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Integrated Modelling of Hydrogen Handling and Fuel-Cell Energy Systems for Maritime Applications

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Abstract

The decarbonization of maritime transport requires the integration of advanced hydrogen technologies into shipboard energy systems. Within the EU funded CleanH2Shipping project, a modelling framework is being developed to analyse the performance and operational behaviour of key hydrogen handling components, with the objective of supporting the design and evaluation of hydrogen-powered vessels. The present contribution provides an overview of the modelling activities carried out at the University of Pisa, focusing on the simulation of large-scale hydrogen storage and supply systems.

First, a numerical model for the filling process of hydrogen compressed Type IV tank-tainers is presented, enabling the prediction of pressure, temperature evolution, and refuelling efficiency under different operating conditions. This is complemented by a dynamic model of the hydrogen compression stage, aimed at characterizing the behaviour of multi-stage compression systems and assessing their impact on energy consumption and downstream storage conditions. Finally, preliminary results from the system-level modelling of ship architecture are introduced, with an initial assessment of hydrogen utilization and fuel-cell performance under representative operating profiles.

The overall aim of this work is to establish an integrated modelling platform that can support the optimization of hydrogen logistics, onboard energy conversion, and system design for maritime applications. These modelling activities contribute to the broader CleanH2Shipping objective of enabling safe, efficient and scalable adoption of hydrogen technologies in the shipping sector.

Keywords:

Hydrogen; Tank-tainer; Direct compression; Zero-dimensional model; Maritime applications; Fuel cells.

1. Introduction

The decarbonization of maritime transport is becoming a major priority in the transition toward more sustainable energy systems. The shipping sector plays a central role in global trade and is still associated with a significant environmental burden, which is driving the introduction of increasingly stringent international and European regulations aimed at reducing greenhouse-gas emissions and promoting cleaner propulsion technologies. In this context, hydrogen is gaining increasing attention as a promising energy carrier for maritime applications, thanks to its zero-carbon exhaust emissions at the point of use and its compatibility with fuel-cell-based and hybrid-electric ship architectures [1,2].

The actual environmental benefit of hydrogen, however, strongly depends on its production pathway. While grey and blue hydrogen may provide partial emission reductions, only renewable-based hydrogen is fully aligned with long-term climate-neutrality targets. At the same time, the continuous development of renewable electricity systems and electrolysis technologies is progressively improving the competitiveness of green hydrogen, thereby supporting its adoption in early maritime applications such as ferries, short-sea shipping, and inland vessels, where operating profiles are often well suited to PEM fuel-cell systems [3–7].

Despite this potential, the large-scale deployment of hydrogen in the maritime sector still faces important technological and logistical challenges. Among them, hydrogen storage, transport, and bunkering remain critical issues, especially for applications requiring operational flexibility, compact layouts, and safe handling in port environments. For mobile and modular systems, compressed gaseous hydrogen stored in composite tanks currently represents one of the most mature and practical solutions, offering a reasonable compromise between weight, safety, storage efficiency, and technological readiness. Compared with liquid hydrogen, compressed storage generally avoids boil-off issues and the high energy penalties associated with liquefaction, although it entails lower volumetric energy density [8–11].

However, the transfer of hydrogen from a compression and storage system to onboard tanks or modular storage units is far from trivial. During refuelling, hydrogen experiences a significant temperature increase due to compression effects, real-gas behaviour, and mass accumulation inside the vessels. These thermal effects may reduce the achievable stored mass and can lead to temperature levels approaching safety limits if not properly controlled. For this reason, the design of hydrogen refuelling systems must simultaneously account for tank thermodynamics, compressor operating conditions, intercooling and possible precooling requirements, as well as the trade-off between filling time, storage efficiency, and auxiliary energy consumption [12–17].

Among the available compression technologies, hydraulic compressors are particularly relevant for high-pressure hydrogen applications because they can combine high discharge pressures, good hydrogen purity, and compatibility with modular refuelling solutions. In particular, multi-stage hydraulic compression systems with intercooling can represent an effective solution for supplying compressed hydrogen tank-tainers while limiting thermal peaks and improving overall process controllability.

In this scenario, modelling tools are essential to support the design and analysis of hydrogen-based maritime energy systems. A component-by-component approach is often insufficient, because storage behaviour, compression performance, and onboard hydrogen utilization are strongly interconnected. For this reason, the present work contributes to the development of an integrated modelling framework within the CleanH2Shipping project, aimed at analysing the performance and operational behaviour of key hydrogen handling components for maritime applications. The work combines previous results on zero-dimensional modelling of large-scale compressed hydrogen storage systems with the analysis of a tank-tainer filling process coupled to a hydraulic compression chain, and it introduces the first elements of a system-level ship architecture model for assessing hydrogen consumption and fuel-cell performance under representative operating conditions.

Overall, the objective of this paper is to show how a multi-level modelling approach can support the design and optimization of hydrogen logistics, onboard storage, compression, and final energy conversion in future hydrogen-powered vessels.[18]

2. Physics and parametric behavior of storage filling

A zero-dimensional (0D) model was adopted to analyse the transient filling of a high-pressure Type IV hydrogen tank representative of large storage modules used in tank-tainer applications. The model, implemented in AVL CRUISE™ M, treats the tank as a lumped control volume with uniform pressure, temperature, and density, while the thermal interaction with the structure is represented through two solid domains corresponding to the liner and the carbon-fibre layer (see Figure 1). Mass and energy balances are solved under real-gas conditions, with hydrogen properties corrected through the compressibility factor and NIST-based correlations, allowing the model to capture the main thermo-fluid dynamic effects occurring during high-pressure refuelling with limited computational effort.

