Comparison of simulative methods for dimensioning of fuel cell-battery hybrid powertrains in FCH2Rail and Virtual-FCS

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Summary

The dimensioning process of fuel cell and batteries in hybrid railway applications is one of the biggest challenges in this kind of powertrain. In this paper, methods for modelling and designing fuel cell hybrid power trains are investigated and functionally compared. Subsequently, an exemplary dimensioning is carried out on the basis of a specific scenario. The tools in focus are, on the one hand, the Hybridization Tool and SEnSOR, both developed by the German Aerospace Center and used in the European project FCH2Rail and, on the other hand, the open source model developed by the European project Virtual-FCS. The approach and target of the tools is fundamentally different. Their features are compared in order to understand which impact different models can have on the design and evaluation process of fuel cell hybrid powertrains.

Keywords: Fuel cell hybrid power pack; FCH2Rail; Virtual-FCS; alternative powertrain dimensioning; railway; powertrain; series hybrid

1 Introduction

This paper focuses on the technical characteristics of railway powertrains for operation on partly or non-electrified tracks. One suitable and locally emission-free solution for these scenarios is a series hybrid system consisting of fuel cells and batteries, such as the Fuel Cell Hybrid Power Pack (FCHPP) developed in the FCH2Rail project [1] (*Figure 1*). A key issue in the design process of such hybrid systems is the dimensioning of the fuel cells and batteries in a way that the energy and power requirements are fulfilled and at the same time the costs, total mass and required space are kept to a minimum. Since there are few empirical values and standards established, the development and application of appropriate methods for component dimensioning and energy management are crucial subjects to ensure success of the technology.

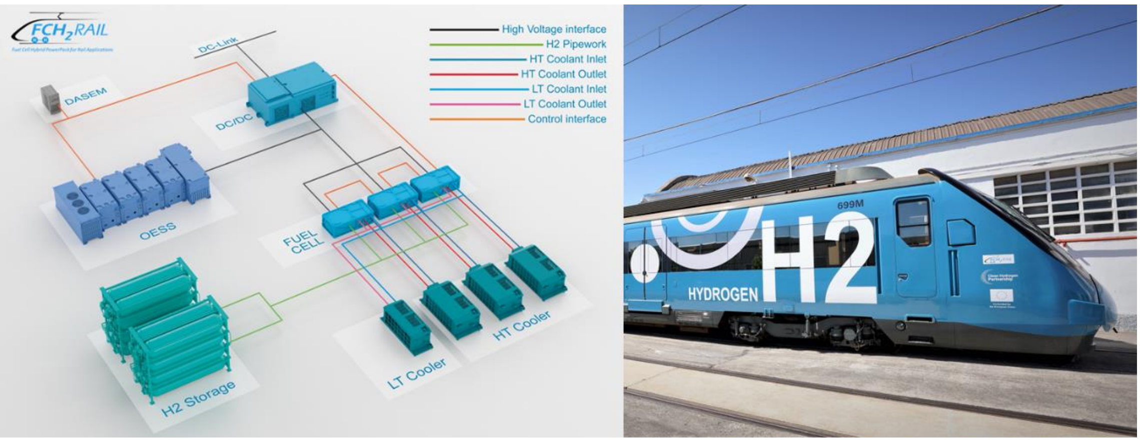

Figure 1: Fuel Cell Hybrid Power Pack (FCHPP) schematic and demonstrator train of FCH2Rail project. [2, 3]

2 Methodology of this study

The study aims to provide a comprehensive understanding of different modeling and design approaches for hybrid fuel cell powertrains. This shall lead to a more profound power pack design, which matches the requirements of individual application scenarios. In the first step, we introduce and describe three different simulation tools (see *Figure 2*). In the second step, we compare the differences in methodology, the characteristics of the models and the underlying assumptions and boundary conditions.

The first two tools, used in the FCH2Rail project [4, 5], are the **Hybridization Tool** and the **Smart Energy and Speed Optimizer Rail (SEnSOR)**, both developed by DLR. The third tool is the open source simulation library developed in the **Virtual-FCS** project [6].

