CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 264

PEM fuel cell systems for marine propulsion

Electrification and Fuel Cells Development

Anton Reiter, AVL List GmbH

Frank Mair, AVL List GmbH
Jörg Zimmermann, AVL List GmbH
Günter Figer, AVL List GmbH

ABSTRACT

Marine transportation is a vital part of the global economy as it handles more than 90% of the global trade volume. The reduction of greenhouse gas emissions is a crucial challenge of our time, and also the maritime industry has to contribute by introducing alternative fuels and new propulsion system technologies. This paper gives an overview about a possible categorization of ship types depending on their shipping pattern and shipping routes. Based on these categories current propulsion system layouts are listed and an outlook for potential future energy carriers and propulsion system technologies - such as fuel cells - is given. In the development of fuel cells for marine applications several challenges arise, which include an increased focus on safety on the part of the classification society but also requirements coming from the application itself. For PEM fuel cells in particular, challenges like explosion protection, electrical isolation resistance as well as environmental aspects are discussed. Overcoming these challenges often requires a collaboration of different skills and the utilization of various development tools. Virtual development tools can significantly reduce the development time and contribute to an improved quality of the final product. With the focus on System Simulation the paper presents different use cases as well as a comparison of simulation results with testbed measurement data for the marine fuel cell system developed by AVL.

1 INTRODUCTION

Marine transportation is essential for the global economy. However, its contribution to the overall anthropogenic greenhouse gas (GHG) emissions has grown from 2.76% in 2012 to 2.89% in 2018 [1]**.** In the European Union, waterborne transport was responsible for approximately 3 to 4% of total CO_2 emissions in 2021 [2]. Despite these numbers, marine shipping continues to handle over 90% of the world's trade volume [3], making it one of the environmentally friendly transport options with respect to carbon emissions.

Various initiatives are aiming to reduce emissions from shipping. The International Maritime Organization (IMO) has adopted the 2023 IMO Strategy on Reduction of Greenhouse Gas (GHG) Emissions from international shipping. The new targets entail a 20% emissions reduction by 2030, a 70% reduction by 2040 (compared to 2008 levels), and the aim of achieving 100% reduction to net-zero emissions by 2050, as shown in Figure 1. The implementation of new regulations is anticipated to commence around mid-2027 [4].

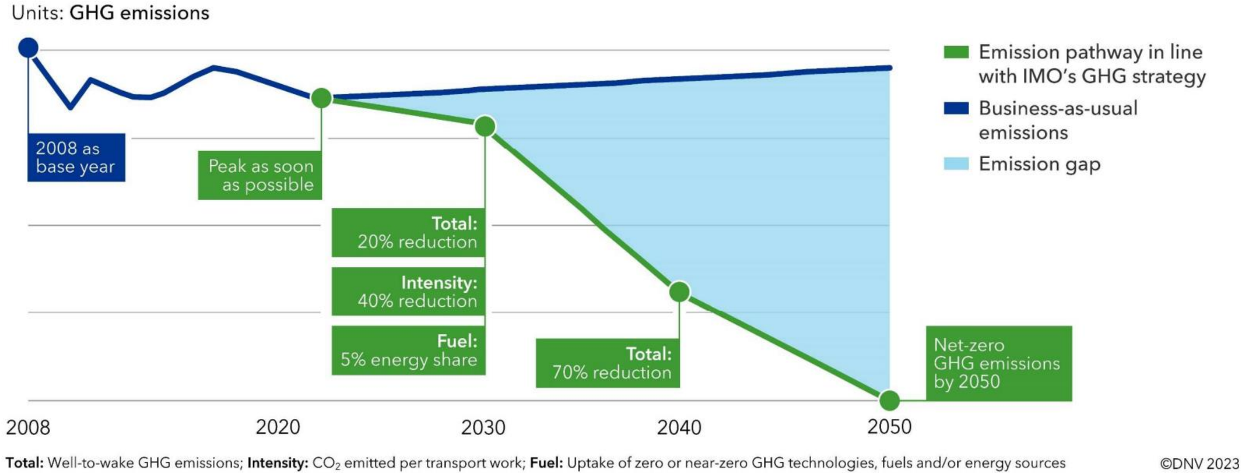

Figure 1. Revised IMO GHG strategy [4]

CO_2 pricing (or carbon pricing) and its influence on the total cost of ownership (TCO) could make alternative fuels and new technologies significantly more attractive. The impact of such regulations can be a fundamental factor in facilitating the shift from traditional fuels to alternative fuels like hydrogen and ammonia as well as to new propulsion technologies.

As a result, IMO member states have agreed to implement carbon pricing in the near future, with various countries presenting different proposals. On a regional scale, the European Union (EU) is taking a leading role in carbon pricing through its EU Emission Trading Scheme (ETS), which includes the shipping industry since January 2024 [5].

The selection of alternative fuels as well as new propulsion technologies depends on multiple factors such as ship type, shipping routes, fuel availability and long-term strategic considerations of fleet owners. Alternative fuels in shipping today typically include LNG, followed by Methanol, LPG, Ammonia and Hydrogen, see Figure 2. Currently, all those alternative fuels are used in internal combustion engines for both main propulsion and auxiliary power. Future marine propulsion systems will also include fuel cells either as part of a hybrid powertrain configuration connected to the DC-link or as standalone power plants for smaller vessels.

This paper provides an overview about a possible categorization of different ship types and their sailing patterns. Based on this classification it is discussed which powertrain configurations are used today and where Fuel Cells can play an important role in the future. Focusing on Proton Exchange Membrane (PEM) Fuel Cells, relevant development challenges specific to marine applications are addressed. Based on the marine PEM fuel cell system developed by AVL the paper presents the utilization of virtual development tools for different use cases.

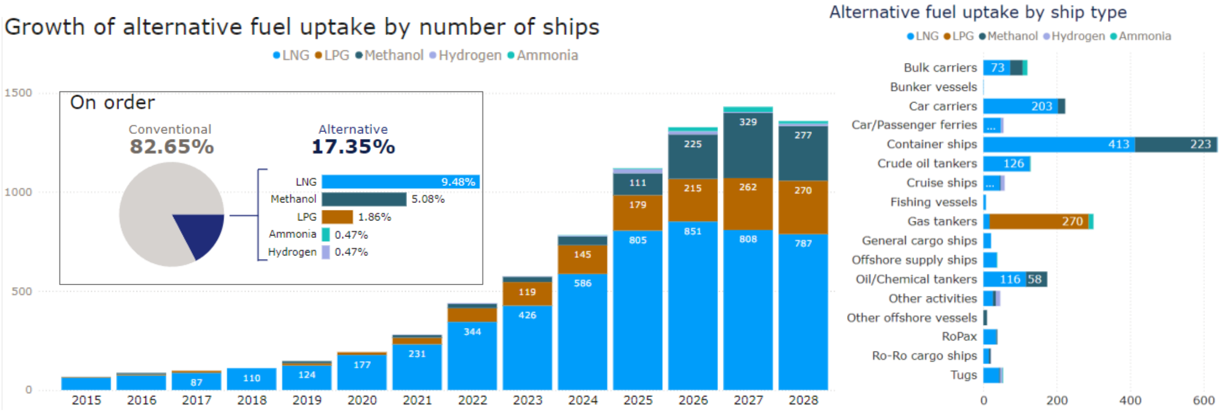

Figure 2. Growth of alternative fuel uptake by number of ships and ship types [6]

2 PROPULSION SYSTEMS FOR DIFFERENT SHIP TYPES

As mentioned in the introduction the use of alternative fuels and new propulsion technologies depends on various factors. Therefore, this chapter gives and overview about different ship types and their current as well as future propulsion system technologies.

2.1 Overview of Different Ship Types

A possibility to classify different ship types is based on their shipping routes and shipping patterns.