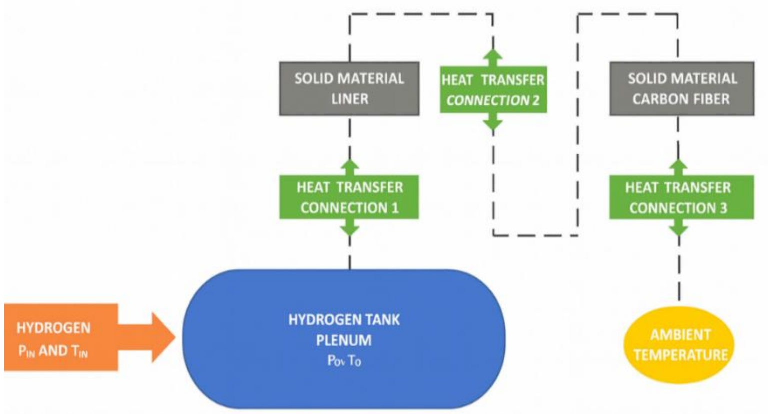


Figure 1. *Zero-dimensional lumped-parameter representation of the hydrogen tank model, including the internal gas control volume, heat transfer paths through the liner and carbon fiber layers, and thermal interaction with the ambient environment*

The reference case is a Type IV tank with a storage volume of about 2000 L, representative of the tanks installed in a modular tank-tainer system made of eight vessels and operated up to 500 bar. In the standalone analysis discussed here, the behavior of a single tank is investigated in order to isolate the influence of the main filling parameters before introducing the upstream compression system. Initial conditions are set at 20 bar and 15 °C for the hydrogen, with the solid domains and ambient at 18 °C. The modelling approach had been previously validated against experimental data obtained on a 29-L hydrogen tank, and was then extended to the analysis of large-scale Type IV storage systems, thus providing a computationally efficient tool for investigating the main thermo-fluid dynamic effects occurring during high-pressure refueling [19].

The first parameter examined is the hydrogen inlet temperature. Results show that reducing inlet temperature significantly improves filling performance. Lower inlet temperature leads to lower in-tank thermal peaks and higher gas density, which in turn increases mass flow rate and final stored mass. In the analysed cases, the condition with inlet hydrogen at −40 °C stores about 5 kg more hydrogen than the 0 °C case, while the 0 °C case is also the only one exceeding the 85 °C thermal threshold by the end of the filling process [20]. This confirms that inlet thermal conditioning is one of the most effective levers for improving both thermal compliance and storage efficiency in direct filling operations.

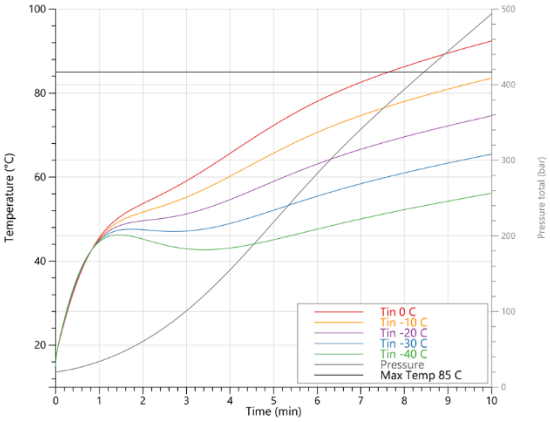


Figure 2. *Average tank gas temperature profile for different inlet gas temperature*

The injector diameter also has a strong influence on filling dynamics. Larger diameters reduce flow resistance at the inlet, allowing the mass flow rate to increase more rapidly and peak earlier during the process. As a consequence, refueling time is reduced and the overall amount of stored hydrogen increases. However, the faster filling associated with larger injector diameters may also intensify thermal effects, because less time is available for heat dissipation through the tank wall. The injector therefore acts as both a hydraulic and thermal control parameter, and its effect must be evaluated together with inlet temperature and operating strategy.

A third key variable is the imposed inlet pressure profile. The simulations show that steeper pressure ramps generate faster pressure increase inside the vessel, higher average gas temperature, larger peak mass flow rate, and higher total hydrogen storage. Conversely, smoother pressure ramps lead to a less aggressive filling process and lower thermal peaks. This behavior highlights that the filling response depends not only on the target final pressure, but also on the trajectory followed to reach it. In practical terms, the inlet pressure profile becomes an operational variable that can be used to tune the compromise between refueling speed, thermal stress, and storage effectiveness.

Overall, the analysis shows that storage filling is governed by a strong coupling between gas thermodynamics, inlet flow resistance, and pressure-control strategy. Lower inlet temperatures increase the final stored mass and limit temperature rise; larger injector diameters accelerate the process and increase throughput; steeper pressure ramps intensify both the hydraulic and thermal response of the tank. These results provide the physical basis for the more comprehensive analysis presented in the next section, where the inlet conditions are no longer imposed independently but are generated by the dynamic interaction between the storage system and a hydraulic compression chain.

3. Tank-tainer filling process and performance analysis of a hydraulic compression system

For maritime hydrogen applications, tank-tainers can enable a modular bunkering strategy based on the delivery, onboard installation, and subsequent replacement of pre-filled storage units. In this approach, the tank-tainer is not only a storage component but also a logistics asset: it can be filled onshore, transported through existing intermodal chains, directly connected to the shipboard fuel-cell system, and replaced once depleted. This swapping-based concept reduces refueling downtime, limits the need for permanent piping and dedicated port infrastructure, and supports flexible and scalable hydrogen supply chains, particularly in the early deployment phase and in ports where fixed hydrogen facilities are not yet available. These characteristics make tank-tainers especially attractive for ferries, workboats, demonstrators, and other vessels requiring operational flexibility and simplified bunkering procedures.