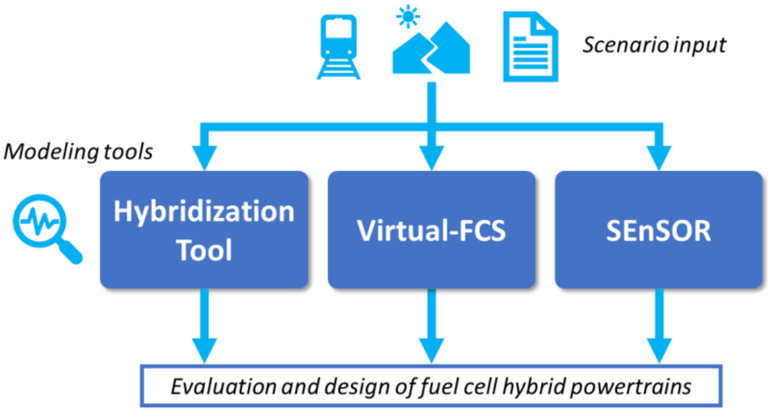

Figure 2: Modeling tools for powertrain design, analysis and component dimensioning.

Each tool offers a specific scope with varying benefits and disadvantages, e.g. in component sizing or estimation of hydrogen consumption. This is caused by difference in modelling approach, powertrain dimensioning and energy management strategy (EMS), as well as degree of model detail. This paper will provide a functional, qualitative assessment of all tools. As an outlook, we also provide first results for the Hybridization Tool as an indication on the component sizing. Future works will use these results as input for the other tools to provide a quantitative analysis.

3 Characterization of the Powertrain Tools

3.1 Hybridization Tool

The Hybridization Tool is part of a DLR in-house software tool box for simulation and optimization of energy systems in railway vehicles. Its main features and goals are:

- Data-driven system dimensioning (battery- and fuel cell component sizes)
- Rule-based EMS for fuel cell hybrid powertrains
- Estimation of hydrogen consumption based on realistic operation conditions and component characteristics

With a given power profile at the wheels, it is possible to evaluate the main components of a fuel cell hybrid system either by automatically determining the necessary component sizes or by estimating the hydrogen consumption with predefined sizes. For this purpose, a heuristic, rule-based EMS for the power split between the fuel cell and battery was developed. The modelling of power flows in the fuel cell hybrid system includes all electric components in the efficiency chain between the DC-link of the train and the battery and fuel cell, respectively. Additionally, the drivetrain components (motor/generator and traction inverter) are included. The H2 storage is not explicitly modeled. The same applies to the fuel cell coolers, which are considered as auxiliary demand for the balance of plant (BoP).

3.2 Virtual-FCS

The primary objective of the Virtual-FCS library is to enhance the design process of hybrid fuel cell and battery systems by achieving the following key objectives [6]:

- *“Accurately predicting the lifetime, reliability, and performance of systems to effectively reduce costs.*
- *Facilitating improved hybridization and control strategies for various fuel cell applications.*
- *Enabling the integration of software-model-hardware in-the-loop design for hybrid systems.*
- *Demonstrating and validating the approach with the support and involvement of end users.*
- *Establishing the continuous development and widespread adoption of the tool”*

This research primarily focuses on the functionalities of hybridization, the control strategy pertaining to objective 2, and the energy output results, which act as inputs for objective 3.

The Virtual-FCS library offers three distinct drivetrain options: A battery electric drivetrain, a serial hybrid drivetrain, and a parallel hybrid drivetrain. Among these, the serial hybrid drivetrain has been validated, making it the most developed option. The structure of the serial hybrid is pictured in *Figure 3*.

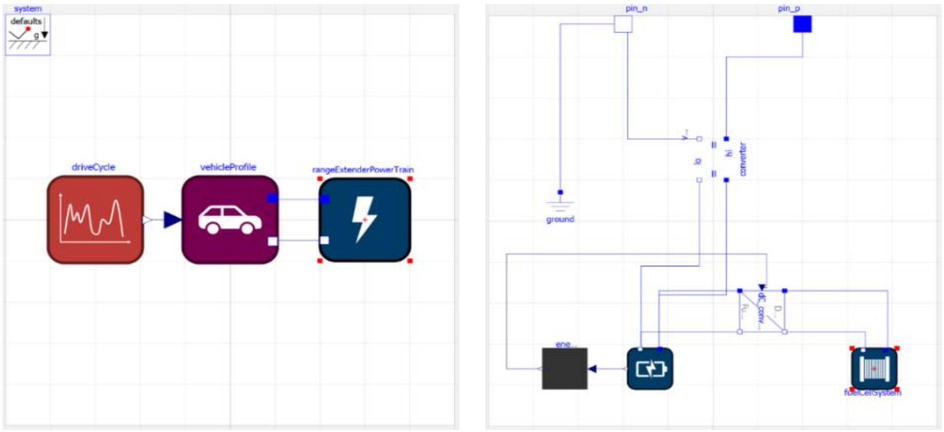

Figure 3: Range extender vehicle model: (left) Modelling assembly including the input of the powertrain; (right) serial hybrid consisting of battery system, fuel cell system, EMS and DC-link

