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The FCH2RAIL Project: A Demonstration of a Modular Fuel Cell Hybrid Power Pack

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Abstract

In this paper, the Horizon 2020 project FCH2RAIL is outlined. The project aims to develop a bi-modal propulsion system, which combines an overhead catenary powertrain and a hydrogen fuel cell battery electric hybrid system to enable operation on tracks with mixed electrification. A key element is the fuel cell hybrid power pack and its modularity. To enable a wide range of applications, a modularity definition process in terms of installed fuel cell power and battery size is carried out. Therefore, a methodology was developed to derive generic and well-suited fuel cell and battery block sizes. Hereby, a work flow is set up, which incorporates a longitudinal vehicle dynamic simulation and a fuel cell hybrid propulsion system model. Using statistical analysis, required block sizes in terms of power and energy content of the main powertrain components are derived. Afterwards, the evaluated component block size ranges are compared to market-available components. The results obtained with the developed algorithms were 17 kWh for the smallest defined battery block and 47 kW for the fuel cell block. These dimensions are well-covered by market-available components, which demonstrates the applicability of the proposed methodology.

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Keywords: EU Project FCH2RAIL; Fuel Cell Hybrid Power Pack; Modular Propulsion System; Railway Application; Future Powertrain Design; Zero-Emission Powertrains

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1. Introduction

In order to reach Europe's ambitious goals of CO_2 neutrality (European Comission, 2021), a reduction of end energy consumption can yield significant benefits as an accompanying measure to decarbonisation. Germany's largest

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consumer of end energy can be classified into the sectors transport, industry, commerce and households. Thereof, transport constitutes for 27% of the total end energy demand of Germany, of which 73.6% were attributable to motorised individual transport in 2019. (Drosihn, 2022; Wilke, 2022) When the specific energy demand per passenger-kilometre of personal motorised transport (2.14 MJ/PKM) is compared to the in contrast very low value for the public railway (0.47 – 0.83 MJ/PKM) (Rathmann, 2021), it becomes apparent that a shift towards public railway-based mobility solutions is a key factor to reduce today's energy demand. To enable a seamless and comfortable substitution of individual mobility by the railway, the existing network must be expanded to achieve the flexibility of today's individual transport. However, the instalment of the required electrical infrastructure to deploy non-fossil fuel reliant propulsion systems is not always feasible from an economic and ecological standpoint. Thus, emission- and catenary-free propulsion systems must be developed. Technologies such as the fuel cell (FC) enable such flexible, zero emission and potentially cost-competitive solutions to replace current diesel propulsion systems.

In this study, an overview of the FCH JU funded project Fuel Cell Hybrid Power Pack for Rail Applications (FCH2RAIL) and its main goals are given. One of its core objectives are the development of a novel propulsion system and the development of an approach to segment the main components into block sizes. Thus, the remainder of the paper will highlight a method which enables such indicative definition of block sizes for both fuel cell and battery. Therefore, the used simulation toolchain is explained and applied on a set of use cases.

2. Project Objectives

In the ongoing EU-project FCH2RAIL, a novel fuel cell-based powertrain architecture is developed, build, tested, homologated and implemented in an existing three car electric multiple unit (CAF CIVIA). To appeal to a wide range of application scenarios in railway operation, the advantages of an overhead electric traction and a fuel cell hybrid powertrain system are combined. The novel bi-modal fuel cell hybrid powerpack (FCHPP) incorporates two primary (FC & catenary) and a secondary power source (electric energy storage system). The general powertrain topology of discussion is depicted in Fig. 1. On electrified network segments, the conventional pantograph is used to cover the train demand during operation and recharge the battery. Only on non-electrified sections the power for operation, composed of traction, auxiliary and battery recharging power, is provided exclusively by the FCHPP. The possibility to operate both on electrified and non-electrified track sections while having the opportunity to draw electricity from the overhead wire makes such bi-modal powertrain a flexible and local emission free option.

The application field for the novel FCHPP shall include multiple units, shunting, mainline operation as well as the opportunity to retrofit existing trains with the newly developed FCHPP. This imposes the necessity to dimension the bi-modal powertrain, especially the FCHPP, according to its use case specific demand profile. Hence, the investigation on a modular and scalable FCHPP is a core task in FCH2RAIL.