Within such a modular framework, direct compression represents a particularly relevant refueling solution. In the analyzed architecture, hydrogen is compressed upstream and injected into the tank-tainer without intermediate high-pressure buffer storage or dedicated pressure-regulation stages. This approach simplifies the overall system layout, reduces the number of auxiliary components, lowers pressure losses, and facilitates integration into compact and mobile bunkering solutions. By eliminating intermediate vessels and additional gas-handling stages, direct compression can also reduce capital and maintenance costs, hydrogen residence time, and potential leakage points, while improving the compatibility of the refuelling system with modular tank-tainer logistics. These features are especially valuable in maritime applications, where space, weight, and operational simplicity are critical design constraints. However, the same layout also introduces significant thermal-management challenges, since hydrogen enters the tanks at conditions directly determined by the compressor outlet. As a consequence, tank temperature rise, final stored mass, cooling demand, and refuelling duration become strongly coupled.

For this reason, the present analysis extends the standalone tank approach discussed in Session 2 to an integrated model of the complete compression-cooling-filling chain. A zero-dimensional (0D) numerical model was developed in AVL CRUISE™ M to simulate the dynamic behavior of a complete hydrogen refueling system representative of modular maritime storage applications. The simulated configuration consists of a tank-trainer composed of eight Type IV composite tanks of 1934 L each, filled in parallel up to a target pressure of 500 bar. The inlet hydrogen flow rate delivered by the upstream system is evenly distributed among the tanks, resulting in identical thermo-fluid dynamic evolution of pressure, temperature, mass, and density in each vessel. The modelling approach is based on the previously validated 0D hydrogen tank-filling model and adopts the same lumped-parameter representation of the gas and solid domains.

Each tank is represented as a single gas control volume with uniform thermodynamic properties, coupled with two solid domains corresponding to the polymeric liner and the carbon fibre reinforced polymer wall, as reported in Session 2.

Upstream of the storage system, the process includes a compression chain consisting of two hydraulic compressors in series, starting from 30 bar and 15 °C. The first compressor, namely DDE, is a two-stage unit equipped with intercooling after each stage; the second, namely MDH, is a single-stage compressor also followed by cooling. In all cases, the intercoolers restore the gas temperature to 40 °C. A 100 L plenum between the two compressors acts as a buffer, damping pressure oscillations, ensuring flow continuity, and dynamically decoupling the two units. In addition, an optional precooling component is placed downstream of the MDH and upstream of the tank-tainer distribution manifold in order to impose a prescribed tank inlet temperature, T_{H2in}, independently of the compressor discharge temperature. This makes it possible to assess the impact of inlet thermal conditioning on both in-tank thermo-fluid dynamics and auxiliary cooling demand.

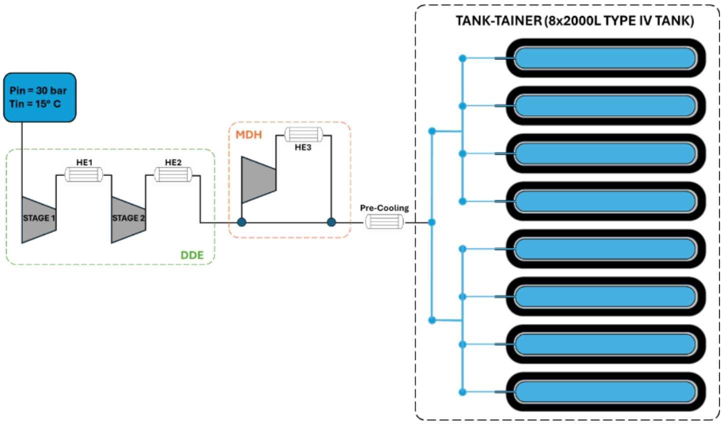


Figure 3. *Zero-dimensional model layout of the hydrogen compression and refueling system, showing the multi-stage compression chain (DDE and MDH), intercooling and precooling units and gas distribution network*

Two compressor control strategies were considered. In the standard control logic (SCL), only the DDE operates during the initial phase, while the MDH is activated once the intermediate plenum pressure exceeds 200 bar. In the alternative control logic (ACL), both compressors operate throughout the entire filling process. In addition, the influence of hydrogen inlet temperature was analysed by varying (T_{H2in}) between -40 °C and +40 °C. Two reduced-flow cases, corresponding to 80% and 60% of the nominal value, were also investigated under the standard control logic to evaluate their effect on filling time, final stored mass, temperature evolution, and thermal compliance.

As reported in Figure 4, the results show that the total filling time required to reach 500 bar is on the order of 6.1-6.6 h under nominal conditions, with nearly identical values for ACL and SCL. This indicates that the control strategy has a limited influence on the global filling dynamics and on the thermo-fluid behaviour inside the tanks. By contrast, hydrogen inlet temperature strongly affects the final storage state. Warmer inlet conditions systematically lead to higher in-tank temperatures and lower final hydrogen density and stored mass, whereas colder inlet conditions improve storage effectiveness. This confirms that inlet thermal conditioning is one of the most influential operating variables in direct-compression architectures.

