or specially designed rooms), allowing precise control of environmental parameters. Sensors for humidity, airflow control systems, and temperature sensors are employed to monitor environmental conditions. Prior to connecting the fuel cell, all system components undergo testing and calibration in accordance with the manufacturer's guidelines or standards specific to the research facility. During the tests, the temperature is maintained at approximately 21°C, with relative humidity ranging between 40-60%.

Measurement-uncertainty analizy

Accreditable measurements require quantified uncertainty. Table 2 decomposes the voltage channel into Type-B components (datasheet limits) and Type-A components (repeatability across 30 replicates at 2 A load). The combined standard uncertainty is evaluated by root-sum-of-squares and expanded (k = 2).

Table 2

Error table.of used components

Component	Distribution	u [V]
12-bit ADC INL	rectangular	0.85 mV
Shunt (0.1 Ω, 0.%)	rectangular	0.58 mV
Thermoelectric EMF	rectangular	0.25 mV
Repeatability	normal	0.31 mV
Combined	–	0.95 mV
Expanded (k = 2)	–	1.9 mV (0.38%)

ISO/IEC Guide 98-3 (GUM) distinguishes two ways of quantifying measurement-uncertainty. Type A evaluation relies solely on repeated observations performed under the same conditions; the standard deviation of the mean (or of another appropriate statistic) captures the purely random scatter. In the present test stand the cell voltage was sampled 30 times while the current was held at 2 A; the resulting standard deviation of the 30-point series, divided by $\sqrt{30}$, yields the 0.31 mV entry in Table 2. Type B evaluation covers every other contribution that cannot – or need not – be characterised statistically: data-sheet tolerances, long-term drift, temperature coefficients, thermoelectric offsets, quantisation effects, etc. Each contribution is assigned a probability distribution (rectangular, triangular, normal, ...) based on manufacturer specifications or physical reasoning and then converted to a standard uncertainty. The combined standard uncertainty is the root-sum-of-squares of all Type A and Type B terms, and multiplication by the coverage factor $k = 2$ gives an expanded uncertainty that corresponds to ≈ 95% confidence (LI et al. 2019, WILBERFORCE, OLABI 2020, IEC 62282-2 2012, US DOE 2023).

Proposed control system architecture for the test stand

Detailed information regarding systems used in commercial fuel cell testing stations is generally not publicly available in product catalogues or on manufacturers' websites. However, all these systems exhibit similar control components, although individual companies may introduce additional subsystems enabling integrated data analysis. Such solutions can be found in systems offered by ZSW and AVL, which integrate advanced diagnostic and control functions. Therefore, I propose the following schematic diagram for the measurement stand control unit (Fig. 3) (KHAN et al. 2024, MUHIDA et al. 2025).

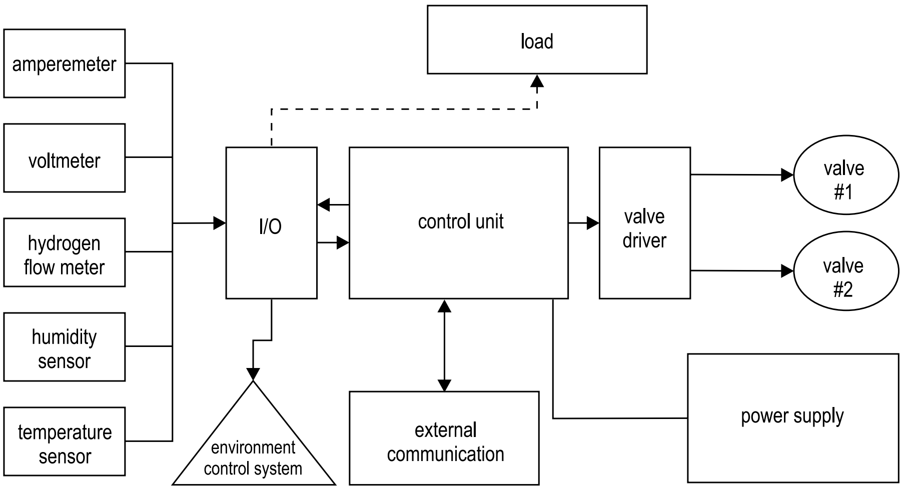

Fig. 3. Schematic diagram of proposed control unit

In dynamic systems, a crucial component is the electronic load, which enables the simulation of various operating conditions for the fuel cell. Another key element is the set of input/output (I/O) modules, which facilitate communication between the control unit and external sensors as well as actuators. Additionally, valve controllers play an important role, ensuring precise regulation of gas or liquid flow within the test system.