Figure 3 shows the overall layout incorporated in the open source software environment Open Modelica. The Virtual-FCS tool requires a driving cycle with speed as a function of time as input. Initially designed for simulating passenger vehicles or heavy-duty vehicles, this setup can be adapted for use in any drivetrain application. The right side of *Figure 3* illustrates the sub model of the serial hybrid powertrain, consisting of the fuel cell system and a battery system, connected via an ideal working DC-DC converter to the battery system. An EMS sub model regulates the energy distribution between the fuel cell system and the battery system. A detailed explanation and comparison of the underlying EMS will be presented in chapter 4. Virtual-FCS entails comprehensive component modeling, including thermal models for the battery and fuel cell, as well as a detailed model of the fuel cell stack and the BoP.

3.3 Smart Energy and Speed Optimizer Rail (SEnSOR)

SEnSOR [7, 8] is a DLR in-house algorithm for numerical optimization of various aspects of railway operation. The two key targets are optimized EMS and speed profile. Here, SEnSOR is capable to optimize each of them individually or both simultaneously. It utilizes a gradient-based solver with non-linear direct method optimization. Given track, train and electric component characteristics, SEnSOR aims to provide a tailored solution for each individual scenario, i.e. adapting the speed profile to the specific train and power sources for minimum energy demand. Moreover, through reduced energy throughput and additional constraints, degradation accelerating behavior (wear and tear as well as component ageing) is also reduced. The three main use cases are (see also *Figure 4*):

1. **Speed profile optimization**: If the internal train characteristics are unknown, the pure speed profile can be optimized at the wheels, with regards to energy demand. The result (speed and power profile at the wheels) can be used for track analysis or fed into any EMS.
2. **EMS optimization**: Given a speed and power profile at the wheels or the DC-link, the EMS is optimized, i.e. the power split between different power sources and charge control of the batteries. The result is an energy management control and the consumption at the sources.
3. **Combined optimization**: Taking benefits of both features described above, this gives a holistic optimization of the operation, yielding the lowest energy consumption with coordinated EMS and speed control. This means that, within the given boundary conditions of the timetable etc., the speed can be adapted to optimal operational points of the fuel cell, for example.

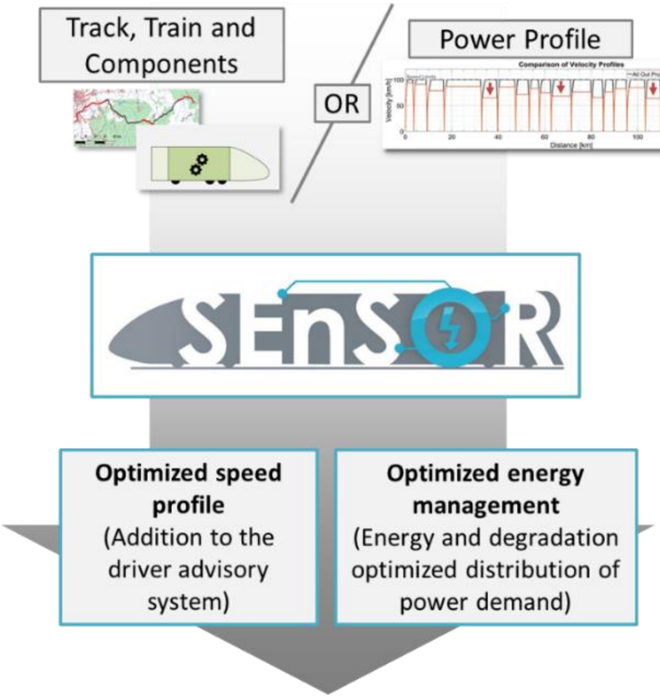

Figure 4: Smart Energy and Speed Optimizer Rail – general data flow with inputs and results.

With these features, SEnSOR can serve as a benchmark for EMS. In the current version of the tool, multiple powertrain architectures are implemented (battery electric multiple unit, fuel cell electric multiple unit, bi-modal fuel cell train). Other architectures can also be optimized, as the modular algorithm is easily adaptable to different powertrain architectures.