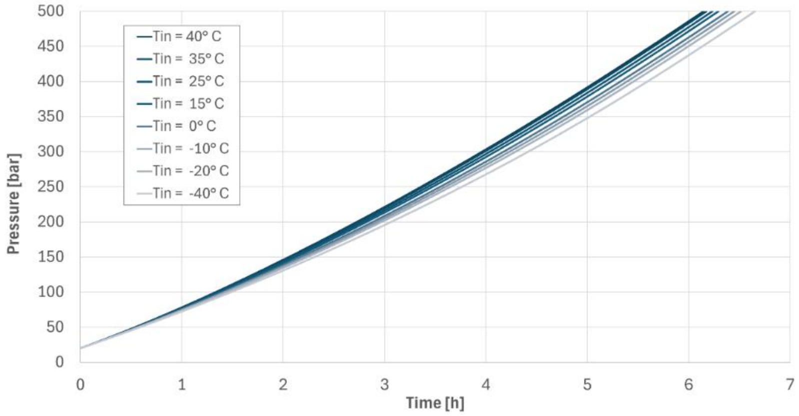


Figure 4. *Pressure trend in the single tank as a function of TH2-in for the alternative control logic (ACL) scenario*

From a thermal point of view, the model highlights a critical limitation of direct compression without adequate inlet conditioning. Even with filling times much longer than those typical of automotive fast-refuelling protocols, the final tank temperature may approach or exceed the 85 °C limit prescribed by SAE J2601 when moderate or warm inlet conditions are considered. This result is consistent with the intrinsic trade-off between refuelling speed, storage efficiency, and thermal control that characterizes direct injection strategies. In this respect, precooling and reduced-flow operation emerge as two possible mitigation measures, although both imply penalties in terms of auxiliary cooling demand or longer turnaround time (see Figure 5).

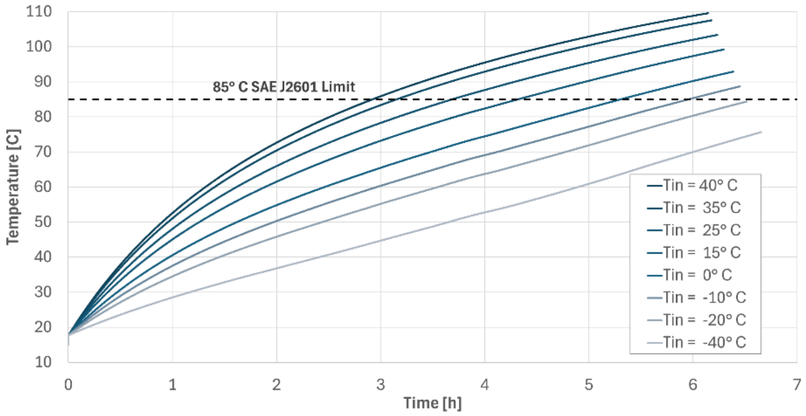


Figure 5. *Temperature trend in the single tank as a function of inlet hydrogen temperature*

The reduced-flow simulations (i.e. 60% and 80% of the nominal mass flow rate) clarify this compromise. Lower flow rates significantly increase the total filling time, up to about 12 h in the most conservative cases, but they also reduce the in-tank temperature rise and can slightly improve final stored mass and density. Therefore, slow refuelling can represent a viable operational strategy when minimizing thermal stress or avoiding aggressive precooling is more important than minimizing turnaround time. This aspect is particularly relevant for maritime bunkering, where service schedules and logistics constraints may differ substantially from those of road-transport applications.

The integrated model also provides a quantitative characterization of the hydraulic compression system. Although the two control logics yield nearly identical filling behavior at the tank level, with total refueling times on the order of 6.1-6.6 h, they substantially alter the distribution of compression work among stages. Under ACL, the MDH operates continuously and carries the largest share of the duty, whereas under SCL the delayed MDH activation shifts a larger fraction of the compression burden to the DDE, especially to its second stage. Despite this redistribution, the overall specific energy consumption of the compression chain changes only marginally between the two strategies, remaining within less than 1%. Similar considerations apply to the cooling system: the total intercooling demand remains comparable, but its distribution among the three heat exchangers changes depending on the compressor operating sequence. Quantitatively, HE1 shows only a weak dependence on TH2in, with an average duty of about 6.58 kW at -40° C and 6.55 kW at +40° C, while HE2 remains the most loaded intercooler, with an average duty of about 48 kW. The precooling duty is mainly governed by the selected value of TH_{2in}: in the analyzed cases, the average duty of the precooler ranges from about 0.21 kW up to approximately 10.94 kW, confirming that inlet thermal conditioning may introduce a non-negligible auxiliary energy penalty.

Overall, the integrated compression-filling analysis shows that the performance of a hydrogen tank-tainer system cannot be evaluated only in terms of final pressure or stored mass. Refuelling time, thermal compliance, compressor duty distribution, intercooling load, and precooling requirement must be assessed simultaneously. This confirms the usefulness of a system-level modelling framework capable of linking storage behaviour to the upstream compression chain. Such an approach is particularly relevant for maritime applications, where modular bunkering, swapping strategies, and onboard hydrogen utilization must be evaluated consistently from both thermodynamic and operational perspectives.

4. Preliminary system-level modelling of ship architecture

In addition to the component- and subsystem-level analyses presented in the previous sections, the modelling activity is progressively extended to the ship scale in order to assess the interaction between hydrogen storage, supply, and onboard energy conversion within a representative maritime architecture. The objective of this stage is to move from the analysis of isolated refueling and compression processes toward a system-level description capable of linking hydrogen availability to the operational requirements of the vessel. In particular, the ship model is intended to provide a first assessment of hydrogen consumption, fuel-cell behavior, and overall energy-system response under representative operating profiles, thus supporting the preliminary sizing and integration of the main hydrogen-based onboard components. Although still at an early stage, this activity represents a key step toward the development of an integrated modelling framework for hydrogen-powered ships, where storage, bunkering, and final energy utilization can be evaluated consistently within a single simulation environment.