The shipping routes can be categorized for example into tramp sailing, fixed scheduled roundtrip and point-to-point sailing. Tramp sailing is flexible and demand-driven, with ships operating without fixed schedules, often transporting bulk commodities. Fixed schedule roundtrip vessels operate on fixed routes and are commonly used for container ships, roll-on/roll-off (Ro-Ro) ferries and passenger ships. Point-to-point shipping are ships traveling between designated ports and is a cost-effective way for various types of cargo.

The shipping patterns are categorized according to the area of operation as well as the distances being covered. Some examples are inland waterway transport (IWT) for local and inland shipping, island and Ro-Ro ferries for coastal shipping as well as container vessels and bulk tankers for deep sea shipping.

For the discussion of different fuels and future propulsion systems, we categorize the vessels into the ship types Local Shipping, Super-Yacht, Short-sea RoPax (roll-on/roll-off vessel for vehicle transport along with passenger accommodation), Short-sea Cargo, Cruise and Deep-sea shipping, as shown in Figure 3.

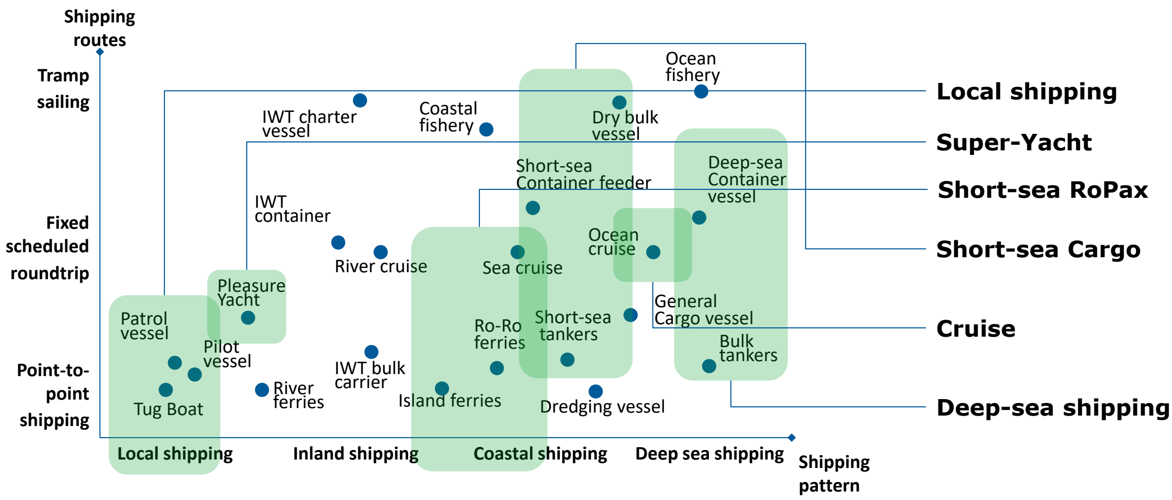

Figure 3. Categorization of Different Ship Types, based on [7]

2.2 Future Ship Propulsion Systems

Figure 4 provides an overview of the propulsion systems used today for the ship types we have defined. In addition, the figure shows factors influencing the choice of future propulsion systems and provides an outlook on future energy carriers and favored propulsion systems. All of the fuels discussed in this paper can be processed by Solid Oxide Fuel Cells (SOFC) and in principle also by PEM Fuel Cells in combination with advanced fuel processing systems, forming a broad range of possible solutions for maritime fuel cell applications.

Today, we see mainly 4-stroke internal combustion engines for both auxiliary power as well as for propulsion in a mechanical or diesel-electric powertrain. For short-sea cargo and for deep-sea shipping where noise and vibration requirements play a subordinate role and where the focus is on high powertrain efficiency 2-stroke engines with a mechanical coupling between engine and propeller are used.

PEM fuel cells are perfectly suited for marine applications and offer high power density, high efficiency as well as good dynamic performance. AVL expects the best chances for a future PEM fuel cell technology penetration for cruise ships and super-yachts where requirements like low noise and emission-free utilization are of high importance. For other use-cases, PEM is still ranked as one of the possible technologies but is not ranked first. For local shipping where battery energy storage systems can provide sufficient range, battery electric propulsion systems may be preferred due to the higher energy efficiency. For short-sea cargo and especially for deep-sea shipping 2-stroke engines together with ammonia or methanol will be the preferred solution based on high powertrain efficiency, low CAPEX as well as lowest weight and smallest packaging.

For commercial use-cases (Cruise and cargo shipping), AVL expects that new solutions need to result in significant financial benefits for ship owners to accept the risk related to the handling of hydrogen, lack of experience in maintenance and repair, and lack of track record. Taking these additional requirements into account, an initial penetration of LT-PEM fuel-cells seems most realistic as auxiliary power for short-sea cargo and deep-sea shipping use-cases, initially replacing 1 or more of the 4-stroke auxiliary engines.

	Local shipping	Super-Yacht	Short-sea RoPax	Short-sea Cargo	Cruise	Deep-sea shipping	
Propulsion layout	Mechanical / Diesel-electric	Mechanical / Diesel-electric	Mechanical / Diesel-electric	Mechanical	Diesel-electric	Mechanical	**TODAY**
Propulsion engine	4-stroke engines	4-stroke engines	4-stroke engines	2-stroke engine	4-stroke engines	2-stroke engines	**TODAY**
Auxiliary engine	4-stroke engine(s)	4-stroke engines	4-stroke engine(s)	4-stroke engines	4-stroke engines	4-stroke engines	**TODAY**
Major characteristics / factors	▪ Short operating range ▪ Space constraint ▪ Hydrogen at port	▪ Low noise important ▪ Varying range ▪ Space limited	▪ Hydrogen at port ▪ MeOH within comfort zone ▪ No NH_3	▪ Short voyages ▪ Space constraints ▪ Specific business case is important	▪ MeOH preferred ▪ New class rules ▪ Some distributed space available	▪ Less space constr. bulkers & tankers ▪ Limited Auxiliary power required	
Energy carrier	▪ Battery ESS ▪ Hydrogen	▪ Methanol ▪ Hydrogen	▪ Battery ESS ▪ Methanol ▪ Hydrogen	▪ Methanol ▪ Ammonia ▪ Hydrogen	▪ Methanol ▪ Biogas ▪ Biodiesel	▪ Ammonia ▪ Methanol ▪ Biogas	**OUTLOOK 2030+**
Favorite propulsion	1. Battery Electric 2. PEM 3. ICE	1. PEM 2. ICE 3. HT-PEM	1. Battery Electric 2. PEM 3. ICE	1. ICE 2. PEM	1. PEM 2. ICE 3. HT-PEM	1. ICE 2. (PEM) 3. (SOFC)	**OUTLOOK 2030+**
Favorite auxiliary power	See propulsion	See propulsion	See propulsion	1. LT-PEM 2. ICE 3. (SOFC long term)	See propulsion	1. PEM 2. ICE 3. (SOFC long term)	**OUTLOOK 2030+**

Figure 4. Propulsion Systems for Different Ship Types

3 MARINE PEM FUEL CELL – DEVELOPMENT CHALLENGES

The marine industry introduces challenging requirements for fuel cells. These include an increased focus on safety on the part of the classification societies, but also requirements from the application in terms of service life, efficiency, integration and ease of maintenance. A brief overview of some of these challenges shall be given in this chapter.

Requirements for the classification of fuel cells in marine applications are currently based on the "IMO (International Maritime Organization) Interim Guidelines for the Safety of Ships using Fuel Cell Power Installations". In terms of safety, special attention has to be paid to the explosion analysis, where failures which can lead to dangerous overpressures have to be investigated. Overpressures can for example be caused by a gas pipe rupture or a blowout of gaskets with subsequent explosion. Due to the properties of hydrogen and its wide flammability range, these scenarios can result in significant explosion pressures depending on the design, operating pressures and leakage scenarios of the specific fuel cell system. Ideally these overpressures caused by an explosion are contained within the fuel cell system without having an impact on the surrounding environment on the ship.