4 Functional Comparison

From the description above, it is evident that the tools differ in their main functionalities and implementation. **Virtual-FCS** serves mainly as an evaluation tool to estimate the system efficiency and hydrogen consumptions. Its focus is on road vehicles, but it can be adapted with an interface to utilize power profiles from other vehicles as well. The **Hybridization Tool** is specifically developed for dimensioning the powertrain architecture in railway applications. However, all power profiles and generic components characteristics are accepted as input. Thus, it is not restricted to railway scenarios. Similarly, **SEnSOR** focuses on various rail applications. When not using the speed optimization, it has an interface to read in power profiles for pure EMS optimization (case 2). Thus, it can be used for other vehicles as well. In general, the scope is to provide a benchmark of the EMS and hydrogen consumption of the hybrid powertrain. In the following subchapters, the most important distinctions between the tools are analyzed.

4.1 Energy Management Strategy (EMS)

The three modelling tools are capable of estimating the final energy demand in terms of the hydrogen consumption. However, the underlying EMS of the hybrid powertrain varies significantly. Both the Hybridization Tool and Virtual-FCS utilize a rather simple rule-based control EMS, which results in a deterministic approach to estimate the hydrogen demand.

Virtual-FCS offers a BoP and detailed thermal models, but a simplified two-point EMS. In this control strategy, the fuel cell power switches between a high and low power level, depending on the SoC of the battery, i.e. high power if the battery needs to be charged and vice versa to maintain the SoC within the desired range.

The **Hybridization Tool** goes one step further by utilizing power tracking and use case specific power levels of the fuel cell. When the battery does not need to be charged, the fuel cell follows any positive power demand on the DC-link. At the same time, the high-power level of the fuel cell is lowered to a more efficient operating point as long as charge-sustaining operation is still guaranteed (see *Figure 5*).

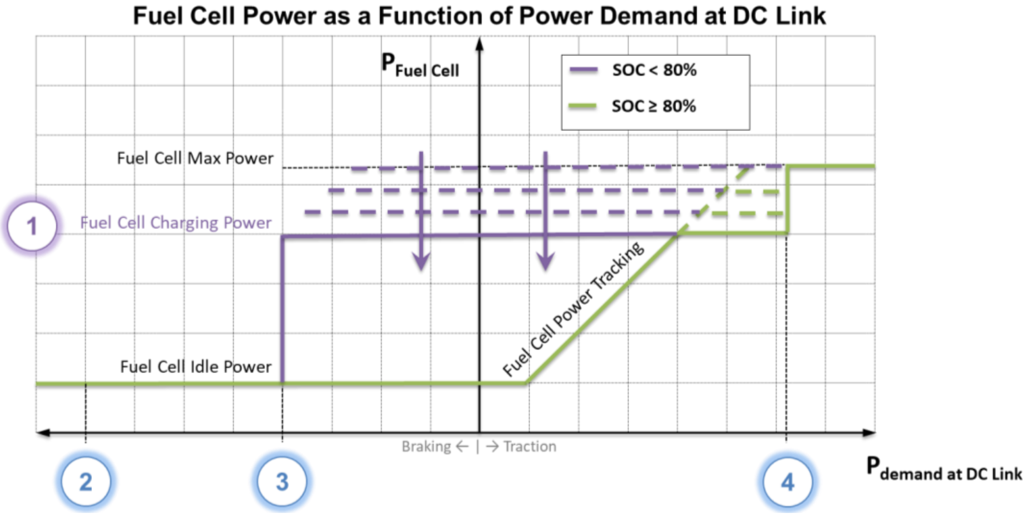

Figure 5: EMS of the Hybridization Tool – Hysteresis with two power levels and power tracking.

In order to enable energy savings in hybrid powertrains, optimization of the energy management is required. **SEnSOR** offers this functionality by providing an optimized power split in each operating point. While considering the efficiency characteristics in each operation point, SEnSOR also holistically considers the boundary conditions of the optimization problem, ensuring charge-sustaining operation and operability in each part of the track. To achieve this, the algorithm includes the following steps:

- Pre-Processing: Process data input, automatic generation of objective functions and constraints based on the given input, automatic calculation of derivative matrices
- Solving: interface to IPOPT [9]
- Post-Processing: analysis and visualization of results

Here, pre-processing is the most extensive and important step as it determines the capabilities and computational performance of the algorithm. A high grade of modularity, automatization and code efficiency enable SEnSOR to provide converging results of long tracks (>100 km) within the order of minutes. This process leads to a highly complex EMS, which is currently not real-time capable, but serves as a benchmark.