4.1. Drivetrain overview

The preliminary system-level modelling activity was developed by taking as reference the vessel configuration defined within the CleanH2Shipping project. In particular, the adopted ship architecture is based on the drivetrain layout identified for the Sylvania vessel, which represents the case study used in the project for assessing the integration of hydrogen-based power systems in maritime applications. Starting with this reference configuration, the modelling work aims to describe the interaction among the main onboard energy-conversion, storage, and propulsion components, thus providing a first basis for the analysis of hydrogen utilization and power management under representative operating conditions.

The reference vessel architecture (see Figure 1) is based on an integrated electric drivetrain arranged around a common DC electrical bus, which supplies both propulsion and auxiliary loads.

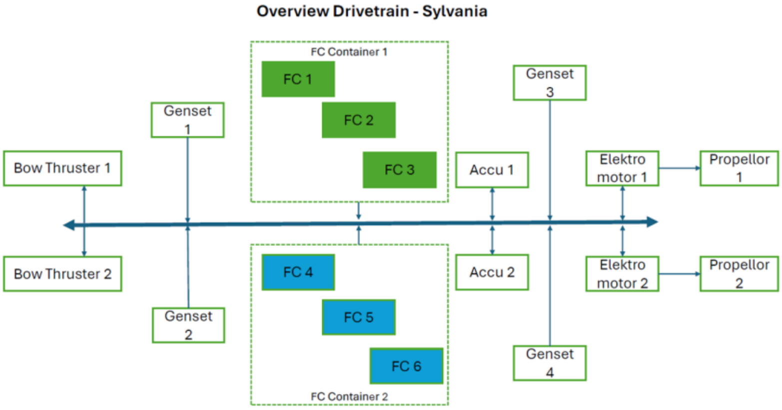


Figure 6. *Overview of the Sylvania Drivetrain*

The main power generation system consists of two fuel-cell containers: FC Container 1, hosting FC1–FC3, and FC Container 2, hosting FC4–FC6. These fuel-cell units represent the primary energy-conversion devices of the vessel and are connected to the common electrical backbone to support the onboard power demand. In addition, two battery systems, namely Accu 1 and Accu 2, are coupled to the bus in order to provide short-term energy buffering, peak shaving, and improved operational flexibility during load transients. Four generator sets (Genset 1–4) are also connected to the same distribution network and can be used as auxiliary or backup power sources. Propulsion is ensured by two electric motors (Elektro motor 1 and Elektro motor 2), each driving a dedicated propeller (Propellor 1 and Propellor 2), while manoeuvring operations are supported by two bow thrusters connected to the same electrical backbone. Overall, this configuration defines a hybrid shipboard energy system in which fuel cells, batteries, auxiliary generators, and electric propulsion devices interact through a common power distribution architecture, thus providing the basis for system-level modelling of hydrogen utilization and power management.

4.2. PEMFC model description and single-cell validation

To extend the modelling activity from hydrogen storage and bunkering to onboard energy conversion, a PEM fuel cell model was developed in AVL CRUISE™ M. The adopted approach is based on the PEM-FC RD block, which provides a semi-physical representation of the main voltage-loss mechanisms, including activation, ohmic, and mass-transport contributions (see Figure 7). In particular, ohmic losses are associated with proton conduction through the membrane and electrode materials, while activation losses are treated separately for the anode and cathode and depend on local reactant conditions. Transport limitations are described through effective diffusion coefficients accounting for the behavior of the gas diffusion layers and the progressive onset of mass-transfer resistance at increasing current density. The model also includes membrane humidification effects, considering initial water content, diffusive transport in the ionomer phase, and electro-osmotic drag, which are essential for a realistic prediction of membrane conductivity and cell performance. Pressure losses are represented directly within the stack model, allowing a consistent coupling between electrochemical behavior and gas-side fluid dynamics. From a thermal point of view, the stack is treated as an electro-thermal component with variable temperature, equivalent thermal capacity, and heat-transfer coefficients between gaseous and solid phases. In addition, reactant-starvation correction is included so that the cell voltage is automatically reduced under insufficient hydrogen or oxygen availability, enabling a realistic representation of limiting operating conditions.

