

EXPERIMENTAL VALIDATION OF A FUEL CELL SYSTEM DIGITAL TWIN FOR A FULL-ELECTRIC AIRCRAFT POWERTRAIN

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Abstract

The transition toward sustainable aviation requires the development of efficient and reliable electrified propulsion systems to reduce the environmental impact of air transport. In this context, Digital Twin technology is emerging as a key enabler, offering high-fidelity virtual models that support system design, validation, control development, and predictive analysis. This paper focuses on the development and experimental validation of the digital twin of one of the key subsystems of a full-electric propulsion architecture, namely the fuel cell system. The model is developed within a Model-Based Systems Engineering framework inspired by the V-model, ensuring consistency between system requirements, architecture definition, simulation activities, and validation procedures. An experimental campaign has been carried out under representative operating conditions to acquire high-quality data for calibration and correlation. The comparison between simulated and measured results shows that the developed model is able to reproduce the behaviour of the physical system with satisfactory accuracy, confirming its value as a reliable tool for virtual testing, performance prediction, and further optimization of electric propulsion systems for future aviation applications.

Keywords: Electric Aircraft Propulsion; Fuel Cell System; Digital Twin; Model-Based Systems Engineering.

1. Introduction

Progressive electrification of transportation is widely recognized as a key enabler for reducing the sector's environmental footprint [1]. Within this context, aviation faces a particularly demanding transition, as it requires substituting conventional combustion-based propulsion with more electrified or fully electrified systems. The air transport domain therefore stands at the forefront of efforts toward climate neutrality, where propellers can be driven by electric motors powered through battery packs and/or hydrogen fuel cell technologies [2].
To investigate and validate these innovative propulsion concepts, an experimental facility has been designed and realized to reproduce a full-electric powertrain under realistic operating conditions. The

setup (hereafter experimental rig or electric rig) enables the emulation of key aircraft subsystems - including fuel cell stack, battery modules, electric motor, and power electronics - acting as an intermediate validation step between numerical modelling and full-scale testing, this platform supports model verification, control logic assessment, and performance evaluation in a repeatable and controlled framework.

In this context, a comprehensive Digital Twin (DT) of the entire test rig system has been implemented to support the experimental activities, by accurately reproducing system behaviour in real time by combining physics-based models with both experimental and operational data. Establishing a strong correlation between the Digital Twin and the test bench is pursued to ensure that the virtual environment faithfully represents the real system. Achieving and maintaining close alignment between experimental and simulated results, significantly enhances the predictive capability o of the Digital Twin. This ongoing refinement empowers the DT to support advanced functionalities, including precise anomaly detection, performance optimization, and virtual testing of innovative control strategies—ultimately driving greater reliability, efficiency, and innovation. Within this framework, the present work focuses on the Fuel Cell System (FCS) as the primary case study, presenting the experimental data acquired from the test rig alongside the verification and validation activities performed on the corresponding FCS Digital Twin model.

2. Methodology

The methodology adopted in this study is based on a Model-Based Systems Engineering (MBSE) framework [3] and is structured according to the V-Model development logic [4]. This approach provides a rigorous foundation for managing system complexity through the formalization of requirements, architecture, behaviour, and interfaces within a coherent model-based workflow. At the same time the V-model ensures a clear correspondence between design stages and their associated verification and validation activities. In this context, the left side of the V-model supports the progressive definition of stakeholder needs, system requirements, functional decomposition, and architecture synthesis. Conversely the right side focuses on the verification and validation of both the developed models and the integrated system against the initial specifications.

Following the definition of the system architecture, physics-based component and subsystem models are developed to represent the real behaviour of the full-electric propulsion system. These models are implemented with traceable links to the corresponding requirements and are progressively refined as additional design and experimental information becomes available. This process supports the construction of a digital twin able to reproduce the dynamic response of the propulsion system over a broad range of operating conditions [5].

Within this framework, verification and validation constitute the key methodological pillars of the study [6]. Verification addresses whether the model has been correctly built, ensuring that the mathematical formulations, software implementation, interfaces, and parameterization are consistent with the defined architecture and with the intended modelling assumptions. Validation, in contrast, examines whether the appropriate model has been developed, that is, namely whether the integrated model can reproduce the physical behaviour of the real system with sufficient accuracy for its intended use. In the present work, verification and validation are performed through systematic comparison between simulation outputs and experimental measurements obtained from the test rig. This correlation-based process is essential not only for assessing model fidelity, but also for establishing confidence in the predictive capability of the digital twin.

The resulting methodology ensures traceability linking requirements to models and models to experimental evidence, thereby strengthening the reliability, transparency, and reusability of the development process. In particular, the explicit pairing between modelling activities and verification/validation steps enables a structured demonstration that the proposed DT is both correctly implemented and experimentally representative of the real propulsion system.