Another focus area is the electrical isolation resistance. In the automotive industry the minimum required isolation resistance on powertrain level is usually based on standards like ISO 6469-3 which aims to limit body currents to non-harmful levels (see also IEC 60479-1). For marine applications these limits are of course also valid, however significantly higher isolation resistances in the MΩ range may be required in order to facilitate the integration into the overall powertrain or also for reasons of limiting galvanic corrosion when the ship is connected to shore power.

Furthermore, various challenges can arise from environmental influences in maritime applications. For example, air with high salt contents and other contaminants like sulfur oxides especially in port areas require special process air filtration systems in order to avoid accelerated degradation of the fuel cell membrane electrode assembly. But also, continuous inclinations of up to 30 ° (for emergency power equipment) and the high required lifetimes of approximately 35.000 – 50.000 h have to be considered in the development.

4 AVL MARINE FUEL CELL SYSTEM – OVERVIEW

To solve the mentioned challenges and meet the requirements arising from marine applications, AVL has developed a PEM Fuel Cell Stack and Fuel Cell System specifically for the marine market, see Figure 5.

Focus of the development was on achieving highest possible power on a single Fuel Cell System without compromising efficiency, as the hydrogen consumption has a crucial influence on the overall total cost of ownership (TCO) of a ship.

Figure 5. AVL Marine Fuel Cell System

The System fulfills the stringent requirements from the marine classification societies and features highest power density and efficiency which can be seen in the technical data listed in Table 1.

Table 1. AVL Marine Fuel Cell System - Technical Data

Technical Data	Specification
Fuel Cell Type	Proton Exchange Membrane
Net Rated Power	325 kW
Efficiency at Rated Power	46.2 % (BOL, based on LHV of H2)
Fuel Quality	Hydrogen (ISO14687:2019 Grade D)
Fuel Consumption	<20.5 kg/h (at rated power BOL)
Operating Voltage Range	760 … 1100 VDC
Current at Rated Power	412.5 A
BoP Supply Voltage	695 … 770 VDC
Mass (operational)	1550 kg
Power Density	0.133 kW/l; 0.210 kW/kg
Dynamics t_{90}	<5 s
Target Lifetime	35.000 h
Ambient Temperature	0 … 45 °C
Max. Inclination	30 °

The main focus when introducing new fuels and propulsion technologies onboard of a ship is safety. Special attention was therefore paid to the explosion protection. The design of the fuel system features a separate, sealed compartment housing the fuel cell stacks and all hydrogen carrying components which can withstand the explosion load even in case of a full pipe rupture. This way, an inherently safe design was achieved which significantly reduces the efforts for the integration of the Fuel Cell System on board of a ship.

5 UTILIZATION OF VIRTUAL DEVELOPMENT TOOLS

For the challenges mentioned in chapter 3, different development processes and tools can be utilized. Often it is a combination of various disciplines and tools which are required for complex tasks and which enable an efficient development with best possible results.

For example, for the explosion analysis, AVL has chosen a combined approach of virtual development and explosion testing. The explosion tests were used to gain vital experimental results for dynamic pressure curves of an explosion in open and closed vessels, which were used for the calibration and proof of quality of the 3D CFD simulation models. With the 3D CFD explosion analysis different hydrogen leakage scenarios and resulting explosion pressures were investigated. Based on these results and together with Finite Element Analysis, the structure of the fuel cell system was improved in such a way, that the explosion load can be contained within the fuel cell system without any negative impact on the surrounding environment. This approach of a mostly virtual development has a significant cost and time advantage in the development, compared to a solely experimental approach.

Also the mentioned challenge of improving the electrical isolation resistance of the fuel cell system requires different tools. The isolation resistance in a fuel cell system is mainly influenced by the cooling system, as coolant is in contact with live electrical parts of the fuel cell stack. Virtual development tools can assist in optimizing the isolation resistance via simulation of the electrical resistance networks. But also non-virtual development is required – for example material tests in order to ensure material compatibility and therefore low electrical conductivity of the coolant.

The system simulation which connects all relevant components of the fuel cell system was used to address the challenges related to the validation of component requirements and specifications, for software development and testing as well as calibration tasks.

6 FUEL CELL SYSTEM SIMULATION

System simulation is a well-established task in automotive development [8]. Many approaches from automotive engineering can be adopted for the development of a marine propulsion system. In this chapter the focus is put on the utilization of virtual development tools on Fuel Cell System level throughout the whole development process from requirements and specification phase to integration and testing of the system.

In Figure 6 an overview of the development process of the Fuel Cell System is shown. System simulation supports the whole process throughout all stages. Depending on the stage of the system development different input data are available. Together with the availability of these input data the simulation develops to a higher level of model fidelity throughout the development process.

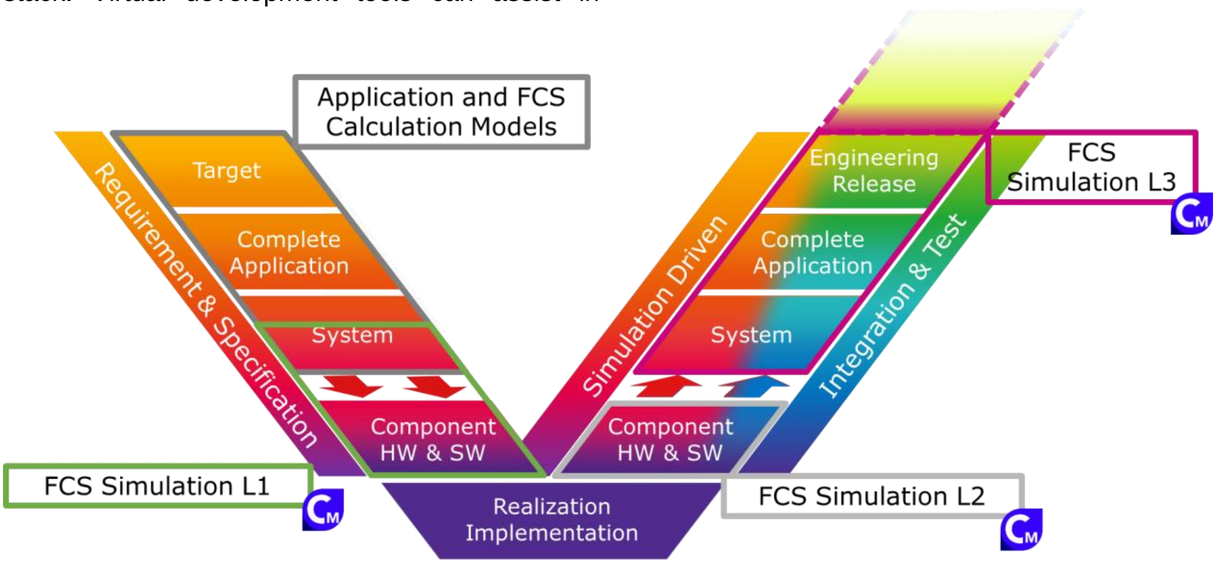

Figure 6. Development cycle of a Fuel Cell System and different model fidelity levels

Throughout the first phase of the development process the system's architecture and requirements are defined. Following the systems engineering approach subsequently its subsystems and all BoP component requirements are derived. These development steps are supported by FCS calculation models and focus on the systems rated power considering only little interaction between the components of the system.

For best utilization of the simulation environment by the development engineers a smooth development process with as little toolchain changes as possible is required. Once the basic system architecture and BoP component requirements are defined a continuous modelling concept with different model fidelity levels ranging from L1 to L3 has been established and is well supported by the multi-physical system simulation tool CRUISE M [9].

Besides model fidelity model usage must be considered. Especially a SiL environment can be used with all different system simulation model fidelity levels.