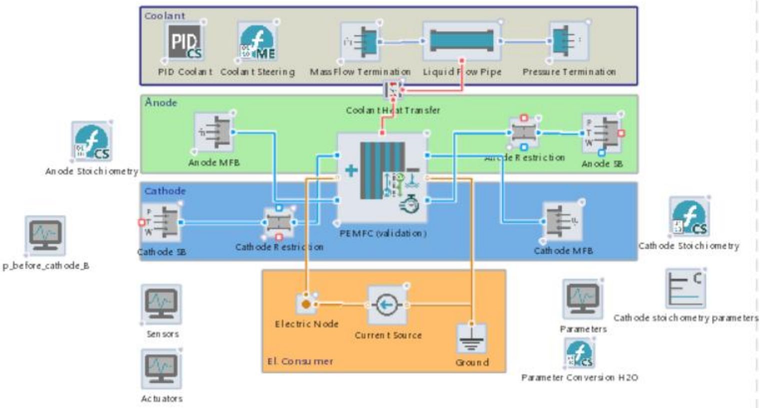


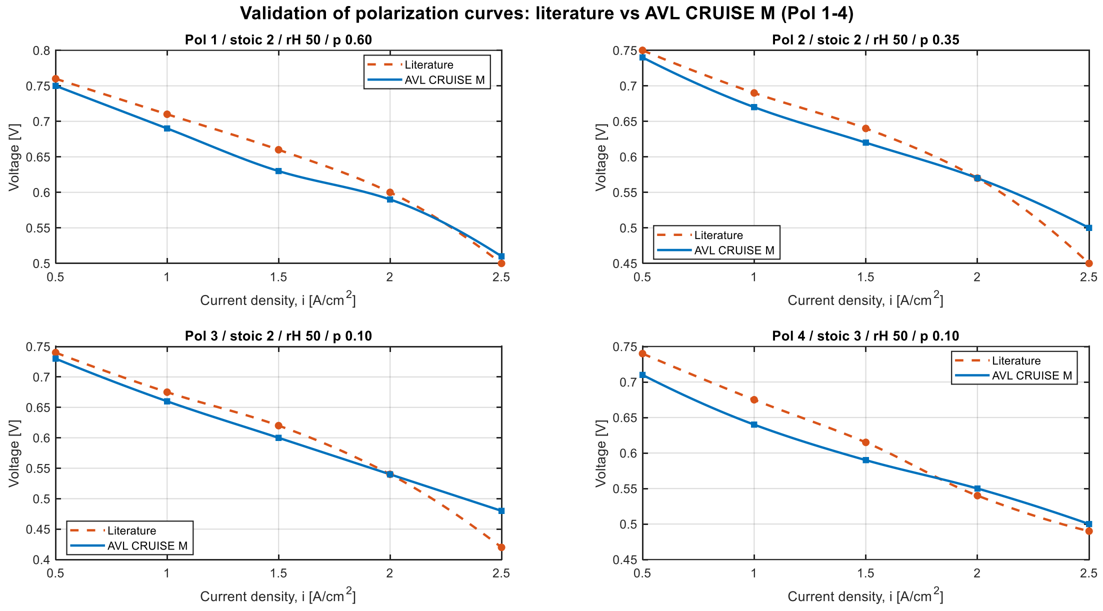
Figure 7. *AVL CRUISE™ M single-cell model layout / PEMFC block scheme*

The validation activity was carried out at single-cell level because detailed internal data for the commercial 200 kW module adopted as system reference were not available from the manufacturer, which treats the stack as a black-box component. For this reason, the model was validated against literature [21] data from a published PEMFC study and then used as the elementary building block for the subsequent stack-scale implementation. The reference dataset consists of eight polarization curves obtained at an operating temperature of 65 °C and covering a current-density range from 0 to 2.5 A cm^2. The analyzed operating conditions (see Table 1) backpressure levels corresponding to approximately 1.1, 1.35, and 1.6 bar (absolute), cathode air relative humidity values of 40%, 50%, and 75%, and air stoichiometric ratios of 2 and 3. Hydrogen relative humidity and hydrogen stoichiometric ratio were kept constant at 50% and 1.25, respectively. The single cell was modelled in AVL CRUISE™ M using a lumped electrochemical approach with an active area of 25 cm^2, while the geometric parameters were chosen consistently with the reference experimental setup, namely a channel length of 250 mm, channel width of 0.4 mm, channel height of 0.4 mm, and rib width of 0.6 mm. During validation, the model was operated in current-controlled mode so that the current was imposed and the corresponding voltage was computed point by point, thereby reconstructing the full V–i characteristics. Reactant flow rates were derived from Faraday's law and corrected through the imposed stoichiometric coefficients, ensuring consistency between electrochemical consumption and inlet supply.

Table 1. Polarization curves dataset characterization

	P [bar]	**Air RH [%]**	**λ_{air} (air stoich.) [-]**	**H_2 RH [%]**	**λ_{H_2}(H_2 stoich.) [-]**
POL 1	1.6	50 %	2	50 %	1.25
POL 2	1.35	50 %	2	50 %	1.25
POL 3	1.1	50 %	2	50 %	1.25
POL 4	1.1	50 %	3	50 %	1.25
POL 5	1.1	75 %	3	50 %	1.25
POL 6	1.6	50 %	3	50 %	1.25
POL 7	1.6	75 %	2	50 %	1.25
POL 8	1.6	40 %	2	50 %	1.25

The comparison between simulation results and literature data showed a good overall agreement for all the considered polarization curves (as reported in Figure 8), confirming that the model can reproduce both the absolute voltage level and its variation with operating conditions. In particular, the validation highlighted the expected positive effect of increasing air stoichiometry, which improves oxygen availability and reduces mass-transport limitations. This effect is especially evident at high current density, where diffusion phenomena become more relevant, whereas it is less pronounced at low pressure. A similarly beneficial trend was observed when increasing operating pressure, since higher reactant partial pressures improve both electrochemical kinetics and mass transport over the entire operating range. The influence of cathode humidity was found to be more complex. At low pressure, increasing air humidity improved performance because the membrane benefitted from enhanced hydration without quickly reaching saturation. At higher pressure, instead, the system already operated close to optimal humidification conditions, and both excessive and insufficient humidity led to lower voltage: in the first case because of flooding-related transport limitations, and in the second because of reduced membrane conductivity. Overall, the validation results confirmed that the model captures the correct physical sensitivity to the main operating parameters governing PEMFC behaviour.