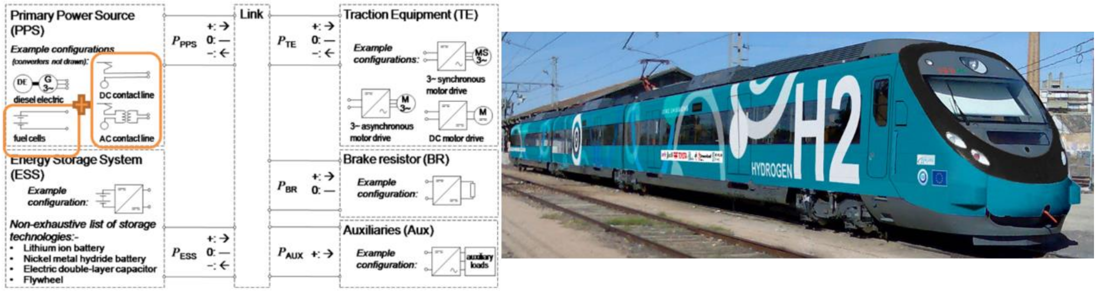

Fig. 1. General System Topology of the FCHPP's primary and secondary Energy Source (left) and CIVIA Demonstrator Train as used in the FCH2RAIL Project (right). Illustrations taken from FCH2RAIL Projekt. (FCH2RAIL Consortium)

To realizes these goals, a consortium composed by partners from Spain, Portugal, Belgium and Germany was brought together. The project is part of the Horizon 2020 Innovation Action and funded by the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership). With a budget of 14 million euros, the consortium aims to develop, demonstrate and approve the novel bi-modal FCHPP powertrain for railway applications until the end of 2024. (FCH2RAIL Consortium) The project is divided into 9 work packages, of which one concentrates on the digital layout process of the FCHPP, wherein the following method is allocated.

3. Digital Layout Methodology

The investigation of the FCHPP and its modular character is at the heart of the project. Thus, in the FCH2RAIL project, a methodology was developed to incorporate the FCHPP's modular character into the powertrain dimensioning process. This methodology represents a sequential approach.

In order to define the component sizes for fuel cell and battery, the operational demand profile must be determined. The power demand profile is obtained with the Trajectory Planner Tool (TPT). This algorithm, developed by DLR, represents a longitudinal dynamic simulation of rail vehicles. The TPT provides a physical base model, including the equation of motion and driving resistances to simulate the power demand and velocity profile of the railway vehicle. Further considered input variables are the timetable and route data as well as characteristic vehicle data, such as mass, traction power and acceleration capabilities. (Schirmer et al., 2018)

The velocity and power demand profiles generated by the TPT are then analysed in order to dimension a suitable fuel cell hybrid powertrain. Therefore, an algorithm was developed, which is used to assess these propulsion systems and the possibility for a sensible segmentation of respective components into block sizes. This novel method consists of the following steps: (I.) definition of a feasible battery size paired with the initial dimension of the fuel cell, (II. – III.) feasibility check of the propulsion system paired with a comprehensive energy management, (IV.) statistical analysis of the results and segmentation into the final block sizes for fuel cell and battery.

3.1. Step I. – Initial Dimensioning of Component Sizes

In the first step, an initial dimension for the fuel cell and battery are derived from the simulated demand profile for each individual simulation respectively. The fuel cell and battery dimensions are determined by the analysis of the power demand at the DC-Link. From the whole traction demand, the average is calculated. This approach is based on the assumptions that the fuel cell has to be operated at a constant load point to mitigate potential harming operation conditions. (Deng et al., 2022; Huan Li et al., 2017) Thus, the average traction demand is subtracted from the dynamic traction power. The remainder of the demanded energy has to be covered by the battery. To avoid chemically unfavourable battery end of life charge states the maximum depth of discharge is set to 60%. Thus, the resulting operation range of the battery is between 20% and 80% of the installed battery capacity. (Deng et al., 2022; Huan Li et al., 2017)