In the scope of the Fuel Cell System (FCS) simulation model L1 the system architecture including all relevant BoP components and sensors is modelled. Parametrization and setup of the components is based on the component requirements or – if already available – based on component specifications. This model already considers all relevant interactions between the components and couples the different domains. This includes the thermodynamic domain for cathode and anode gas flow, liquid domain for high and mid temperature liquid coolant circuits, thermal domain for heat transport, electric domain and signal domain for signal and data handling. The signal domain includes the definition of a standardized interface for model export as FMU. With this setup all relevant interactions of the BoP components in the FCS are already captured and the simulation model can be used for the simulation of stationary points and transient test cycles to investigate component interactions and system behavior for various operating conditions. This model is available far ahead of the real system, but already allows many insights into the system behavior and enables several use cases which would otherwise require the full system.

Once measurement data from testbed of individual components or the FCS are available a continuous improvement of the individual components is performed. L2 model fidelity defines a modelling stage utilizing individual BoP component test data and first steady state measurements such as an IV curve of the system at normal operating conditions.

L3 model fidelity level focuses on a highly accurate simulation model representing the physical UUT for non-freezing conditions. The underlying model parametrization is based on specific measurements including stationary and transient conditions. Depending on intended use cases of the model a further extension to freezing conditions or durability and degradation simulation might be feasible as well.

To put it in a nutshell the different modelling levels describes the model parametrization quality. A L1 model focuses on system level output prediction with qualitatively correct interactions of all components. The model is based only on component requirements or specifications without usage of system measurements. The L3 model focuses on component level actuator prediction in the scope of the system simulation. Thus, a quantitatively correct system behavior is achieved based on specific measurements on the physical system.

6.1 FCS modelling

As outlined in the previous section the modelling of the FCS comprises the representation of the real UUT as a digital twin.

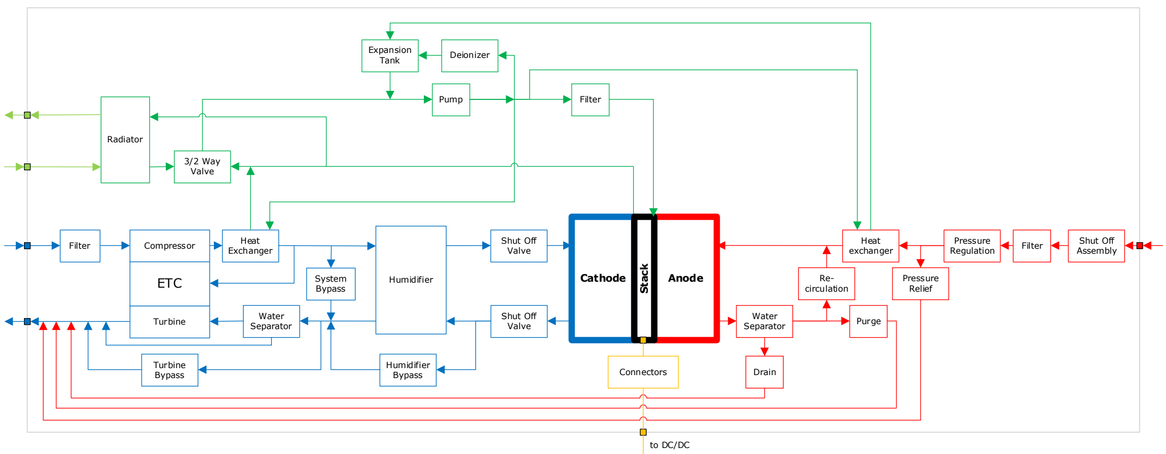

Figure 7. Simplified mechanization of the Fuel Cell System

In Figure 7a simplified mechanization of the Fuel Cell System is shown, Figure 8 shows the simulation model of the Fuel Cell System.

The model includes the complete cathode path from air intake to exhaust, the anode path with H2 supply to the system and the recirculation loop including purge and drain gases disposed to the exhaust line as well as the stack and electric circuit. Furthermore, the fuel cell high temperature coolant circuit and mid temperature coolant circuit (ship side) which is responsible for waste heat dissipation. Moreover, the housing of the stacks

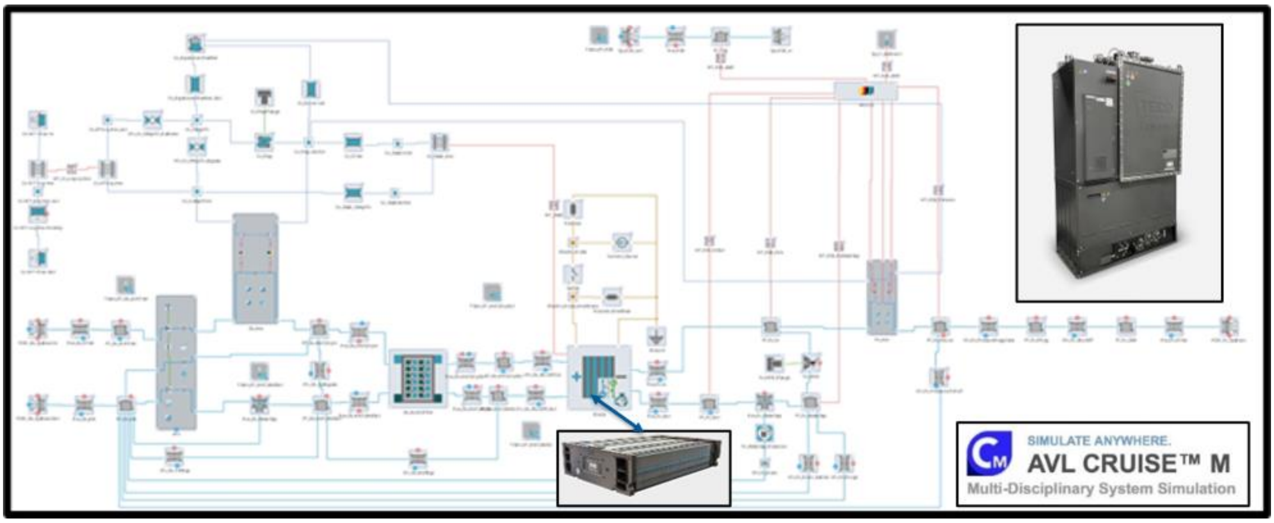

Figure 8. Simulation model of the Fuel Cell System

including required ventilation is represented by the simulation model.

To ensure the best compromise between modelling accuracy, numerical stability and performance a mixed approach of 0D and 1D simulation is chosen. All volumes and pipes of the physical system are simplified and modelled as 0D elements. Thus, the gas path is modelled as a sequence of flow and state components (restrictions and volumes). Modelling especially of temperature sensors is essential as well to correctly represent their thermal inertia and coupling to material temperature. Some parts of the physical system are designed as parallel paths. In the scope of the system simulation the parallel lines are simplified to one line with scaled components. This approach allows a more robust numerical setup and a higher real time factor.

The stack component and the associated heat exchanger in the coolant path compromises a 1D discretization along the flow direction of the channels into several segments. This approach enables a proper representation of cathode and anode gas concentration as well as temperature changes along the channel. Furthermore, formation of liquid water inside the channels and MEA is considered [9,10]. In the scope of the system setup it is assumed that all cells have identical behavior. The cell voltage spread is simulated on a stochastic approach in a separate model.

For a good accuracy between performance and stability a solver with a fixed time step of 1 ms is used. This setup allows for fast and stable simulations with a real time factor of ~ 0.55 on a typical office simulation laptop.

For best usability of the model the interfaces and access points during simulation execution are essential. This allows for easy testing of different conditions. Typical access points include:

- Initial temperature, pressure and gas concentrations for all subsystems
- Ambient temperature, pressure and humidity
- Air and hydrogen supply temperatures, pressure and humidity
- Secondary (ship-side) coolant temperature and flow
- Fuel cell box ventilation flow and conditions

Additionally, several component specific access points which are accessible online during a simulation are available including leakage simulation, heat transfer efficiency, pressure losses or stack performance losses to evaluate the system reaction.

The used system simulation tool CRUISE™ M provides for all relevant elements of the Fuel Cell System template components. Based on geometric information and performance data the individual elements and thus the whole Fuel Cell System is customized to match the physical system.

For details about the individual components and their features it is referred to the CRUISE M Manual [2].