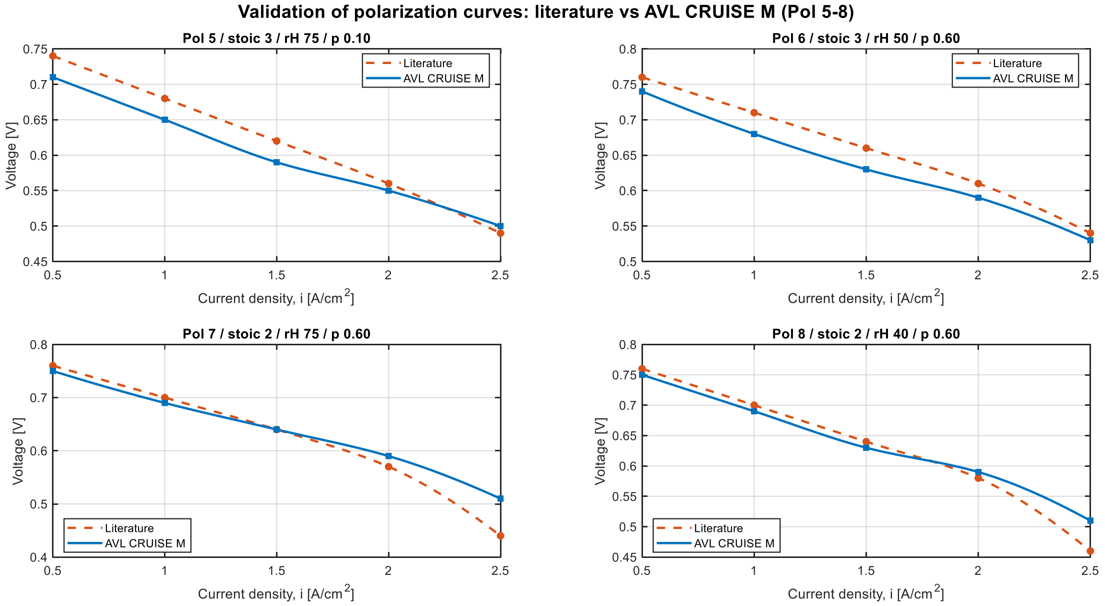


Figure 8. *Validation of polarization curves, simulated vs literature data*

The corresponding power curves as a function of current density further support the consistency of the model (see Figure 9), since the predicted trends remain physically coherent over the entire operating range and reflect the same dependence on pressure, stoichiometry, and humidification observed in the polarization behaviour. On this basis, the validated single-cell model was considered suitable for use as the elementary unit for the construction of a 200-kW class stack and for its subsequent integration into the vessel-level simulation framework.

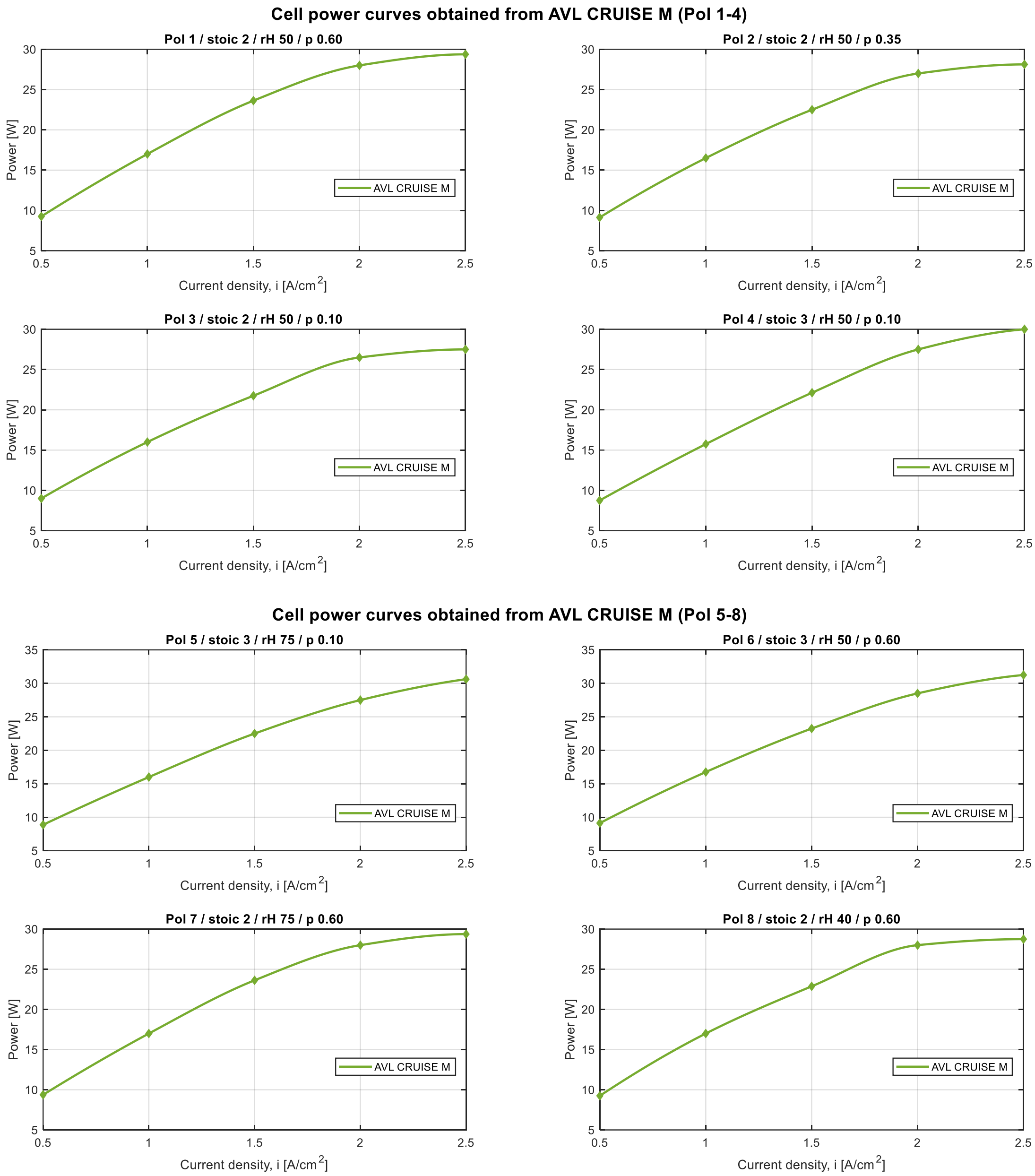


Figure 9. *Cell power curves vs current density*

4.3. Vessel-level model implementation

Starting from the validated single-cell model, a system-level representation of the onboard PEMFC powertrain was developed in AVL CRUISE™ M for the reference vessel considered within the CleanH2Shipping project. To preserve the physical detail of the electrochemical and Balance of Plant sub-models while keeping the computational effort acceptable, the adopted strategy consists in simulating one representative PEMFC module and scaling the vessel power demand to account for the presence of six identical modules onboard.