In Fig. 2, the general analytical approach to determine the initial assumption for the components is depicted. The battery and initial dimension for the fuel cell are then tested in the hybridization algorithm. The hereby applied energy management is simplified in such a way, that the fuel cell system operates continuously at the maximum installed power. Only if power from the fuel cell would be send to the rheostatic brake due to the charging limit of the battery, the fuel cell is operated at its idle point. If a balanced State of Charge (SoC) of the battery at the end of operation cannot be fulfilled, the fuel cell will be increased in its power rating, until the required final SoC can be met under maximum fuel cell load. Thus, a well-substantiated initial assumption for the sizing of the components in the first step is crucial to reduce computational time, otherwise the iteration loop to adapt the fuel cell size is increased. Through the simplified energy management, the battery might potentially experience overcharging during operation. Distinct mitigation measures to avoid misuse of the battery is incorporated in the second simulation step. The resulting FCHPP dimensioning represents the necessary power, which needs to be installed to full fill timetable operation.

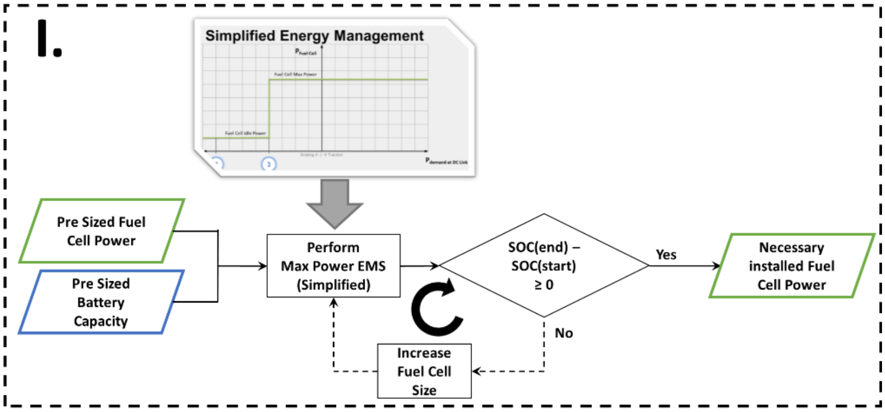

Fig. 2. Initial Dimension calculation with application of simplified Energy Management.

3.2. Step II. – Feasibility Check of Component Sizes

The aim of the second step is to check the feasibility of the defined fuel cell and battery by applying the complete energy management system. This is accompanied by the approach to lower the demanded fuel cell power. This procedure is depicted in Fig. 3. The full energy management consists of additional switch points, which are based on the current SoC of the battery. The addition of further switch points has a significant influence on the possible operation points of the fuel cell. Thus, it leads to the avoidance of battery overcharge, which was previously the case due to simultaneously recuperation and recharging of the battery through the fuel cell. It also achieves an improved battery usage and thus potentially increases overall system lifetime due to an even power distribution among the fuel cell and battery, as well as a reduction of hydrogen consumption through the more effective usage of recuperation.

Through the adapted recharging operation of the battery, the fuel cell has a degree of freedom, which can be used to reduce the average needed fuel cell power. The switch point which triggers the recharging of the battery through the fuel cell is iteratively lowered, see also descending purple line in the energy management schematic. As in the first step (I.), the SoC target of the battery is used as boundary condition.