The full-electric propulsion architecture investigated in this study, illustrated in Figure 1, integrates multiple energy sources and conversion devices to meet propulsive demands. The system comprises a hydrogen PEM fuel cell system, a fuel cell system emulator, high-voltage battery system emulators, inverters, and electric motors. In this context, the term fuel cell system refers to the coupled assembly of a physical PEM fuel cell and its dedicated high-voltage DC/DC converter, which together constitute the actual power-generation unit. The fuel cell system emulator, in turn, reproduces the electrical behavior of this coupled assembly, such that its output terminals deliver voltage and current characteristics equivalent to those that would be measured downstream of a real DC/DC converter. The same principle applies to the high-voltage battery system emulators, which replicate the electrical response of a battery pack interfaced with its conditioning electronics. This architecture is designed to support flexible energy management strategies and to provide redundancy, ensuring efficient power distribution across a wide range of operating conditions.

The full-electric propulsion architecture investigated in this study, illustrated in Figure 1, integrates multiple energy sources and conversion devices to meet propulsive demands. These include hydrogen PEM fuel cell system, fuel cell system emulator, high-voltage battery system emulators, DC/DC converters, inverters, and electric motors. The architecture is designed to support flexible energy management and provide redundancy, ensuring efficient power distribution under a wide range operating conditions.

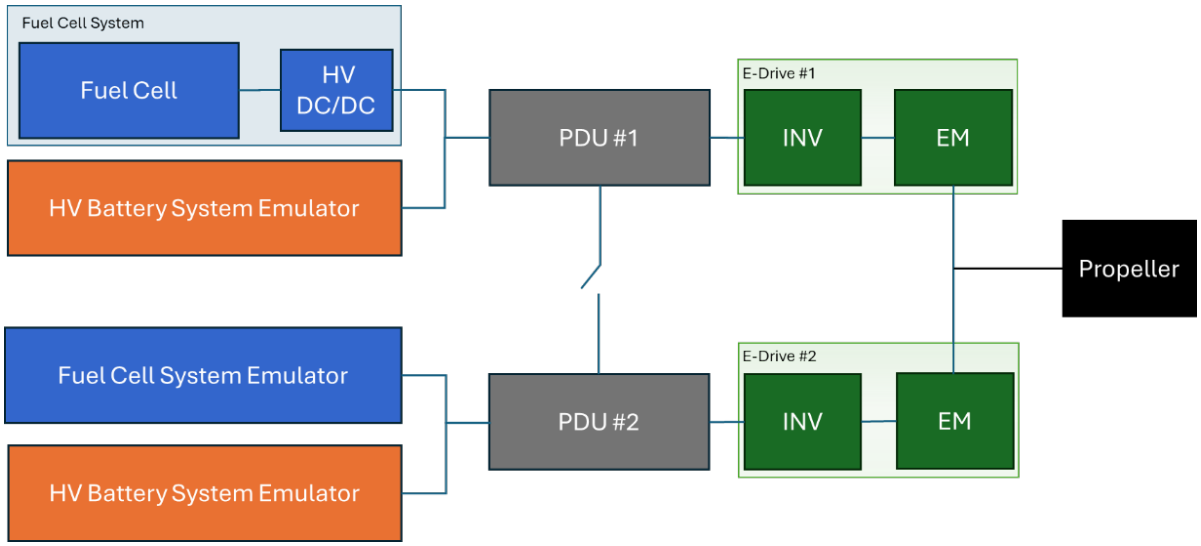


Figure 1 - Electrified propulsion system schema.

Within this context, Simcenter Amesim is employed to model system's dynamic behaviour and performance. This is achieved by integrating physics-based sub-models with semi-empirical components. Each subsystem—such as the hydrogen fuel cell system, battery, electric motor, and power electronics—is characterised using efficiency maps, characteristic curves, or look-up tables, depending on data availability. Figure 2 illustrates the complete test rig architecture as implemented in Simcenter Amesim, allowing simultaneous simulation of the system's energy, mechanical, and thermal behavior .