4.2 Dimensioning

A common goal of both projects, Virtual-FCS and FCH2Rail, is the design process of a hybrid fuel cell powertrain which suits the needs of a specifics use case considering the power demand, lifetime aspects and fuel consumption. The **Hybridization Tool**'s scope and main functionality is directly targeting this by estimating the battery energy content and maximum required fuel cell power. Given the power profile, three steps are followed (see *Figure 6*):

1. The algorithm automatically pre-sizes battery and fuel cell based on accumulated energy values of the power profile and then resizes the fuel cell. In this first dimensioning step, a simplified two-point EMS is used. The size of the fuel cell is then iteratively increased until a charge-sustaining operation of the battery is possible.
2. In the second step, a more advanced EMS (as described in the previous section, see *Figure 5*) is applied to reduce the jumps in fuel cell power. By iteratively lowering the upper limit of fuel cell power, the lowest point is determined which is necessary to fulfil the required boundary conditions of charge-sustaining operation. Taking the characteristic fuel cell efficiency curve into account, the operating points shift towards lower consumption, implicitly using more efficient fuel cell operating points.
3. Finally, the permissible currents at the battery are checked. If they exceed the specified limits, the battery is resized and step two is repeated. Therefore, the whole procedure follows an iterative approach until suitable fuel cell and battery sizes are determined.

Currently, the dimensioning is strictly energy demand-based and thus not optimized with regards to costs, mass or installation space.

Virtual-FCS aims to serve the same purpose. However, at the moment, the dimensioning process has to be done manually in an iterative trial-and-error approach. Automated wrappers could help to improve the dimensioning process in the future, but currently this is not possible. Similarly, **SEnSOR** does not explicitly target the dimensioning of the components. Nevertheless, utilizing the optimized EMS with reduced hydrogen consumption can serve a crucial role in the design process, as it provides an indication if the components are under- or oversized

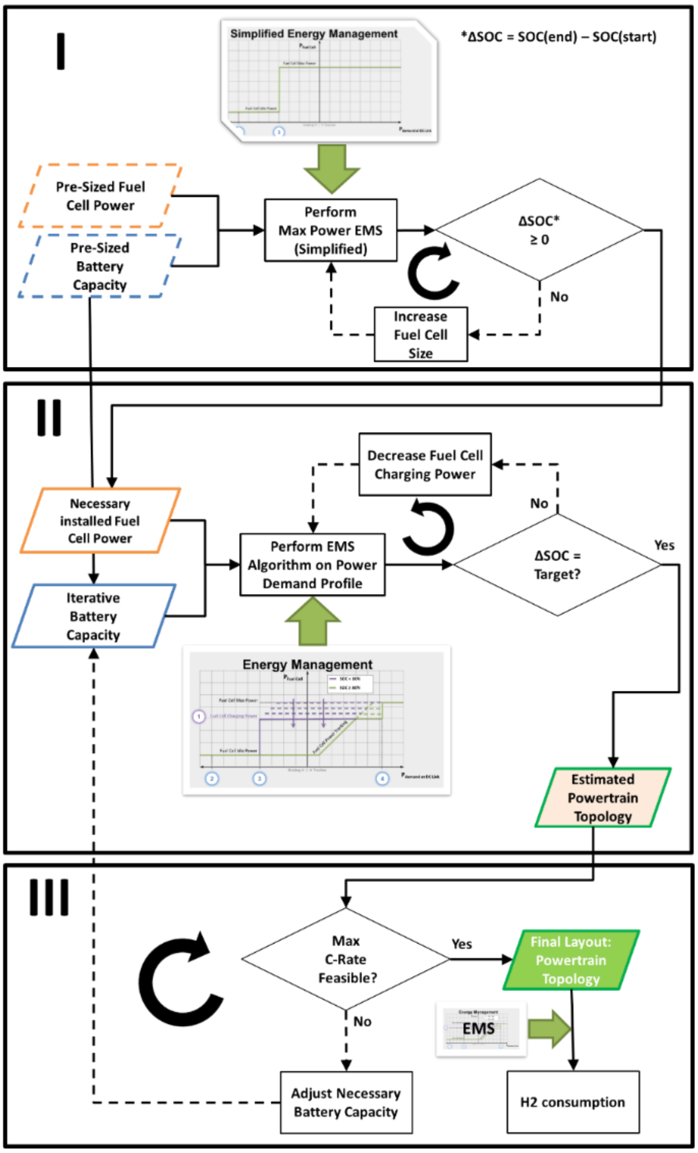

Figure 6: Hybridization Tool dimensioning process in three steps: (I) Determining the necessary fuel cell power, (II) determining the required battery energy content and (III) iteratively adapt above values with respect to system limitations.