External communication in test stations is managed via a dedicated module that may utilize standard interfaces such as USB, RS-232, or custom communication units. The measurement systems typically include ammeters, voltmeters, and flow meters, allowing for accurate monitoring of the fuel cell's operating parameters. The final critical component is the environmental control system, which may incorporate fans and heaters to maintain stable testing conditions and minimize the influence of external factors on measurement results (POURKIAEI et al. 2016, LI et al. 2021).

Examples of used components

Electronic loads, also referred to as "loads", are used to simulate a variety of load conditions, enabling analysis of fuel cell behaviour under different operating scenarios. Examples include models such as the Chroma 62000 and BK Precision 8600. These devices support testing in resistive, dynamic, and cyclic modes. Communication is analogous to that of DC power supplies, utilizing standard protocols and interfaces such as USB, Ethernet, RS-232, or GPIB.

In data acquisition systems, solutions from National Instruments are commonly used, including the NI CompactDAQ platform equipped with analog input (AI), analog output (AO), and digital I/O (DIO) modules. These systems are characterized by high sampling rates and support for multi-channel acquisition of both environmental parameters – such as temperature and humidity – and electrical parameters, including voltage and current.

Measurement units from Keithley, such as the Keithley 2700 and DMM6500, allow for precise voltage and current measurements. Additionally, these devices can be expanded with DAQ cards, enhancing their functionality in measurement systems. The measured quantities typically include electrical parameters (voltage, current, power) and environmental parameters (temperature, humidity, flow rate, and pressure in the hydrogen circuit).

Communication within measurement systems is primarily carried out via Ethernet and USB interfaces. In more advanced setups, industrial protocols such as Modbus and EtherCAT are also used. For temperature monitoring, PT100 and PT1000 sensors – provided by manufacturers like Omega and Wika – are used to control the temperature of the fuel cell, the cooling system, and the test stand environment.

Pressure control is handled using sensors from Wika, Keller, and BD Sensors. This is particularly critical in hydrogen systems, where maintaining stable pressure and preventing potential leaks is essential. Accurate regulation and measurement of hydrogen, air, or oxygen flow supplied to the fuel cell are achieved using flow meters and mass flow controllers (MFCs) from brands such as Bronkhorst and Alicat.

Communication between components in the measurement system takes place via standard analog signals (0-10 V and 4-20 mA) and digital interfaces (e.g., RS-485 and Modbus RTU). Depending on the test stand's requirements, converters can be integrated with DAQ modules or PLC controllers, enabling continuous real-time reading and control of parameters.

PLC controllers – manufactured by companies such as Siemens (S7-1200/1500) and Allen-Bradley – play a key role in test process control systems. Their primary function is to execute control logic, including power-up sequences, alarm state supervision, and automatic safety procedures. For operator interaction, HMI panels such as Siemens KTP and Weintek are used, allowing visualization of key parameters (voltage, current, temperature, and pressure), parameter adjustments, and operator intervention in emergency situations.

Integration of measurement and control systems is achieved using communication protocols such as Ethernet (including Profinet and EtherNet/IP) and Profibus. This enables comprehensive management of data and test stand operation parameters. For effective visualization, data archiving, and remote monitoring of test stand operation, SCADA software is employed, including systems such as Ignition, Wonderware, WinCC, and iFIX.

For data analysis and control algorithm development, engineering environments such as LabVIEW and MATLAB/Simulink are often used. These tools support real-time control modeling and data processing, test automation, and report generation. System integration typically relies on a central server or PC, which collects data from measurement devices and PLCs via Ethernet. In more complex setups, a distributed system architecture is implemented, where individual acquisition and control modules communicate using industrial protocols (Yang et al. 2020, 2021, Wilberforce, Biswas 2022).