6.2 Office model setup

In an office environment and in early development stages the shown FCS model is operated by a simplified control logic based on PID controllers. The operating conditions such as stoichiometry, humidity, temperatures and pressures are provided via current-depended operating-strategy maps with the actuators of the system being operated to meet these target values. The actively controlled components of the FCS include the electric turbo charger (ETC), turbine and humidifier bypass valve, hydrogen recirculation blower (HRB), purge and drain valve, coolant pump und thermostat valve.

This simulation environment is focused on full run of the system and therefore other operating modes such as system start up and shut downs are often not in the scope of an office environment.

6.3 SiL setup

In parallel to office simulation a SiL (Software-in-the-Loop) simulation setup was prepared as a co-simulation environment in Model.CONNECT [11] as shown in Figure 9. In this environment several modules such as FMU's, python code or internal functions and interfaces are coupled. The main elements of the SiL environement include:

- virtual Fuel Cell Controls Unit (vFCCU) as an FMU export of the application software (ASW) from AVL MAESTRA [12] allowing full calibration access
- System simulation model (FCSys) as an FMU export from AVL CRUISE M
- virtual failure insertion unit (vFIU) a python code module allowing signal manipulation
- Cell Voltage Monitoring (CVM) model as an FMU export based on a stochastic modelling approach
- A cycle reader module to be able to read in and automatically execute test cycles.
- Reset-Bus simulation and supporting functions for signal selection and output recording.

The modules are coupled as co-simulation in closed loop with a coupling time step of 10 ms. This setup is used for virtual pre-calibration tasks.

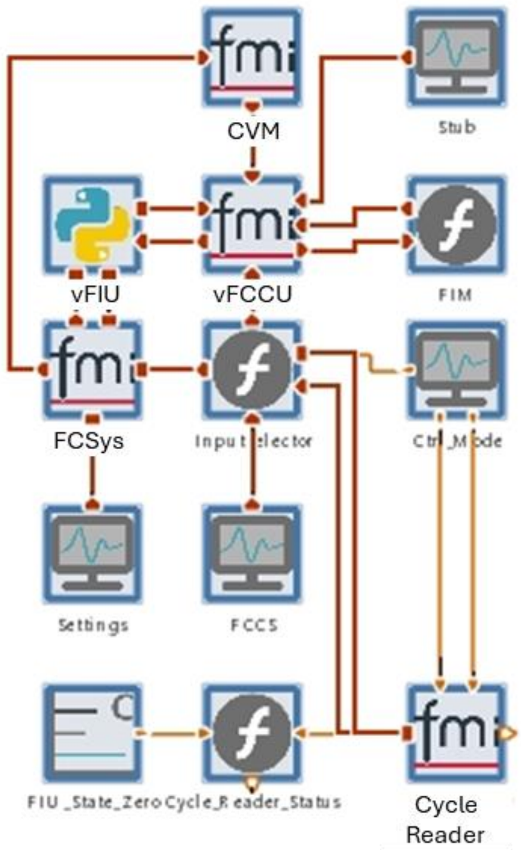

Figure 9. FCS digital twin co-simulation setup

6.4 Data evaluation

Throughout the fuel cell system development and calibration an enormous amount of measurement data is generated. For various evaluations of simulation studies a manual or semi-automatized result evaluation is followed. For many calibration tasks a measurement-by-measurement data and test case evaluation is required which is supported by automatic reporting tools. But still this approach has significant limitations if big amounts of data should be analyzed and trends should be derived. For all tasks requiring a fast overview of all available measurements from all testbed or system simulation AVL Data Analytics (ADA) [13] was used.

In Figure 10 an overview of OCV duration over system operation time is shown, with each point indicating a separate measurement. This evaluation reveals that especially during the initial commissioning phase of the fuel cell system on the testbed a significant share of total OCV time was accumulated. Furthermore, a few other events show are sharp increase of OCV duration vs. total operating time. These events can be well correlated with specific calibration tasks.

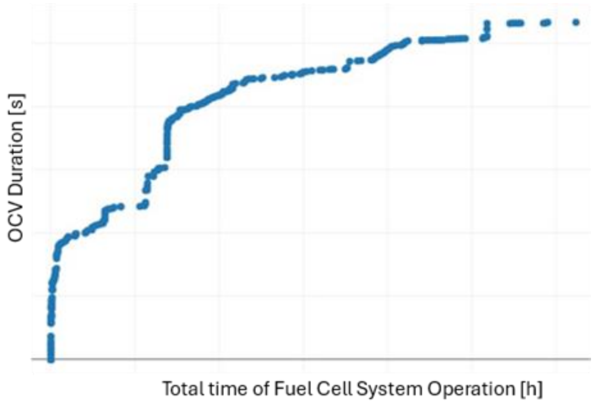

Figure 10. Overview of testbed and system operation during calibration evaluated with ADA

Once a stable calibration and operation status was achieved the increase of OCV duration is small, as it is actively avoided by the controls.

7 USE CASES SYSTEM SIMULATION SUPPORTED DEVELOPMENT

Depending on the development phase different tasks are executed and supported by system simulation. A first differentiation of the use cases is performed in development tasks and calibration tasks. A significant share of system simulation supported development tasks is executed in an office environment and supports system operation and architecture investigations. Additionally, also function development is supported in early phase which includes e.g. early concept investigations or software checks. System simulation tasks are typically performed in a closed loop simulation environment such as a SiL. An overview of potential and executed use cases is provided in Figure 11.

Workpackage/ Category	Subworkpackage/ Task	Concept investigations	Software check	Precalibration (extended office calibration)	First calibration	Fine calibration	Robustness & Tolerance Validation	Final Validation
Development Tasks (Office/MiL environment)								
Preparations for System Operation and Architecture Investigations								
	Oxygen subsystem	☑ (green)	☑ (green)	☑ (green)	☒	☒	☒	☒
	Fuel subsystem	☑ (green)	☑ (green)	☑ (green)	☒	☒	☒	☒
	Thermal subsystem	☑ (green)	☑ (green)	☑ (green)	☒	☒	☒	☒
Function development								
	Control functions	☑ (green)	☑ (green)	☒	☒	☒	☒	☒
Calibration Tasks								
Base calibration								
	State machine calibration	☒	☑ (green)	☑ (green)	☑ (green)	☑ (yellow)	☒ (red)	☒ (red)
	Non-Standard calibration	☑ (green)	☑ (green)	☑ (green)	☑ (yellow)	☑ (yellow)	☒ (red)	☒ (red)
	Transient calibration	☒	☑ (green)	☑ (green)	☑ (yellow)	☑ (yellow)	☒ (red)	☒ (red)
	Robustness	☑ (green)	☑ (green)	☑ (green)	☑ (yellow)	☑ (yellow)	☑ (yellow)	☒ (red)
	Fault management	☑ (green)	☑ (green)	☑ (green)	☑ (yellow)	☑ (yellow)	☑ (yellow)	☑ (yellow)
	Degradation	☑ (green)	☑ (yellow)	☑ (yellow)	☑ (yellow)	☑ (yellow)	☒ (red)	☒ (red)
	Setpoint calibration	☑ (green)	☑ (green)	☑ (green)	☑ (green)	☑ (yellow)	☒ (red)	☒ (red)

☑ (green) Use Case demonstrated
☑ (yellow) Use Case feasible (system depended)
☒ Task not applicable
☒ (red) Task not suitable for virtual environment

Figure 11. Fuel Cell System simulation use case matrix during development project

7.1 Office Simulation Use Cases

Early office investigations allow to evaluate system characteristics long before the physical system is available. Also, for CFD investigations the system simulation gives a significant benefit as gas compositions for exhaust or anode loop can be derived as important boundary conditions for CFD simulations. In the following sections a few use cases of office system simulations in early development phases based on a L1-Model are shown.

7.1.1 Ambient condition variation

Different ambient conditions have a major impact on the process air compressor of the system, as the stack operating conditions are relatively independent from the ambient. To check in early development stages if the compressor is capable of supplying the fuel cell system with enough mass flow at the required pressure level an ambient condition variation case study was executed.