On the hydrogen side, the storage system is not represented through an explicit detailed 500 bar tank model, but through a dynamic boundary condition updated by an external computational block implementing a simplified tank-emptying model based on mass balance and a quasi-polytropic law. The hydrogen consumption of the simulated module is scaled by a factor of six to represent the full onboard system. In addition, a multi-tank switching logic is included so that, when the virtual tank pressure drops to about 20 bar, the model automatically switches to the next tank and restores the initial condition at about 500 bar. This approach allows the main hydrogen supply dynamics to be captured with limited numerical complexity.

The model also includes a simplified but representative Balance of Plant. On the anode side, hydrogen flow is regulated through a Venturi-based injection device and an anode recirculation loop is considered, while purge events are neglected for numerical stability. On the cathode side, ambient air is compressed, cooled, humidified, and supplied to the stack according to the current demand, with the compressor, humidifier, bypass line, and backpressure valve explicitly represented. A single high-temperature cooling loop is adopted to control stack temperature around 65 °C and to account for the interaction between stack cooling and cathode air conditioning.

On the electrical side, the stack is coupled to an equivalent DC/AC converter whose control logic translates the vessel mission power demand into stack current while accounting for conversion efficiency and operating limits. The AC side is represented through an equivalent shipboard bus with dynamic load assignment, while auxiliary loads associated with the compressor and cooling pump are explicitly included. The required power demand is derived from a representative mission profile of a conventional sister ship and then scaled consistently with the six-module PEMFC architecture. Overall, this modelling framework provides the basis for the future analysis of hydrogen consumption, stack operating conditions, auxiliary demand, and power-management behaviour at vessel level.

5. Conclusion

This work presented an overview of the modelling activities developed within the CleanH2Shipping project to support the analysis and design of hydrogen-based systems for maritime applications. The study combined different but complementary modelling levels, ranging from the filling behavior of large-scale Type IV storage tanks to the integrated simulation of tank-tainer refueling with hydraulic compression, and finally to the first implementation of a vessel-level PEM fuel cell model. The overall objective was to contribute to the development of a coherent simulation framework able to connect hydrogen storage, compression, bunkering, and onboard utilization within a common engineering perspective.

The analysis of the standalone storage tank confirmed that the filling process is governed by a strong coupling between thermodynamic conditions, inlet flow resistance, and pressure-control strategy. In particular, lower inlet hydrogen temperatures were shown to reduce thermal peaks and increase the final stored mass, while larger injector diameters accelerated refueling and steeper pressure ramps intensified both the hydraulic and thermal response of the tank. These results highlighted the main physical mechanisms controlling storage performance and provided the basis for the subsequent system-level analysis of the complete filling process.

The integrated modelling of the hydrogen tank-tainer and hydraulic compression chain showed that the performance of modular bunkering systems cannot be assessed only in terms of final pressure or stored mass. Refueling time, thermal compliance, compressor duty distribution, intercooling demand, and precooling requirements must be considered simultaneously. The results confirmed the relevance of tank-tainer swapping as a flexible bunkering strategy for maritime applications and showed that direct compression can simplify system layout and improve compatibility with modular hydrogen logistics, although at the cost of stronger coupling between compressor outlet conditions and in-tank thermal behavior. The comparison between different compressor control logics indicated that the filling dynamics at tank level remain nearly unchanged, while the energetic duty is redistributed among compressor stages and cooling units.

The extension of the modelling activity to the ship scale led to the implementation of a PEMFC-based vessel model in AVL CRUISE™ M. The single-cell validation against literature polarization data showed good agreement and confirmed the capability of the adopted approach to reproduce the effects of pressure, air stoichiometry, and humidification on cell performance. On this basis, a vessel-level simulation framework was developed by combining the PEMFC model, the Balance of Plant, a simplified hydrogen supply model with tank-switching logic, and a representative mission load. Although the complete system-level simulation campaign is still under assessment, the implemented model already provides the basis for future analyses of hydrogen consumption, auxiliary demand, stack operating conditions, and power-management strategies in hydrogen-powered ships.

Overall, the work shows the value of a multi-level modelling approach for supporting the design and optimization of hydrogen technologies in maritime transport. Future developments will focus on completing the vessel-level simulation campaign, integrating the storage and fuel-cell models more tightly, and using the resulting framework to assess system sizing, operational flexibility, and energy-management strategies for representative hydrogen-powered vessels.

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Nomenclature

0D	zero-dimensional
ACL	alternative control logic
CFD	computational fluid dynamics
CFRP	carbon fibre reinforced polymer
CHSS	compressed hydrogen storage system
DDE	double-diaphragm / hydraulic compressor first unit
FC	fuel cell
FCV	fuel cell vehicle
HE	heat exchanger
HRS	hydrogen refuelling station
MDH	metal diaphragm / hydraulic compressor second unit
P&ID	piping and instrumentation diagram
PEMFC	proton exchange membrane fuel cell
SCL	standard control logic
SOC	state of charge

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