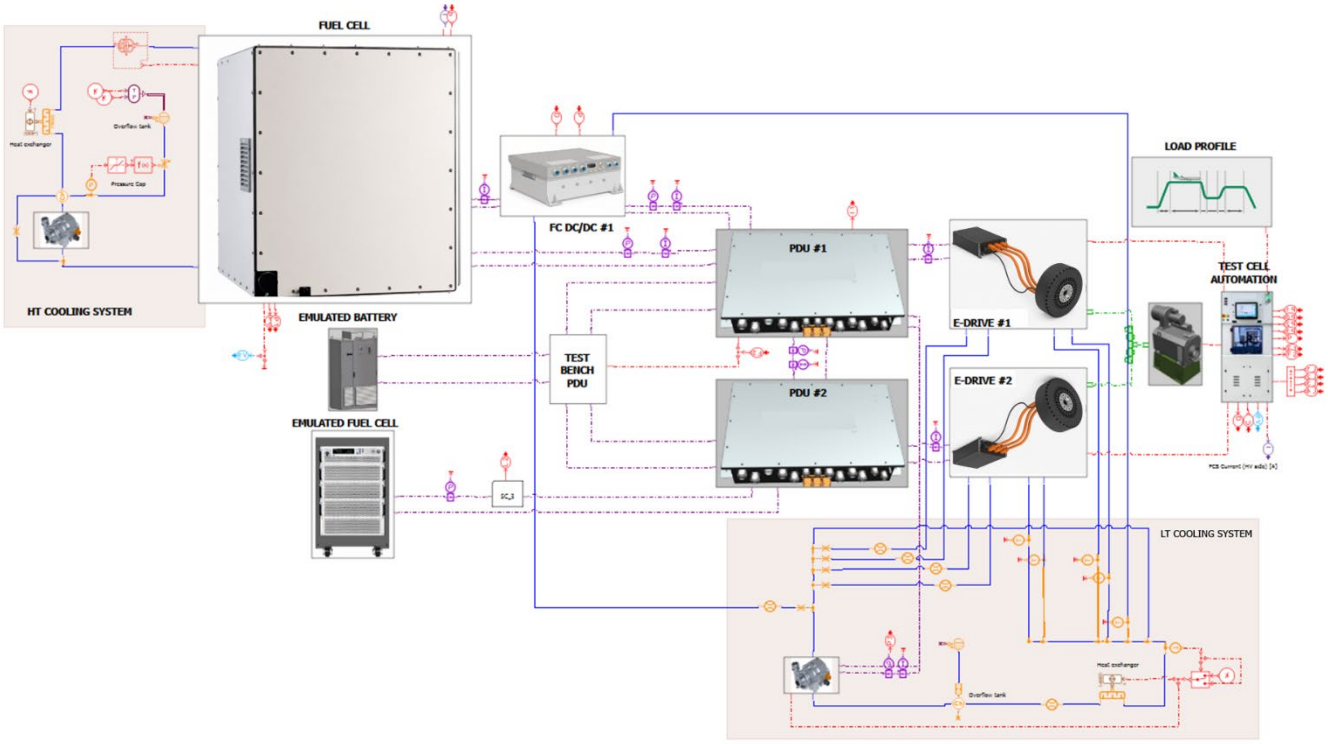


Figure 2 – Test rig architecture in Simcenter Amesim environment

The methodology outlined above is applied to the full-electric propulsion architecture previously described, with particular emphasis on the FCS, which the central focus of the modelling, experimental characterization, and verification and validation activities carried out in this work. To support this effort, an experimental campaign has been carried out on the full-electric propulsion test rig to collect high-fidelity data for model calibration and validation. Within the V-model framework, the FCS plays a key role in the identification phase, providing both electrical power and thermal measurements for model tuning and subsequent validation. Once verified and validated, the FCS digital twin can be exploited to forecast performance, refine control strategies, and accelerate design iterations, ultimately reducing development effort and costs for future electric propulsion systems.

3. Fuel Cell System set up

The FCS is a closed, self-contained module designed to deliver electrical power by converting hydrogen and air into electricity and water through an electrochemical process. From an external standpoint, the system provides only the essential interfaces required for operation, including high-voltage electrical connections, hydrogen and air supply lines, and coolant circuits for thermal management. All subsystems required for safe and efficient operation of the stack are integrated within the enclosure and are collectively referred to as the Balance of Plant (BoP).

The BoP includes auxiliary subsystems, such as hydrogen supply, air management, thermal management, and water management. Specifically, the hydrogen and air subsystems regulate the delivery of reactants to the anode and cathode, respectively. The thermal management system—typically consisting of high-temperature and low-temperature cooling loops—maintains the stack and auxiliary equipment within their ideal operating temperature ranges. Meanwhile, the water management subsystem maintains proper membrane hydration and prevents conditions such as flooding or drying of the stack. Supervisory control and power electronics coordinate all BoP functions to guarantee stable, controllable voltage and current under dynamic load conditions. The Fuel Cell is coupled to a high-voltage DC/DC converter, which adapts the variable DC voltage output of the stack

to the levels required by the rig's high-voltage bus. Figure 3 illustrates the integration of the FC and its associated HV DC/DC converter within the experimental test rig.