4.3 Depth of Model Detail

With regards to model detail, both the **Hybridization Tool** and **SEnSOR** currently work with a mix of efficiency curves and maps in most components. The battery is represented by an internal resistance model in SEnSOR and the fuel cell model is based on polarization curves. Any BoP aspects are subsumed in the auxiliary demands with is assumed as constant or power dependent. **Virtual-FCS** applies varying degrees of model depth. While converters are idealized, fuel cell stack, battery characteristic and their thermal behavior are configured in detail. Given the required input data are available, a detailed thermal simulation of the battery as well as the fuel cell stack is conducted. Hereby, characteristics of hydrogen are based on ideal gas assumptions and BoP aspects are considered with dynamic loads of pumps, compressor.

4.4 Summary of functional comparison

All three models intend to provide powertrain component dimensioning capabilities and are based on a data-driven methodology. However, in the versions tested only the hybridization tool is providing an automatic dimensioning of the main power pack components. The details of the functional comparison can be seen in *Table 1*.

The DLR **Hybridization Tool** applied in FCH2Rail can be utilized for different powertrain alternatives, consisting of batteries and fuel cells. Based on realistic operations and drive train characteristics, the power pack component sizes are determined, taking into consideration the power demand and component limitations. With the deployed EMS, it is also possible to evaluate the hydrogen consumption, once the component sizes have been dimensioned.

The **Virtual-FCS** library is an open-source platform combining software and hardware parameters for designing and optimizing PEM fuel cells and battery hybrid power systems. [10] It is aiming to fit various transport and other mobile applications and further includes a detailed component modelling. The detailed modelling of the subsystems allows to simulate the thermal behavior of battery system, fuel cell stack and system and considers additional aspects besides energy and power requirements. This makes it an interesting tool to learn more about the physical behavior of the powertrain and the power pack components. Currently, an effortful, manual dimensioning process would be required, which has no established standard procedure yet. Furthermore, the level of detail of the battery model is high compared to the efficiency calculation of the fuel cell, which is currently based on a function which is fitting a stored efficiency curve. Announcements of the Virtual-FCS project plan new software releases, which will consider the degradation of the fuel cell system. This functionality could be a great added value.

SEnSOR is centered on achieving an optimized individual power split between the battery and fuel cell components to reduce energy consumption and decrease component wear. This is accomplished through numerical optimization of the EMS. The resulting output provides a comprehensive analysis of battery and fuel cell operation, as well as valuable insights into motor operating points, which play a pivotal role in the powertrain's performance.

The current model boundaries of both SEnSOR and the Hybridization Tool involve simplifications of the battery, fuel cell, BoP and auxiliary components. Enhancing the level of detail within these aspects could potentially yield even more profound results and lead to accurate measures, which lower the energy consumption. It can be concluded that the scopes and the implementation of all three tools are very distinctive. The Hybridization Tool focuses on dimensioning with a simplified EMS. Virtual-FCS currently serves mainly to evaluate hydrogen consumption and thermal behavior. It is publicly available and strives to consider degradation effects, but currently does not provide automated dimensioning or advanced EMS. SEnSOR optimizes the latter in detail without directly targeting the powertrain dimensioning. It is specialized for railway applications and can also be applied to optimize the speed profile of a train.