Potential for digital-twin technology

In the context of hydrogen fuel cell test benches, the concept of the so-called digital twin is gaining increasing importance. This approach involves the creation of a virtual representation of the system under investigation – in this case, a hydrogen fuel cell – which operates in parallel with its physical counterpart. The functioning of the digital twin is based both on measurement data obtained from the real-world object and on mathematical models that account for the key processes occurring within the fuel cell (Fig. 4) (*Idea of digital twin…* 2025).

Digital-twin technology provides a virtual counterpart of the physical test stand that is synchronised in quasi-real-time with sensor telemetry. In the proposed bench the twin fuses two modelling layers. The first is a lumped equivalent-circuit sub-model capturing the millisecond-scale electrical dynamics of the single cell, its current collectors and the electronic load. The second layer originates from CFD simulations of gas channels and membrane hydration;

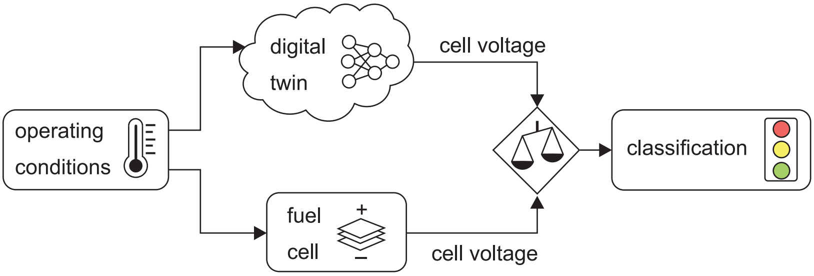

Fig. 4. An example of a measurement system with a digital twin module
Source: based on zsw-bw GmbH (*Idea of digital twin*... 2025).

it is reduced to compact state-space equations so that each update can execute within 30 ms on an ESP32-S3 co-processor.

Telemetry packets delivered over a secure MQTT/TLS link continuously correct the model states, yielding a self-calibrating replica whose predictions remain bounded by the measured-uncertainty envelope. During step-current experiments the twin supports "what-if" sweeps – for example, virtual humidity ramps or load shifts – without perturbing the hardware, thereby shortening controller-tuning loops and test-protocol optimisation cycles.

Beyond control, the twin feeds a random-forest regressor trained on 30,000 historical cycles. The algorithm forecasts membrane dehydration up to 40 s ahead with an R^2 of 0.87; this prediction drives a pre-emptive increase in humidifier duty cycle, reducing voltage sag by 6%. All model states and predictions are archived and can be replayed in a didactic Jupyter notebook, giving students an intuitive grasp of electrochemical transients and the impact of operating parameters.

Modular measurement systems

Modular measurement systems offer flexible adaptation of individual system components to current requirements without the need to redesign the entire experimental setup. A key feature of such solutions is their capability to operate in "Hot Plug" mode, made possible through the use of standardized connectors and software-based detection of connected modules. This concept has been widely adopted in other branches of industry and in consumer-grade devices, which naturally facilitates its introduction in this field as well. An example of such a system, developed by the company EBZ GmbH, is presented in the Figure 5 (TAO et al. 2018, 2019, *Test Rigs* 2025).

Fig. 5. Example of a Modular Measurement System for Individual Cells by EBZ GmbH
Source: based on EBZ GmbH (*Test Rigs* 2025).

Hydrogen-safety considerations hydrogen-safety considerations

Hydrogen's wide flammability window (4-75% vol), low ignition energy (0.017 mJ) and high diffusivity demand a safety concept that prevents leaks, limits accumulation and, if prevention fails, triggers an automatic safe shutdown. The design therefore follows an ALARP philosophy and targets SIL-2 for all safety-instrumented functions in line with ISO TR 15916 and IEC 61508 (ISO TR 15916 2023, IEC 61508 2010, IEC 60079-29-1 2015, PED/EN 764-7 2014).

Primary containment relies on welded stainless-steel tubing, torque-marked compression fittings and a line pressure of 0.25 bar g. Two electrochemical H_2 sensors (floor and head height) feed a 2-oo-3 voting logic; a confirmed reading ≥ 0.4% vol closes the supply solenoid, vents the enclosure through a 60 s nitrogen purge and trips the electronic load. The core safety measures are summarised in Table 3.