Maritime transport or shipping in general is not limited to sea routes. For inland waterway transport or for applications operating on high altitude lakes, the effects of a change in altitude and thus a change in ambient pressure must be investigated.

Ambient conditions variation is based on the international standard atmosphere (ISA) [14] in the altitude range from 0 m to 2000 m in steps of 500 m and ISA temperature deviations of -20 °C / -10 °C / 0 °C / +10 °C / +20 °C / +30 °C for each altitude.

The resulting operating conditions of the compressor are shown in Figure 12 for rated power. In addition to the compressor mass flow rate and pressure ratio also the compressor shaft torque is an important requirement, which is indicated by the coloring of the operating points. Green coloring indicates a compressor torque which is ok, red indicates that the maximum bearable compressor shaft torque is reaching a critial level.

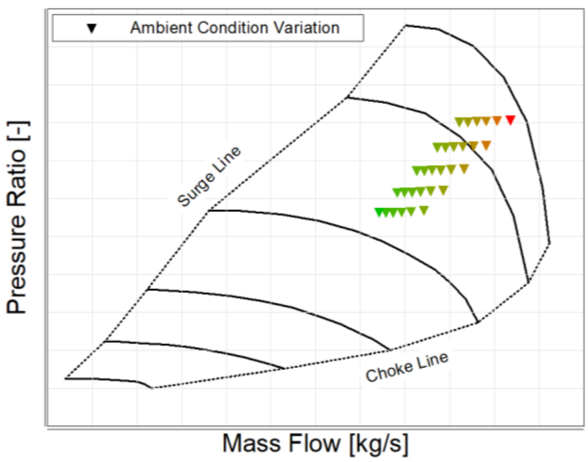

Figure 12. Compressor operating points at rated power conditions for various ambient conditions in relation to the compressor map.

This is especially for some high altitude and high temperature conditions the case. For these conditions a power derating or alternatively changed operating conditions such as e.g. a decreased cathode pressure or stoichiometry is mandatory to protect the system. Therefore, special care must be taken during calibration for high altitude, high temperature conditions.

7.1.2 Impact of stack performance degradation and operating condition variations on coolant pump

The layout of the coolant subsystem is essential to be able to reject the waste heat of the fuel cell system. The stack operating conditions especially delta temperature have a major impact on the coolant pump, due to the different coolant flow demand. Additionally, also stack degradation increases the waste heat which requires a higher coolant demand and thus influences the coolant pump operating point.

In Figure 13 the results of a study evaluating the coolant pump operation at rated power for stack BoL and EoL performance and two different stack delta temperature operating condition variants are shown. This study shows, that the coolant pump would be significantly oversized for operating conditions variant V1. For an optimal selection it is thus essential to have already in early development stages the target stack operating conditions available.

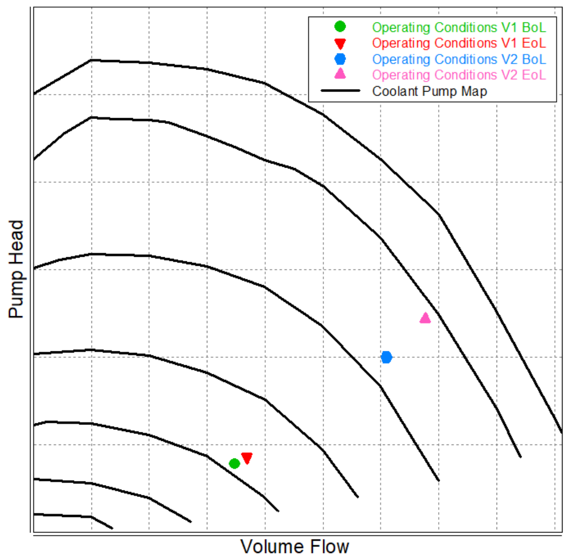

Figure 13: Impact of BoL / EoL stack performance and stack operating conditions on coolant pump operation

7.1.3 Cathode pressure build-up

The cathode operating pressure is one of the key operating conditions of the fuel cell system. In the current system design an architecture with passive pressure build up by the turbine in the cathode line was chosen. Therefore, it is essential, that the turbine builds up the required backpressure. In case of too low backpressure the optimum stack operating pressure might not be reached and in case of too high backpressure the turbine bypass must be opened which results in reduced energy recuperation by the turbine lowering the overall system efficiency.

In Figure 14 the pressure distribution over the cathode over the full power range is shown. The pressure ratio over the turbine is used for energy recovery.

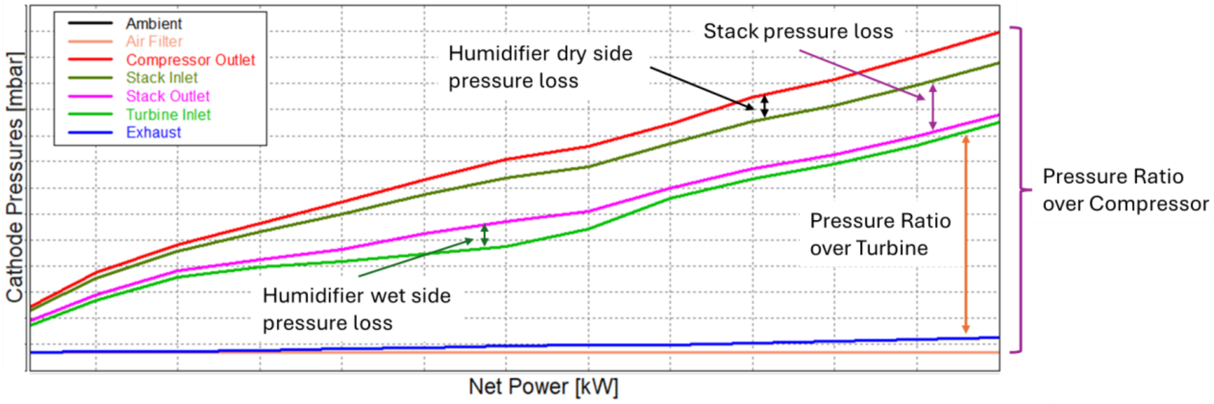

Figure 14. Cathode pressure build-up

7.1.4 Transient model testing against measurement data and further parametrization steps

A first evaluation of stack performance together with temperature and pressure parameters are shown in Figure 15. Overall the comparison of simulated and measured data shows a good result for a L1 model.

Based on this results the consecutive L2 and L3 parametrization is performed. The main calibration tasks are related to transient system behavour and detailed performance parametrization. A special focus during L3 parametriztaion is put on stack hysteresis effects due to oxide formations and stack hydration.

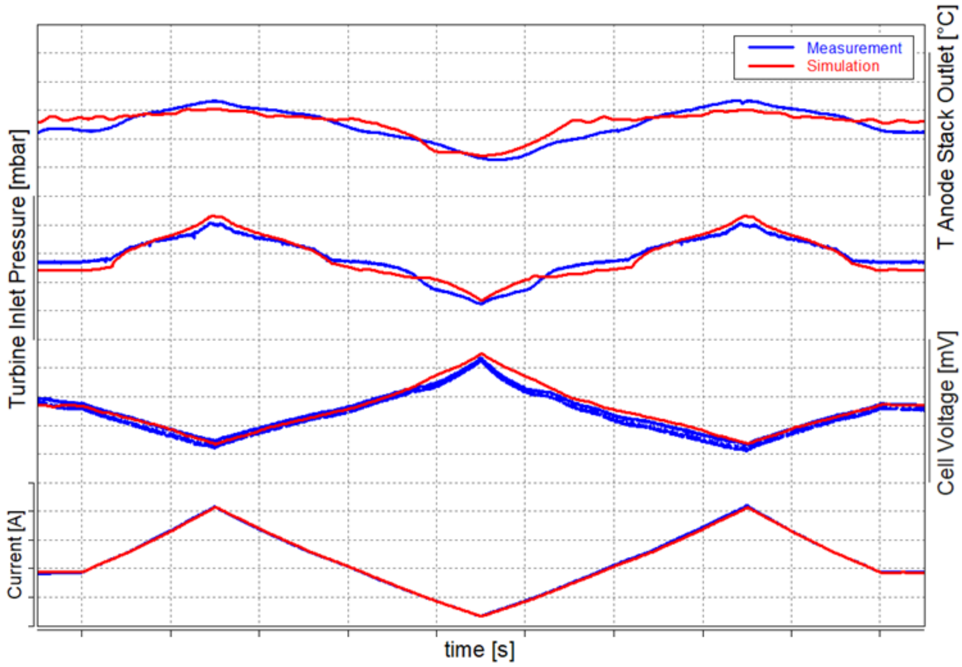

Figure 15. Transient simulation model results from office setup with simplified control unit

7.2 SiL Simulation Use Cases

This test environment focuses on closed loop operation of the system simulation together with the virtual control unit, enabling several calibration use cases. Depending on the model fidelity level, different use cases are possible.