Table 1: Functional Comparison

	Hybridization Tool	**Virtual-FCS**	**SEnSOR**
Language	MATLAB	Open Modelica	MATLAB
Licensing	Proprietary	Open source [11]	Proprietary
Scope	Railway application with series hybrid powertrain (fuel cell and battery, optionally bi-mode with catenary supply)	Various FC hybrid applications (focus road), battery drivetrains, fuel cell-battery hybrid drivetrain (serial and parallel (only fundamental layout available))	Railway applications with any kind of powertrain (tested: electric, battery electric, fuel cell-battery hybrid, bi-mode with catenary supply)
Energy management	Heuristic hysteresis with power tracking	Two-point control	Numerical optimization
Modelling approach	Functional programming: Reverse component models with power flow and iterative steps for dimensioning	Object-oriented equation based: Reverse modeling of road vehicle power cycles and generic powertrain components	Functional programming: Train in specified environment, including track description, timetable, train and component models.
Goal, specific features	• Component dimensioning • Energy consumption calculation	• Energy consumption calculation • System efficiency determination • Temperature tracking and cooling demand estimation	• Optimized energy consumption • Optimized speed profile
Input	• Dynamic time-spaced profiles (*P(t)*, *v(t)*) • Component efficiency parameters (mixture of 2D and 1D characteristics)	Driving Profile: • Driving cycle (*v(t)*) • Driving resistances • Component size and efficiency characteristic (const.)	Three use cases: • Speed optimization: Track and train characteristics • EMS optimization: Component characteristics (1D/2D) • Isolated EMS optimization: Dynamic power and speed profile (*P(t)*, *v(t)*)

Output	Files: mat, csv and fig/png • H_2 consumption • Component Sizes: Battery energy content and fuel cell max. power • Dynamic profiles: fuel cell and battery power, SoC • Analysis of operating points and power split	Files: png, svg, bmp and csv • Fuel consumption • Dynamic profiles: fuel cell and battery power, battery SoC • Temperature of battery and fuel cell system	Files: mat, txt, fig/png • Energy demand • Dynamic profiles: Power at each source, SoC, speed profile • Analysis of battery and fuel cell operation, motor operating points and power split
Boundary Conditions	• Charge-sustaining or depleting operation • Permissible C-rates, SoC window	• Battery: Initial SoC, nominal capacity, mass and size of the battery pack • Fuel cell: mass and size, limiting current	• Drivetrain architecture • Equation of motion with Davis resistance and gradients, force and acceleration constraints • Fuel cell power gradient limitations • Permissible C-rates, SoC window
Limitations	• Simplified models for battery, fuel cell, BoP and auxiliaries • no objective cost model yet	• Constant efficiency of drivetrain and regenerative braking • Efficiency of fuel cell based on a polynomial equation and a specific fuel cell	• Simplified models for battery, fuel cell, BoP and auxiliaries • Local optimization (globality not guaranteed) • Control results can be complex and not necessarily viable for a human driver

5 Exemplary Dimensioning of Power Pack

This chapter presents initial simulations carried out with the Hybridization Tool, aiming to establish the framework for future comparative analyses of energy management and hydrogen consumption of the three tools.

The exemplary use case for dimensioning with the Hybridization Tool is the roundtrip from A Coruña to Ferrol and back in a worst-case scenario with very high auxiliary power demand. This use case was defined in the FCH2Rail project [12]. The key characteristics of this service profile are given in the upper part of *Table 2*. It is a regional track without electrification, speeds below 105 km/h and a stop roughly every 5 km.

Table 2: Use case A Coruña – Ferrol – A Coruña: Service Profile characteristics, power demand at DC-link and dimensioning results for battery and fuel cell system.

Parameter	Value
Service Profile	
Length in km	137,4
Max. Speed in km/h	105
Avg. Speed in km/h	48,3
No. Stops	25
Roundtrip duration hh:mm	02:51
Power demand on DC-Link	
Max. / Min. power in kW	869,6 / -505,1
Avg. power in kW	249,3
Max avg. power for 2 / 5 / 10 min time windows	860,5 / 672,7 / 518,3
Total energy in kWh *(and traction / braking)*	709,4 (841,9 / -132,6)

The power profile is characterized maximum demands at the DC-link of approximately 870 kW, with maximum regenerative power of 505 kW. While the average power is 250 kW, but reaches 5 min stretches with up to 670 kW (see also lower part of *Table 2*). The upper diagram in *Figure 7* also illustrates the demand on the DC-link over time. From this information, the dimensioning of fuel cell and battery is not straightforward, but the Hybridization Tool provides feasible component sizes with viable results in terms of power demands and permissible operation of the components.

The final powertrain design and key performance indicators of this dimensioning by the Hybridization Tool are given in *Table 3*. The fuel cell is sized with a maximum power of 350 kW, while the battery should provide 267 kWh of installed energy.