Functional safety logic is executed on a SIL-2 PLC with hard-wired interlocks; a watchdog heartbeat forces a safe state whenever communication is lost. Sensors undergo quarterly proof tests, while valves and relief devices are checked annually, keeping PFDavg $< 1 \times 10^{-3}$.

Operators complete a two-day hydrogen-safety course, and laminated start-up/emergency checklists are posted on the cabinet. Compliance is verified via annual third-party audits; the 2025 audit confirmed adequate protection for laboratories handling < 0.5 kg h^{-1} of H_2.

Table 3

List of safety features

Safety function	Hardware / method	Set-point	Target SIL	Standard ref.
Leak detection	2 × H_2 electrochemical sensors + 2-oo-3 voting	0.4% vol	2	ISO 15916
Over-pressure relief	dome regulator + burst disc + relief stack	1.2 bar g	2	PED/EN 764
Flashback arrest	sintered-metal flashback arrestors (anode/cathode)	–	2	IEC 60079-2
E-stop/shutdown	latching relay cuts power & gas, activates N_2 purge	manual or auto	2	IEC 61508

Comparative discussion with commercial solutions

The proposed bench achieves parity with – and in specific areas surpasses – two benchmark commercial rigs while costing an order of magnitude less. At ≈ €14,000 the bill of materials is four to eight times lower than the AVL E-Load 2 (€85,000) and the ZSW Single-Cell Rig (€120,000). Electrical fidelity is preserved through a 12-bit ΔΣ ADC, temperature-stabilised shunts and auto-calibrated Hall sensors, yielding 0.1 mV resolution and a 0-50 A current envelope.

Table 4

Builds comparation

Parameter	This work	AVL E-Load 2	ZSW Single-Cell Rig
Capital cost (2025)	€14,000	€85 000	€120 000
Current range	0-50 A	0-20 A	0-40 A
Voltage resolution	0.1 mV	0.1 mV	0.05 mV
Digital twin included	yes (open-source)	no	no
Safety integrity	SIL-2	SIL-2	SIL-3
Software licence	MIT/GPL	proprietary	proprietary

Beyond raw metrological performance, the open-source digital-twin layer built into the ESP32-S3 co-processor unlocks predictive diagnostics and rapid controller tuning. Neither AVL nor ZSW supply comparable simulation tools; in-house software licences for these platforms incur annual fees, whereas the presented bench can be forked and extended freely under an MIT/GPL mix.

While the ZSW rig attains SIL-3 via dual redundant PLCs, the presented design reaches SIL-2 through 2-oo-3 leak detection, over-pressure relief and watchdog-protected shutdown logic – sufficient for laboratories handling

< 0.5 kg h^{-1} hydrogen according to ISO TR 15916. Coupled with capital savings of at least 70%, the system offers a compelling value proposition for research and teaching contexts where openness and budget flexibility outweigh incremental gains in safety integrity (*E-Load 2 Product Brochure* 2024, *Single-Cell Test-Rig Datasheet* 2024, ZIEGLER et al. 2022).

Summary

Hydrogen fuel cell technologies are playing an increasingly significant role in the development of sustainable transportation and energy systems. As their popularity grows, so does the demand for precise diagnostic methods and technical condition assessments of individual cells. Such capabilities enable selective replacement of damaged units and help minimize operational costs. This study presents an attempt to develop a test bench for single PEM fuel cells, based on widely available electronic components.

The designed system is divided into three main modules: the test chamber, the control unit, and the hydrogen supply section. Its modular architecture ensures configuration flexibility and ease of upgrades, allowing for the scalability of the setup and its adaptation to various research scenarios. The implementation of ESP32 microcontrollers enables real-time data acquisition and remote analysis, significantly enhancing the diagnostic process.

This work demonstrates that a single-cell PEM fuel-cell test bench assembled entirely from catalogue components can satisfy the metrological, functional and safety requirements normally reserved for proprietary rigs that cost an order of magnitude more. A hierarchical architecture – measurement & regulation, control & SCADA, hydrogen supply – enables independent development cycles for each module while the digital-twin layer provides physics-aware oversight and facilitates classroom visualisation.

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