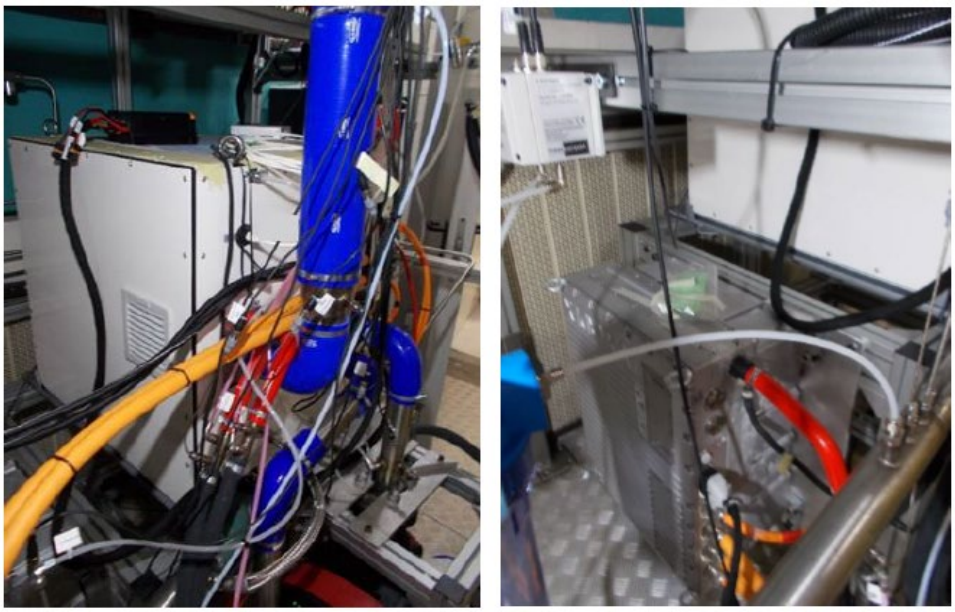


Figure 3 –Fuel Cell System integrated within the experimental test rig

The system operates under power control: a power demand is sent to the FCS, which regulates the stack operating point accordingly. As a result, the net electrical power delivered to the bus is therefore determined by the stack electrochemical efficiency, the auxiliary consumption of the BoP, and the conversion losses introduced by the DC/DC converter. Table 1 summarizes the main operational characteristics of the FC stack, which have been tested with steady-state operation and dynamic load variations.

Table 1 – Fuel cell system characteristic

Parameter	Value
Net power output [kW]	15 – 100
Current output [A]	50 – 450
Voltage output [V]	250 – 500
System efficiency (rated power) [%]	45
System heat output (max) [kW]	151

Taking into account these considerations, the modelling approach employed for the FCS, encompasses a comprehensive representation of its key components and specifies the required level of fidelity for seamless integration within the DT and the experimental test rig. Prior to system-level testing, an initial calibration of the FCS model was conducted on the basis of requirements and performance data provided by the component supplier, ensuring consistency between the simulated behavior and the specified design requirements of each FCS subsystem — a process conceptually aligned with the verification phase of the V-model development cycle.
Subsequently, data collected during the experimental campaign were used to further refine the model

and improve its fidelity. This step enhances the representation of system behavior and the accuracy of parameterization, effectively grounding the model against physical evidence in accordance with the validation objectives of the V-model methodology.

4. Results

Building upon the framework described above, the following sections present the results obtained from both the model calibration process and the subsequent experimental validation campaign. First, the outcomes of the calibration phase are discussed, highlighting how the model parameters were tuned using high-fidelity experimental data. This is followed by a detailed comparison between simulation results and experimental measurements, aimed at assessing the accuracy and robustness of the model. Particular attention is given to the system's dynamic responses under different operating conditions. Overall, these results provide a comprehensive evaluation of the model's capability to reliably reproduce the behavior of the real system.

4.1 Model Verification

As part of the model verification process, the calibration activities were carried out across all BoP components. The main objective was to ensure that both air and hydrogen are delivered to the stack inlet under conditions that support efficient electrochemical reaction and meet electrical load requirements across the full range of operative scenarios. To achieve this, key physical quantities — such us temperature, pressure, mass flow rate, and stoichiometric ratio — were systematically verified against the reference ranges provided by the component supplier, ensuring that each subsystem operates within its specified design envelope.

Among these parameters, the air mass flow rate delivered by the cathode line compressor was selected as a representative case. Ensuring an accurate supply of air to the cathode, consistent with the electrical load demanded by the FC stack, is essential for proper system operation. In fact, the stoichiometric balance between the reactant directly governs the efficiency of the electrochemical reaction and, consequently, the overall power output. Based on the supplier's performance documentation , a reference relationship between the required stack current and the corresponding accordingly. Air mass flow rate was established, and the compressor subsystem within the FCS model was parameterized accordingly.As illustrated in Figure 4, the comparison between model predictions and supplier data is presented in a dimensionless form. Both the simulated and reference air mass flow rates are normalised with respect to the maximum compressor delivery capacity, enabling a generalised evaluation independent of absolute physical magnitudes. Similarly, the stack current demand of the fuel cell is normalised with respect to its maximum rated value, ensuring a consistent and dimensionless framework for analysis and comparison across different operating conditions. The two profiles exhibit close agreement across the entire operative current range. The model successfully reproduces key trends, including low-load plateau, the nonlinear transitional rise, and the high-current saturation region with consistent fidelity. Minor local deviations, observable in the intermediate current range, remain within acceptable engineering tolerances and are attributable to inherent simplifications in the compressor map parameterization.