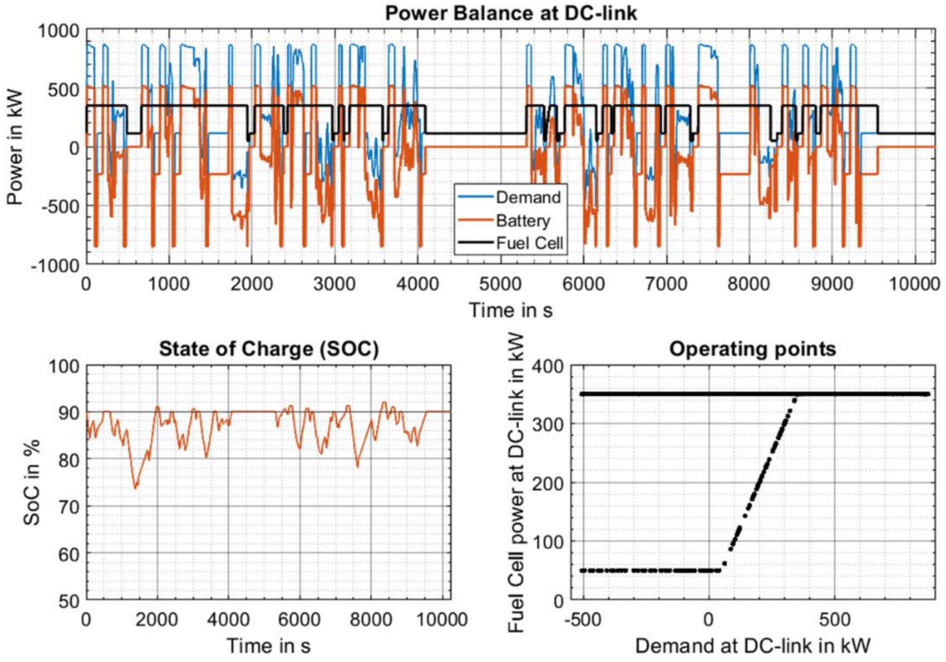

Figure 7: Use case A Coruña – Ferrol – A Coruña: (upper) power demand on DC-link versus time; (lower left) battery state of charge; (lower right) operating points of the fuel cell versus the demand at DC-link.

The behavior of the dimensioned powertrain after application of the Hybridization Tool EMS is presented in *Figure 7*. Besides the demand on the DC-link, the upper diagram includes the power distribution of fuel cell and battery, respectively. In the lower left diagram, the SoC characteristic with an initial charge of 90% and charge-sustaining operation is shown. Minimal deviations above 90% are due to recuperation in recharged state and permissible. In the lower right, the fuel cell behavior according to the EMS is illustrated. The EMS yields a majority of operating points in the high power level, but also utilizes power tracking and the lower level with higher fuel cell efficiency.

As shown in *Table 3*, this leads to a hydrogen consumption of 39 kg per 100 km and maximum C-rates of 3.2. Both, the C-rates and the SoC, stay within the constraint limits.

Table 3: Results of the Powertrain Design of the Hybridization Tool

Results of dimensioning	
Max fuel cell power in kW	350
Battery energy content in kWh	267
Max C-rate battery in 1/h	3,2
H2 consumption in kg/100 km	39,0

6 Conclusions and Outlook

The primary objective of this research was to explore the potential of different approaches by employing three distinct tools in designing a fuel cell hybrid power pack. The tools under analysis were the Hybridization Tool, Virtual-FCs, and SEnSOR, and a functional comparison was conducted.

Based on the analysis, it can be inferred that currently, only the Hybridization Tool has the capability to support automated component dimensioning for a fuel cell hybrid power pack. This ability was demonstrated during the roundtrip from A Coruña to Ferrol as part of the FCH2Rail project, resulting in power pack dimensions of 350 kW Fuel Cell power combined with 267 kWh of battery energy content. Furthermore, the tool Virtual FCS partly offers detailed physical modeling, including the fuel cell balance of plant, providing valuable insights into the system's behavior. On the other hand, SEnSOR surpasses both tools by offering intelligent, optimized energy management strategies. The dimensioning results of the Hybridization Tool will be used in future works to compare the simulation tools and to demonstrate the difference in energy management strategies as well as in analyzation of the hydrogen consumptions based on representative use cases.

As a further outlook, these findings will subsequently be compared with the parameters of existing and projected vehicles, as well as with the findings of the EU StasHH project [13], which focuses on standardizing fuel cell block sizes for diverse applications. [14]

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