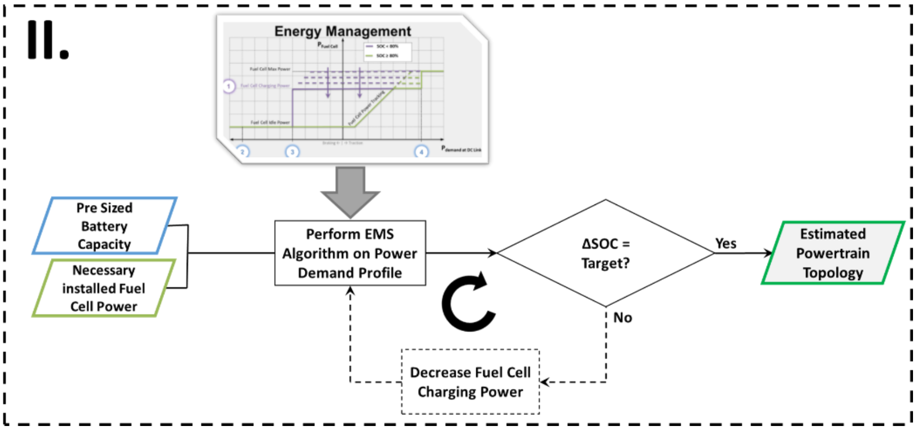

Fig. 3. Feasibility Check of initial Dimension of Fuel Cell and Battery size with complete Energy Management.

3.3. Step III. – Final Component Dimensioning

In the next step, the obtained FCHPP component sizes are evaluated with the goal to check on feasibility with regards to permissible battery load. The method with its recursive iteration is depicted in Fig. 4. The key criterion applied, is the battery C-Rate limit, which is set to 4C for this study. This limit represents a suitable first assumption on allowable battery C-Rates in the railway sector (Wolfgang Klebsch, 2018), without prior knowledge on the deployed cell chemistry. Furthermore, as this study focuses on the methodology, an in-depth investigation on feasible C-Rates is not in the scope of this study and will vary strongly depending on the deployment of high energy or high power batteries. Though, If the C-Rate limit is exceeded during the simulation, the battery size will be adjusted accordingly. The resulting battery size is then used recursively as the initial assumption for the hybridization algorithm. The switch points of the fuel cell are adapted respectively. With the adapted operation and battery, step (II.) is carried out once more in order to define a C-Rate compliant operation. Step (III.) results in the finalized component sizes for the fuel cell and battery.

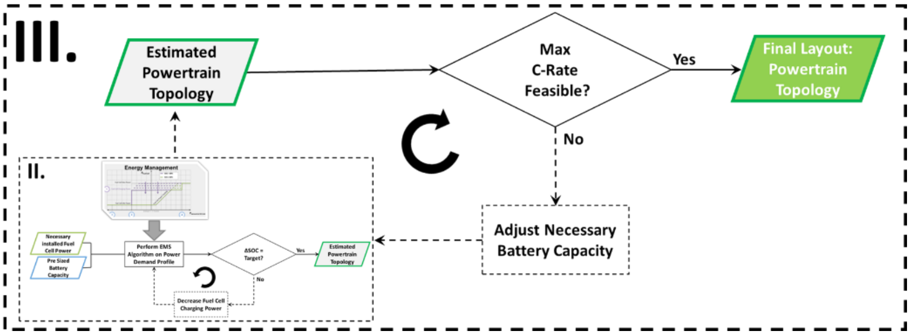

Fig. 4. Overview of the feasibility Check with C-Rate as Key Criterion.

3.4. Step IV. – Analysis

The last step is displayed in Fig. 5. and based on the evaluation of several simulation results obtained with the outlined steps (I.)-(III.) above. The respective final dimensions of battery and fuel cell of all simulations are pooled together with the aim to identify a uniform modular block size. Therefore, the mean value is calculated for the total fuel cell power and battery capacity over the generated data sets. The obtained average value for necessary battery capacity and installed fuel cell power sets the base line (red dotted line in Fig. 5.), which represents a possible standardized core component. The deviation from the base line to each individual simulated component (blue dots in Fig. 5.) is computed afterwards. The absolute deviation around the aforementioned base line is then used as an indicator for possible block sizes.

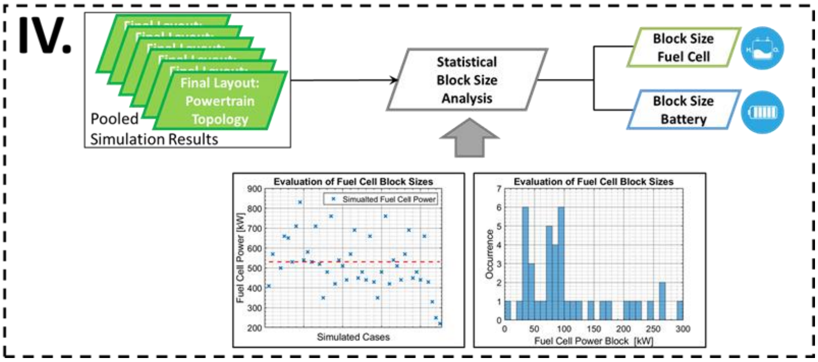

Fig. 5. Derivation of Component Block Sizes. Detailed evaluation given exemplary for the Fuel Cell.