7.2.1 Software development and functional software testing

This use case is supported with a L1 system simulation model. As the SiL setup allows to test the software already before the physical hardware is available and thus tasks can be frontloaded and parallelized. This reduces the development time and simultaneously increases the quality.

Furthermore, the SiL environment is coupled with an automatic test case execution in AVL CAMEO 5 [15] enabling functional testing. Depending on the testcase and related requirements many tests can be executed fully virtual or at least developed and optimized in the virtual environment before execution on the testbed.

In Figure 16 the automatized test execution of the SiL from fuel cell system start up to full run followed by three load jumps is shown. During test execution several input parameters as well a calibration parameters are modified.

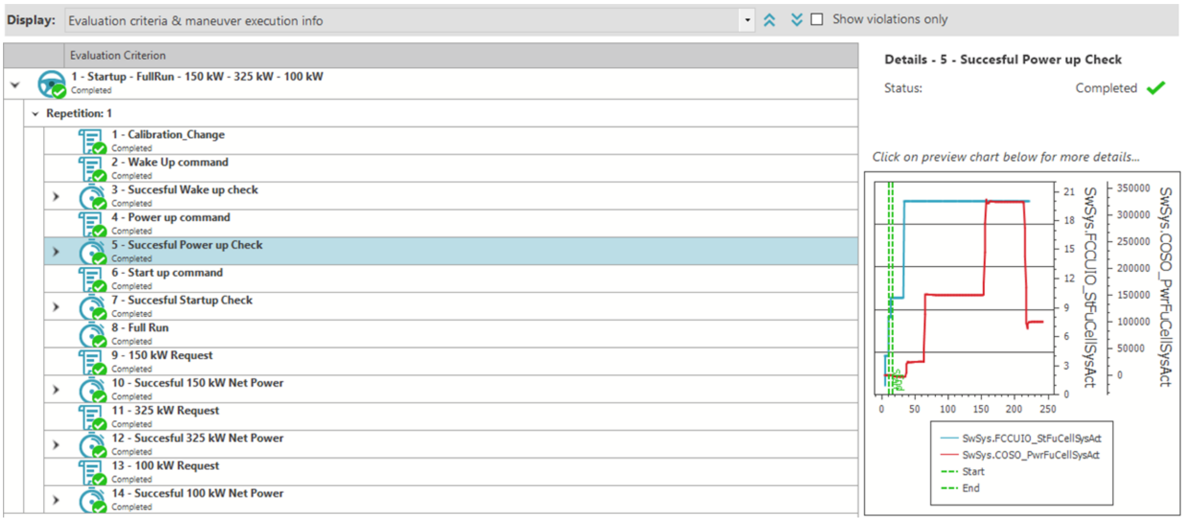

Figure 16. Exemplary SiL functional testing for system start up and load change

System requirements are defind as evaluation criteria to directly indicate if the test execution was successful. Together with the virtual Failure Insertion Unit (vFIU) included in the SiL enviroment a significant share of testcases related to fault dedection and reaction can be executed in the virtual environment. In addition to frontloading possiblities also tests which are associated with high risk of damage to the physical system can be prepared and pre-tested in the virtual environment.

7.2.2 Pre-calibration

Furthermore the SiL environment was used for a virtual pre-calibration of the software, before the physical UUT was available. This task allows to generate already feasible calibration before the first testbed operation. Especially for a newly developed system this is a major advantage as no pre-calibration is available and execution of this task is feasible with a L1 system simulation model.

7.2.3 Performance evaluation: Measurements vs simulation

For optimal support of tasks related to more advance calibration quality gates also the model fidelity should be increased. These model parametrization steps require the availability of measurement data from the testbed. The required measurement data include IV-curves, load variations, transient cycles depending on the system design and target use as well as specific tests for subsystem and component parametrization.

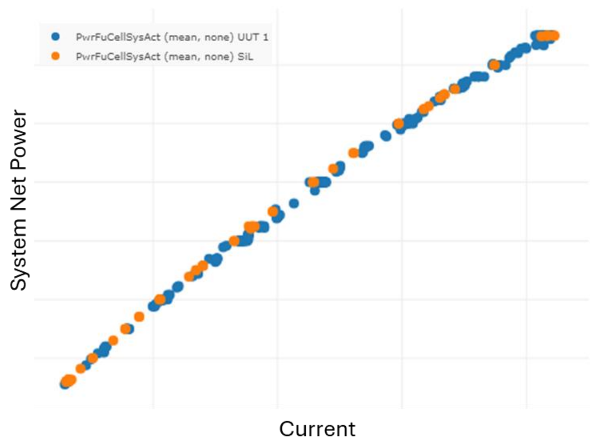

Figure 17. Comparison of fuel cell system net power output vs. stack current

To evaluate the accuracy of the SiL with the L1 system simulation model ADA is used to evaluated obtained SiL simulation results with testbed measurement data. This data includes transient test cycles with an overall duration of more than 10 h. Data evaluation is based on stationary points (30 seconds) which are automatically detected for all measurement files.

Figure 17 shows the fuel cell system net power output vs stack current for the whole operating range from idle to rated power. SiL system simulation results (orange symbols) show an excellent match with system net power output measured on the testbed.

For a more detailed anaylsis of all measurement and simulation data the compressor was chosen as an example. In Figure 18 an overview of the compressor operation including outlet pressure, compressor speed, compressor mass flow and compressor power is provided.

Overall a good match of simulation with measurement is obtained, however especially in low load ranges a signficant deviation of compressor outlet pressure and speed is observed at the current model fidelity level and must be addressed with model L2 and L3 improvements. The significant discontinuity in compressor mass flow and power is related to a changing cathode stochiometry in the mid power range.