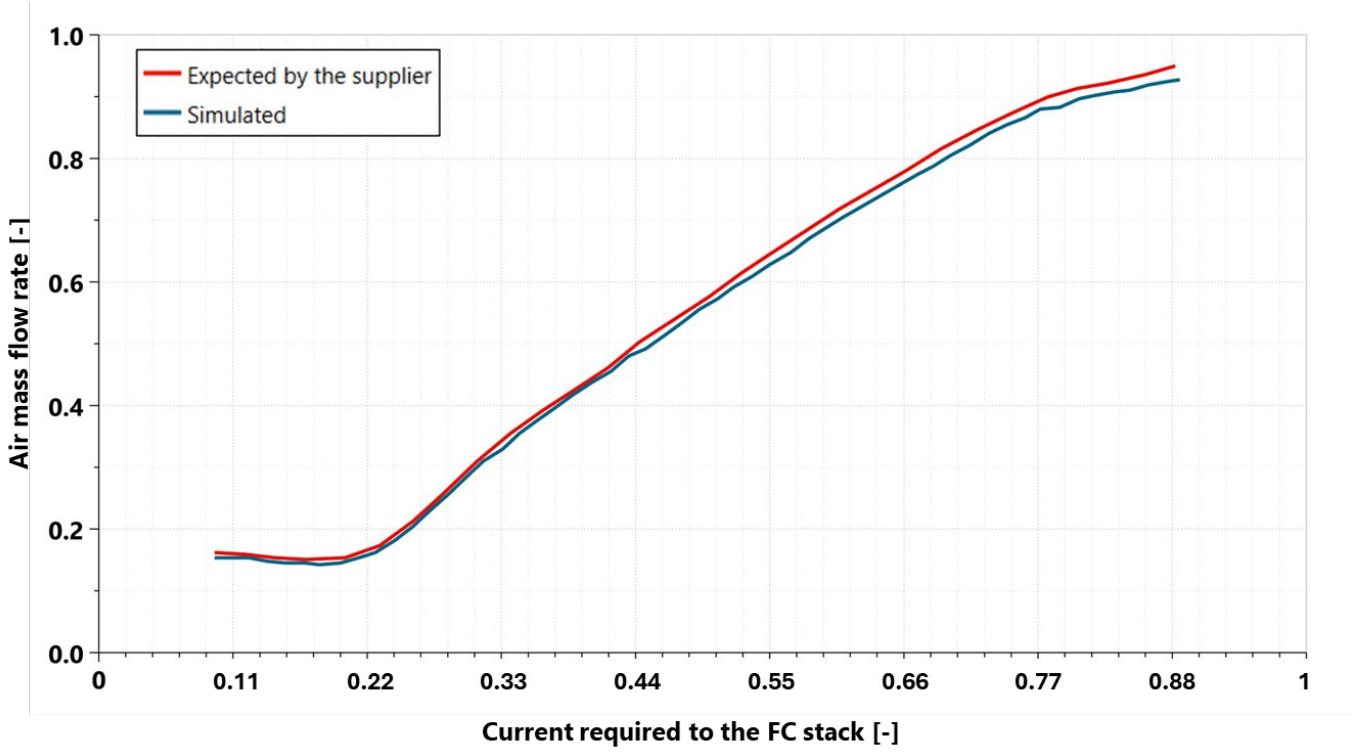


Figure 4 – Consistency between dimensionless simulated and expected air mass flow at cathode inlet

The final step in the verification process involved assessing the stack voltage response across varying current load conditions. As the current demanded was swept over the operative range, the simulated stack voltage was found to closely follow the characteristic polarisation curve provided by the supplier. The mean deviation between the simulated values and the expected trend is estimated to be approximately 3%. This discrepancy is primarily attributable to the steady-state nature of the simulation model, which cannot capture transient fluctuations and dynamic variability inherent in the experimental measurements. Despite these limitations, the overall agreement confirms that Digital Twin of the fuel cell accurately represents the real system behavior thereby allowing the verification phase to be successfully completed.

4.2 Test Execution

In order to support the validation process of the DT model, two distinct experimental test campaigns were designed and executed on the test rig, each targeting different aspects of the FCS operational behavior.

- Steady-State Tests: aimed at evaluating the propulsion system performance across a range of requested power levels, from idle to peak power. All tests were carried out with the inlet coolant temperature controlled at 45°C, focusing on the most demanding operating scenario, namely the discharged battery condition. By maintaining a consistent power output, stable operating parameters were preserved, allowing for precise measurement of key performance indicators such as efficiency, power conversion, and thermal behavior. This approach minimized transient effects and external disturbances, providing an accurate assessment of the system's baseline performance characteristics.
- Mission Profile Tests: designed to simulate operational conditions representative of a typical flight mission. These tests encompassed all characteristic mission phases — including taxi,

take-off, climb, cruise, descent, and landing — allowing for a comprehensive assessment of the propulsion system behavior under dynamic load conditions that closely replicate real operational scenarios.

4.3 Model Validation

The validation of the DT model is carried out by comparing the simulation outputs against the experimental measurements acquired during the test campaigns. Key performance indicators—such as FCS power-flow, voltage and current dynamics, fluidynamics of the BoP—were systematically compared under various operating conditions. Discrepancies between simulated and measured results were thoroughly analyzed to iteratively refine and calibrate the model parameters, enhancing the accuracy and fidelity of the digital twin.

As a first validation step, the simulation results were compared against some of the experimental data collected during the steady-state test campaign. For each Power Ratio (PR) step of the propulsion system, the comparison focuses on two key quantities:

- Net power delivered by the FCS, P_{FCS}, which corresponds to the power delivered by the system after accounting for the losses introduced by the boost converter and the share allocated to the BoP auxiliaries.
- Hydrogen mass flow rate consumed by the fuel cell, $\dot{m}_{H_2}$, which represents the actual quantity of hydrogen consumed by the stack to generate the corresponding electrical power output of the FCS.