4. Use Cases

The use cases considered represent a selection of Spanish, Portuguese and German lines. The simulated vehicles are a selection of currently running diesel units, which are assumed to be generally compatible to operate with an electric drive system, as well as a generic set of two and three car multiple units. In the following Table 1, the general characteristics of the train models are listed. The traction power values depict only the non-catenary operation.

Table 1. Overview of characteristic Data for Train Models used for Simulation under non-electrified Operation.

	Generic 2 Car	Generic 3 Car	S599 3 Car	Regio Shuttle 1 Car
Reference Load (seated) [t]	165	202	194	46
Power at the Wheel [kW]	1240	1490	1298	536

5. Evaluation of Results

The results obtained by the developed method on the introduced use cases are summarized in Fig. 6. Depicted are the expected results of the method at the different stages (I.-IV.). Hereby (I.-III.) displays the results per train, while (IV.) represents a percentile summary over all block sizes obtained. It is clearly visible, that the proposed algorithm for the initial dimensioning, as used in steps I.-II., of the battery rarely lies within the desired maximum load corridor of 4C. Thus, the in step (III.) carried out adoption of the recursively defined battery power in order to meet the operation target is needed and works as intended. The distinct separation of the two visible fuel cell power levels after the C-Rate is limited are traceable to the different maximum traction efforts the simulated multiple units can provide. The statistical analysis carried out in step (IV.) represents a percentile evaluation of the obtained results. Particularly outlying high loads can be explained by very challenging operation scenarios, thus high demand profiles. This indicates either an adaption of the targeted timetable for the real-world application or the non-suitability of fuel cell hybrid propulsion systems deployment on these specific tracks. Since particularly large components were identified here, which would entail high costs and system weight or installation space restrictions.

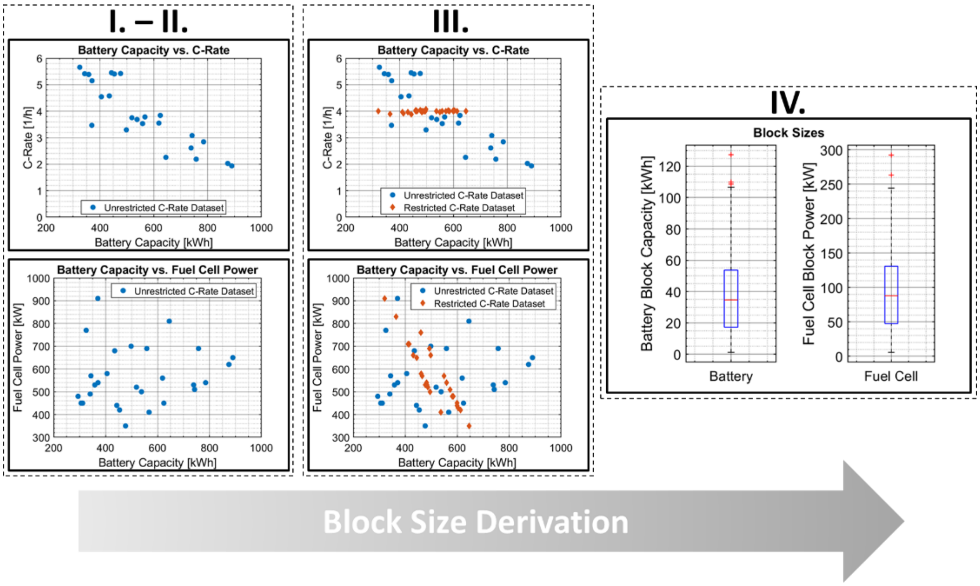

Fig. 6. Results of the FCHPP Block Size Study.