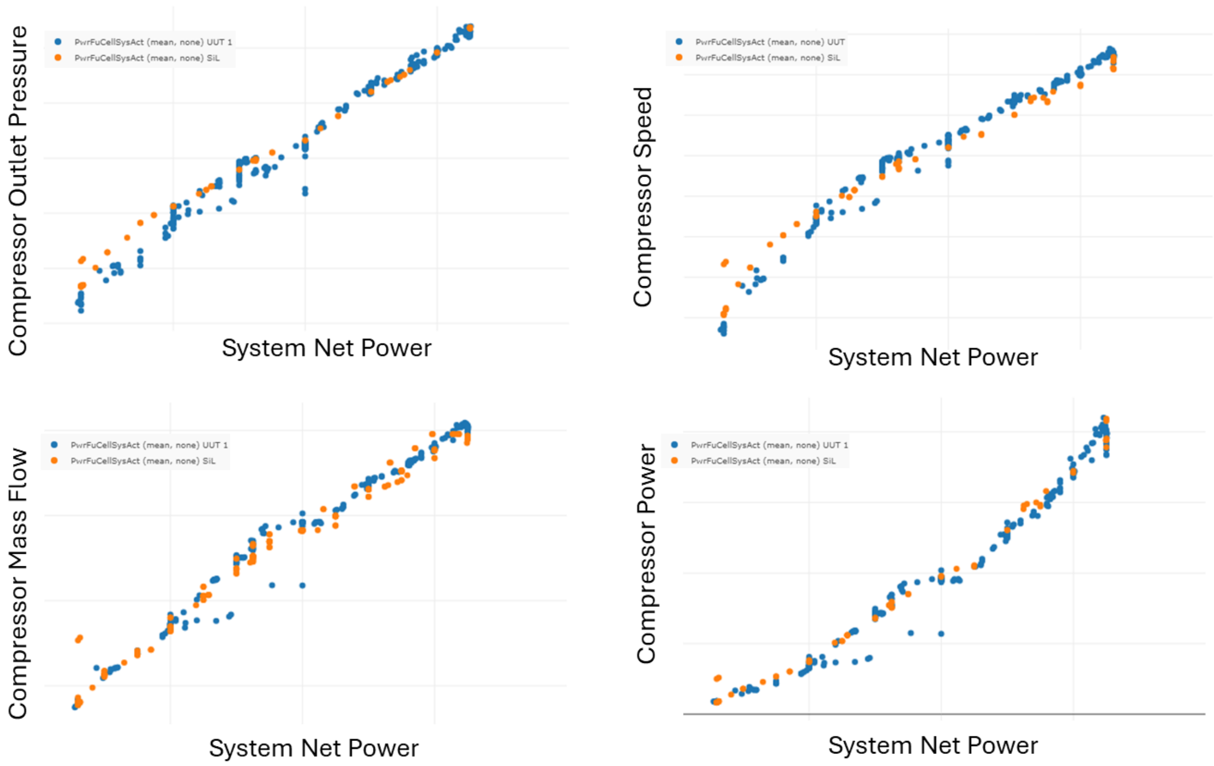

Figure 18. Compressor Performance evaluation simulation vs. testbed accross all measurements

7.2.4 Outlook on further SiL supported use cases for the next development and calibration steps

The current SiL setup is fully running and can be used as a digital twin to support calibration activities and analyze the impact of calibration changes. Furthermore, the measurement data will be used for detailed system simulation parametrization to increase the accuracy level to L3. With increased model accuracy the system simulation can strongly support the next calibration steps as outlined in Figure 11 by the orange marked calibration tasks. Furthermore the system simulation model can be extended by a chemical stack degradation model [9] to stronger support degradation and robustness use cases.

8 CONCLUSIONS

In order to decarbonize the shipping industry and contribute to the overall reduction of greenhouse gas emissions it is necessary that alternative fuels and new propulsion system technologies are used onboard of ships in the future. PEM Fuel Cell Systems offer high power density, high efficiency, good dynamic performance and are perfectly suited for marine applications. Challenges which arise from marine specific safety and application requirements can lead to increased efforts in the development compared to other areas where fuel cells are already in use for a longer period of time. However, virtual development tools can be used in various areas and contribute to a reduced development time and increased product quality. This includes the whole development cycle from supporting the requirements engineering and component selection, software development and virtual testing and calibration. Especially a SiL environment is a big enabler for frontloading and parallelization of tasks.

9 DEFINITIONS, ACRONYMS, ABBREVIATIONS

ADA: AVL Data Analytics™

ASW: Application Software

BOL: Beginning of Life

BoP: Balance of Plant

CFD: Computational Fluid Dynamics

CAPEX: Capital Expenditure

DC: Direct Current

EoL: End of Life

ESS: Energy Storage System

ETC: Electric Turbo Charger

FCS: Fuel Cell System

FMU: Functional Mock-Up Unit

HRB: Hydrogen Recirculation Blower

HW: Hardware

HT: High Temperature

HT-PEM: High Temperature PEM Fuel Cell

ICE: Internal Combustion Engine

ISA: International Standard Atmosphere

IWT: Inland Waterway Transport

LHV: Lower Heating Value

LNG: Liquefied Natural Gas

LPG: Liquefied Petroleum Gas

LT: Low Temperature

OCV: Open Circuit Voltage

PEM: Proton Exchange Membrane (Fuel Cell)

PID: Proportional-Integral-Derivative

SiL: Software in the Loop

SOFC: Solid Oxide Fuel Cell

SW: Software

TCO: Total Cost of Ownership

UUT: Unit Under Test

vFCCU: virtual Fuel Cell Controls Unit

vFIU: virtual Failure Insertion Unit

10 REFERENCES AND BIBLIOGRAPHY

[1] IMO, “Fourth IMO GHG Study 2020”, https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf, accessed on 25.06.2023

[2] European Commission, “European Green Deal: Agreement reached on cutting maritime transport emissions by promoting sustainable fuels for shipping”, https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1813, accessed on 25.06.2023

[3] International Chamber of Shipping, “Shipping and World Trade: World Seaborne Trade”, 2023, https://www.ics-shipping.org/shipping-fact/shipping-and-world-trade-world-seaborne-trade/, accessed on 10.01.2025

[4] Nyhus, E., Longva, T.: MEPC 80 - Increased emission reduction ambitions in revised IMO GHG strategy, DNV Webinar, July 11th, 2023, https://www.dnv.com/maritime/webinars-and-videos/on-demand-webinars/access/mepc-80-increased-emission-reduction-ambitions.html, accessed on 11.07.2023

[5] European Commission, “Reducing emissions from the shipping sector”, https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-shipping-sector_en, accessed o 10.01.2025

[6] DNV Alternative Fuels Insight Statistics, 2025, https://afi.dnv.com/statistics, accessed on 10.01.2025

[7] Oloruntobi, Olakunle & Chuah, Lai & Mokhtar, Kasypi & Gohari, Adel & Onigbara, Vincent & Chung, Jing Xiang & Mubashir, Muhammad & Asif, Saira & Show, Pau-Loke & Han, Ning. (2023). Assessing methanol potential as a cleaner marine fuel: An analysis of its implications on emissions and regulation compliance.

[8] Knaus, O. and Wurzenberger, J.C. 2021 *System Simulation in Automotive Industry*. Book chapter in Systems Engineering for Automotive Powertrain Development, Springer International Publishing

[9] AVL CRUISE™ M, AVL webpage: https://www.avl.com/de-at/simulation-solutions/software-offering/simulation-tools-a-z/avl-cruise-m, visited on January 7 2025

[10] Kravos, A., Ritzberger, D., Tavčar, G., Hametner, C. et al., Thermodynamically Consistent Reduced Dimensionality Electrochemical Model for Proton Exchange Membrane Fuel Cell Performance Modelling and Control," Journal of Power Sources 454 (2020): 227930, doi:10.1016/j. jpowsour.2020.227930.

[11] AVL Model.CONNECT™, AVL webpage: https://www.avl.com/de-at/simulation-solutions/software-offering/simulation-tools-a-z/modelconnect, visited on January 7 2025

[12] AVL MAESTRA®, AVL webpage: https://www.avl.com/de-at/engineering/automated-and-connected-mobility-engineering/software-and-controls-development-and-verification/software-development-toolchain, visited on January 7 2025

[13] AVL Data Analytics™, AVL webpage: https://www.avl.com/en/testing-solutions/all-testing-products-and-software/connected-development-software-tools/avl-data-analytics, visited on January 7 2025

[14] Airbus, 2000, Getting to Grips with Aircraft Performance. Flight Operations Support & Line Assistance, Airbus Customer Services, Blagnac

[15] AVL CAMEO 5, AVL webpage: https://www.avl.com/de-at/testing-solutions/all-testing-products-and-software/connected-development-software-tools/avl-cameo-5, visited on January 7 2025

11 CONTACT

Dr. Anton Markus Reiter
AVL List GmbH
Senior Development Engineer PEM Systems
AntonMarkus.Reiter@avl.com
https://www.linkedin.com/in/anton-reiter-96a48b12a/

DI Frank Mair
AVL List GmbH
Project Manager Fuel Cell
Frank.Mair@avl.com
https://www.linkedin.com/in/frank-mair-5706b5177/