The relevance of these two quantities lies in the fact that their combined knowledge enables a direct assessment of the overall conversion performance of the FCS, and consequently provides a quantitative indicator of how efficiently the powertrain operates at each load condition. By relating the net electrical power delivered by the FCS to the chemical energy associated with the hydrogen consumed by the stack, the overall fuel cell system efficiency can be evaluated for every operative condition according to Eq. 1:

$$\eta_{FCS} = \frac{P_{FCS}}{\dot{m}_{H_2} \cdot LHV_{H_2}} \tag{1}$$

In accordance with common practice in fuel cell system performance assessment, the efficiency is referenced to the Lower Heating Value ($LHV = 120\ MJ/kg$) of hydrogen, given that the water produced during operation is typically released as vapour and the latent heat of condensation associated with the Higher Heating Value (HHV) is not recovered. The LHV therefore provides a more representative measure of the usable chemical energy available to the system.

Table 2 reports the experimental reference data, corresponding to a representative operating point sampled during some steady-state condition, in terms of FCS net power output. For each sampling point, the FCS efficiency derived from the experimental measurements ($\eta_{FCS\,EXP}$) through Eq. 1 is compared against the corresponding value predicted by the DT model ($\eta_{FCS\,DT}$). The two datasets exhibit a consistently good agreement across the entire operating range, with a mean absolute percentage error of approximately 1.2% and local deviations never exceeding 2.4%. This close match further confirms the capability of the DT to accurately reproduce not only the gross power response of the FCS, but also its conversion performance under a wide spectrum of load conditions.

Table 2 - Fuel Cell System steady-state data

Test ID	PR [%]	P_{FCS} [kW]	η_{FCS_EXP} [%]	η_{FCS_DT} [%]
1	15	0.00	0	0
2	20	45.03	49.97	50,0
3	25	55.77	46.80	46,80
4	30	67.82	43.95	44,10
5	35	73.36	42.81	42,90
6	40	78.96	40.92	40,90
7	45	84.72	38.45	38,50
8	50	90.63	37,28	38,00
9	55	91.12	37,35	38,10
10	60	91.63	37.50	38,40
11	65	92.36	37.77	38,60
12	70	93.34	38.26	39,10
13	75	92.94	38.15	38,10
14	80	92.91	38.03	38,80
15	85	91.99	37,76	38,10
16	90	92.68	38.01	38,80
17	95	90.56	37.03	37,80
18	100	89.74	36.84	37,60

As shown in Table 2, the FCS reaches its maximum net output power at approximately 50% throttle (Test ID 8), well before the upper end of the PR range. This arises directly from the adopted test configuration in which the FCS was operated at its maximum power output to emulate the most demanding operative condition, specifically, the scenario in which the battery state of charge approaches the recharge threshold. Under these circumstances, the BoP power consumption attains its maximum expected value, while the battery absorbs significant charging power to compensate for the difference between the electrical demand of the system and the power supplied by the FCS.
For throttle levels above 85% — highlighted in yellow in Table 2 — the total power demand of the propulsion system surpasses the maximum output capacity of the FCS alone. As a result the battery must actively support power delivery alongside the fuel cell. Such conditions can only be sustained when battery state of charge remains sufficiently high, and therefore they should not be interpreted as steady operating points, but rather as transient peak-demand phases within the mission profile.