The results from the block size analysis are summarized in Table 2. In order to exclude the exceptional high block size results for the battery and fuel cell, the values within the 25th – 75th percentile range are used for further assessment only. It is visible that especially the battery and fuel cell block sizes represent roughly a multiple of each other, thus indicating the theoretical possibility to reduce the block size to the 25th percentile.

Table 2. Summary of Fuel Cell and Battery Block Sizes.

	25th Percentile	Median	75th Percentile
Battery Block Capacity [kWh]	17	34	53
Fuel Cell Block rated Power [kW]	47	87	130

To put the results from the presented study into practical context, we compared the block sizes to market-available components. For the battery, common scalable modules are available from 15 up to 40 kWh as for example provided by AKASOL or SAFT (Akasol, 2022; Saft SA, 2015). The identified smallest block size of 17 kWh as well as the median of 34 kWh from the analysis thus match the available block sizes on the market. The assumed maximum of 4C in this study reflects an elaborated starting point from which the general principle of this methodology could be proven. Though, for a comprehensive C-Rate analysis, a time-based load collective has to be investigated. In real world applications allowable C-Rates can exceed 4C in pulsed operation.

Toyota provides fuel cell systems with a rated output of 60-80 kW (Toyota Motor Corporation, 2021) and Cummins offers fuel cells which range from 45 up to 90 kW (Cummins Inc., 2022) of continuous power output. Ballard, as another large fuel cell manufacturer for railway applications, has a modular fuel cell system designed for heavy duty and railway applications in their portfolio ranging from 30 – 100 kW. (Ballard Power Systems Inc., 2022) The obtained 25th and median block size for the fuel cell lie within the available range as well.

6. Conclusion & Outlook

In this paper, the project FCH2RAIL was introduced and its key goals in innovation and research highlighted. At the heart of the project is the development of the FCHPP and its aspect of modularity in order to be suitable for a wide range of applications. Therefore, a methodology was developed which allows to investigate possible layouts for a fuel cell hybrid as well as the segmentation of the installed battery and fuel cell into dedicated block sizes. Hereby, a comprehensive simulation approach was developed, which includes a longitudinal dynamic simulation model for rail vehicles, a comprehensive hybrid powertrain model as well as a statistical analysis to examine feasible fuel cell and battery block sizes.

The methodology was applied on a selection of Portuguese, Spanish and German use cases. Respective block sizes ranging from 47 to 130 kW for fuel cells and 17 to 53 kWh battery capacity were obtained. The identified block size ranges, both for the fuel cell and battery, match component sizes which are currently available in the market. Thus, the general applicability of the methodology's concept is demonstrated. Additionally, it was found that for the fuel cell and the battery, the computed block sizes represent a multiple of the smallest defined block size. Leading to the conclusion that the smallest identified block presents potentially the most suitable. Though, an economic and installation space driven analysis must accompany this decision. Furthermore, the key criterion to define feasible component sizes is based on the battery's experienced C-Rate during operation. This represents a valid though simplified approach as it neglects time dependent component harming operation conditions. Further studies shall be carried out in order to evaluate the effect of time dependent load collectives on the battery and fuel cell.

Despite this, the ambition of the innovative FCHPP to be suitable for a wide range of applications is taken one step forward through the development of the methodology, which assists in the definition of suitable block sizes. In the future, the proposed method to set up a modular FCHPP-based propulsion system can potentially serve as a decision support for rail manufacturers, operators and to rail authorities. Thus, FCHPP's modularity and flexibility shall facilitate the uptake of the technology and propel zero-emission powertrains forward.

Future will address an optimal energy minimizing control strategy, which flexibly adapts the train operation with respect to a hydrogen consumption minimizing energy management of the FCHPP. This novel approach shall then be benchmarked against a current rule-based operation. Previous studies have shown that a reduction of approximately 20% in primary energy demand can be expected. (Schenker and Kühlkamp, 2021) This opens up the possibility to define a modular FCHPP with an optimal energy management, promoting fuel cell hybrids as an optimal zero emission drivetrain for the future even further.

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Author's contribution

Draft preparation, method development and visualization, F.K.; Review and editing, M.V.,A.F.,H.D.,S.H.P.,J.P,M.S.

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