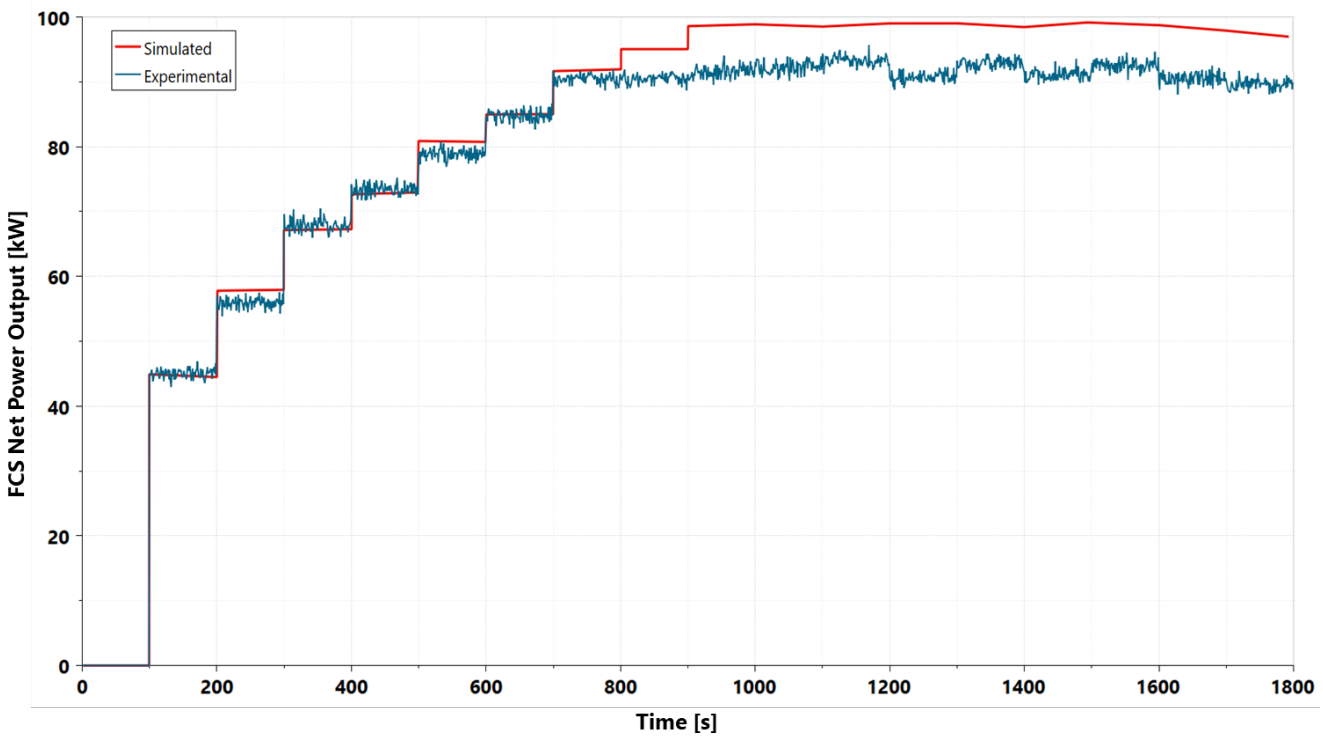


Figure 5 – Correlation between simulated parameters and test-rig measurements at different steady state conditions

Figure 5 compares the experimentally measured P_{FCS} values reported in Table 2 with the corresponding simulation results across the full PR range. In the lower throttle region, the agreement between the two curves is satisfactory, with discrepancies remaining within acceptable engineering tolerances. However, a more pronounced deviation becomes evident at higher power levels, attributable to a thermal derating phenomenon observed during the test campaign. Specifically, it was found that when the coolant temperature exceeds a critical threshold — generally around 55°C — the HV DC/DC converter activates a current limitation strategy on its input side in order to prevent thermal damage to its internal components. This derating condition inevitably reduces the maximum net power deliverable by the FCS, causing the experimental output to stabilize at approximately 92 kW beyond the mid-throttle range, rather than continuing to increase as predicted by the nominal simulation, thus introducing a systematic offset between the two curves at higher power ratio levels.

Following the observations discussed in the previous section, the model was recalibrated by setting the maximum FCS net output power to approximately 92 kW, in order to reflect the operating envelope identified through the experimental analysis. Once this adjustment was implemented, the improved model was validated against a mission profile test, with the aim of verifying the system response to the time-varying power demands imposed by the electric motor and the resulting power redistribution among the energy sources under dynamic conditions representative of a typical mission. The corresponding results are presented in Figure 6, which illustrates the comparison between the simulated and measured FCS net output power over the entire mission duration of approximately 7200 seconds.

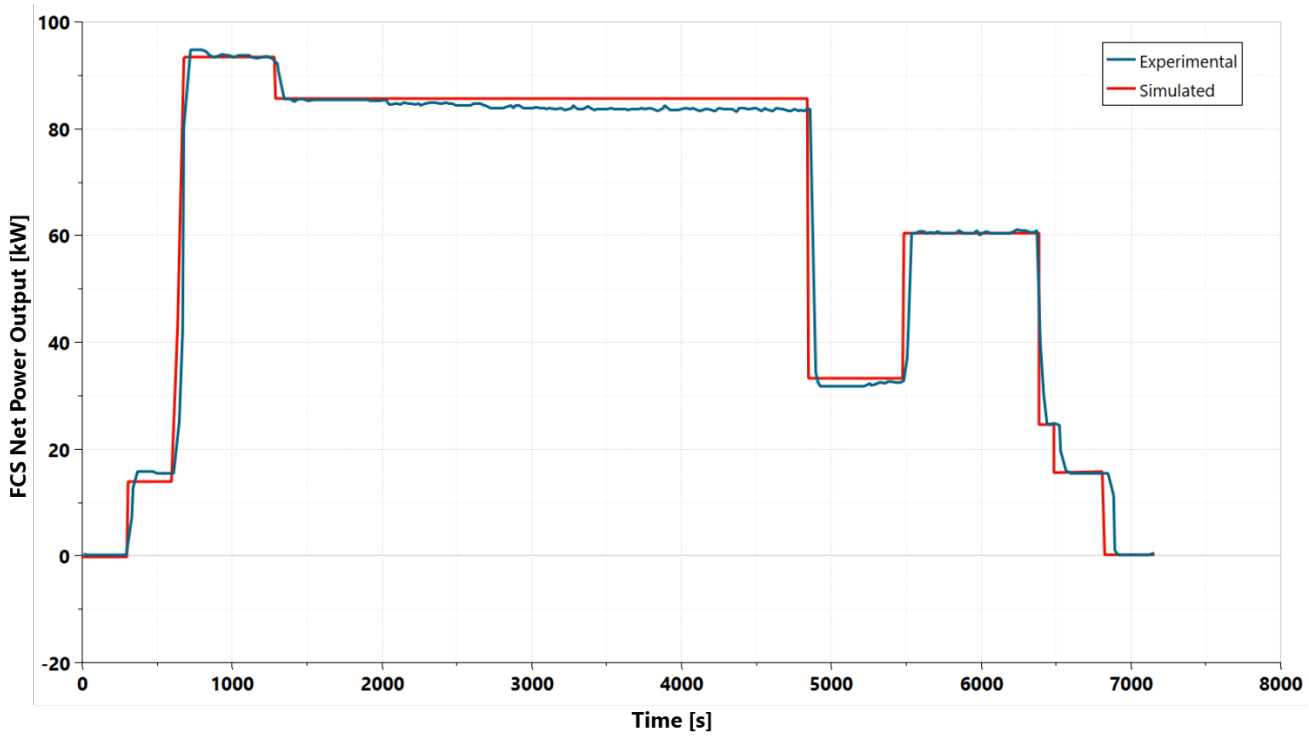


Figure 6 – Correlation between simulated parameters and test-rig measurements during a mission profile test

The two curves exhibit a remarkably close agreement across all flight phases, confirming that the corrective measures introduced into the model effectively captured the real system behavior. A quantitative comparison between the experimental and simulated traces yields an average relative error of approximately 1.8% over the entire mission profile, a value that confirms the high fidelity of the DT under both steady-state and transient operating conditions. During the high-power phases — corresponding to take-off and initial climb, where the FCS output reaches approximately 92 kW — the simulated and sensored curves are nearly coincident, with only negligible transient deviations.

Throughout the extended cruise phase, both profiles stabilize at approximately 85 kW. The experimental curve exhibits small oscillations, which can be attributed to real-world load fluctuations and control system dynamics, while the simulation maintains a smooth steady-state output consistent with its deterministic nature. It is precisely in this region, together with the steep power transitions between flight phases, that the local deviation between the two curves is most pronounced. This residual discrepancy is likely to originate from electromagnetic disturbances generated by some of the high-power components of the powertrain, which introduce a small but non-negligible measurement margin in the sensor readings. Since these signals are subsequently processed by the Power Control Unit (PCU) to regulate the distribution of electrical power across the entire powertrain, any such bias is unavoidably reflected both in the data acquired during the experimental campaign and in the closed-loop response of the system itself.

In the descent and loiter phases, where the demanded power drops to approximately 33 kW and subsequently rises to 60 kW, the model accurately reproduces both the magnitude and the timing of the power transitions. The final approach, taxi-in, and shutdown sequence are equally well captured, with both curves converging to zero in a consistent manner. Overall, the strong agreement observed throughout the entire mission profile demonstrates validity and robustness of the Digital Twin, confirming its capability to accurately reproduce system behavior under a broad range of dynamically varying operating conditions.

5. Conclusion

This work described the development and experimental validation of a digital twin of a fuel cell system for an application in full-electric aircraft propulsion. The emphasis on the FCS stems from both its inherent technical complexity and its strategic relevance within the propulsion architecture. From a systems engineering perspective, it represents one of the most challenging subsystems as it governs the primary energy conversion process while involving tightly coupled electrochemical, fluidic, and thermal phenomena that evolve on different timescales and interact nonlinearly under transient operative conditions. From a broader technological standpoint, a rigorous characterisation of its behaviour under realistic operating conditions is therefore essential not only for the development of the present system, but also to establish the modelling and experimental foundations required for future hydrogen-powered aircraft architectures. The adopted methodology is rooted in Model-Based Systems Engineering principles and follows a V-model development framework, where the experimental test rig provides the reference data necessary to anchor the simulation model to physical evidence.

The verification and validation phases confirmed the capability of the FCS Digital Twin to accurately reproduce the system behaviour across a wide range of operative conditions, encompassing both steady-state and dynamic mission profile scenarios. Notably, the test campaign led to the identification of a thermal derating phenomenon affecting the HV DC/DC converter, which was subsequently incorporated into the model parameterization, resulting in a significant improvement in simulation fidelity under thermally demanding conditions. The main result of this work is a robust, experimentally validated digital twin of the FCS, capable of supporting predictive analysis, advanced control development, and real-time monitoring of full-electric propulsion systems. The integration of physics-based modelling, MBSE methods, and experimental validation within a unified development cycle ensures coherence between design intent and validation evidence, strengthens confidence in the predictive capability of the digital model, and lays the foundation for its future integration into operational control and health monitoring applications for hydrogen-powered aircraft.

Future work will focus on extending the DT capabilities towards real-time operation, enabling its deployment as an on-board monitoring and prognostic tool capable of tracking system health, detecting anomalies, and supporting predictive maintenance strategies. Further work will also address the characterisation of degradation phenomena affecting the fuel cell stack over extended operational lifetimes, with the aim of incorporating ageing models into the DT framework. In parallel, the methodology established in this work provides a replicable foundation for the development of additional propulsion subsystems, progressively expanding the scope of the virtual representation towards a fully integrated aircraft-level Digital Twin.

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