Report

H_2UpScale

Deliverable 3.1

System Requirements and Architectural Design

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Table of abbreviations

Abbreviation	Meaning
2PC	2 Phase Cooling
C-WTVC	China World Transient Vehicle Cycle
ECU	Engine Control Unit
EGW	Ethylene-Glycol Water
EMS	Energy Management System
FC	Fuel Cell
FCS	Fuel Cell System
HEX	Heat Exchanger
HiL	Hardware-in-the-Loop
HRB	Hydrogen Recirculation Blower
KPI	Key Performance Indicator
MFCS	Multi-stack Fuel Cell System
PEMFC	Polymer Electrolyte Membrane Fuel Cell
P&ID	Process and Instrumentation Diagram
QA	Quality Assurance
SRIA	Strategic Research and Innovation Agenda
WHR	Waste Heat Recovery
WP	Work Package

Table of Contents

1 Introduction

1.1 Context

This deliverable D3.1 is the outcome of Task T3.1 within Work Package (WP) 3 “System Design and Optimisation” of the H_2UpScale project. WP3 focuses on the development of scalable, modular, efficient, and cost-effective Polymer Electrolyte Membrane Fuel Cell (PEMFC) system architecture blueprints that support the transition toward high-power applications across multiple heavy-duty sectors, including on-road transport, maritime, stationary power and aviation. Task T3.1 builds directly on application-specific and Fuel Cell (FC) system-specific requirements established in WP2. These include operational constraints, performance targets, and boundary conditions informed by industrial use cases and stakeholder input. Within the framework of WP3, D3.1 plays an initiating role in aligning system architecture development and optimisation with both technical and economic viability and supports reaching the strategic objectives set in WP3:

- Objective 3.1: determine the state-of-the-art in high-power PEMFC system designs and identify critical technical and architectural challenges;
- Objective 3.2: simplify FC system architectures to reduce complexity and cost, while improving efficiency and gravimetric power density;
- Objective 3.3: optimise FC system design concepts to support upscaling to multi-MW applications;
- Objective 3.4: perform qualitative cost and feasibility analysis to inform FC system concept definition.

1.2 Purpose and outline of the document

D3.1 reports on the current State-of-the-art of high-power PEMFC installation designs, investigates them to identify gaps and challenges relative to requirements set in WP2, as well as Clean Hydrogen Joint Undertaking Strategic Research and Innovation Agenda (SRIA) targets, relevant to the project. Finally, the deliverable provides a definition of system architecture blueprints for three power nodes: 350, 700 and 1050 kW. These blueprints are subjected to subsequent design optimisation activities in tasks T3.3 on FC system design and T3.4 on FC thermal system design. The document in organised in the following sections:

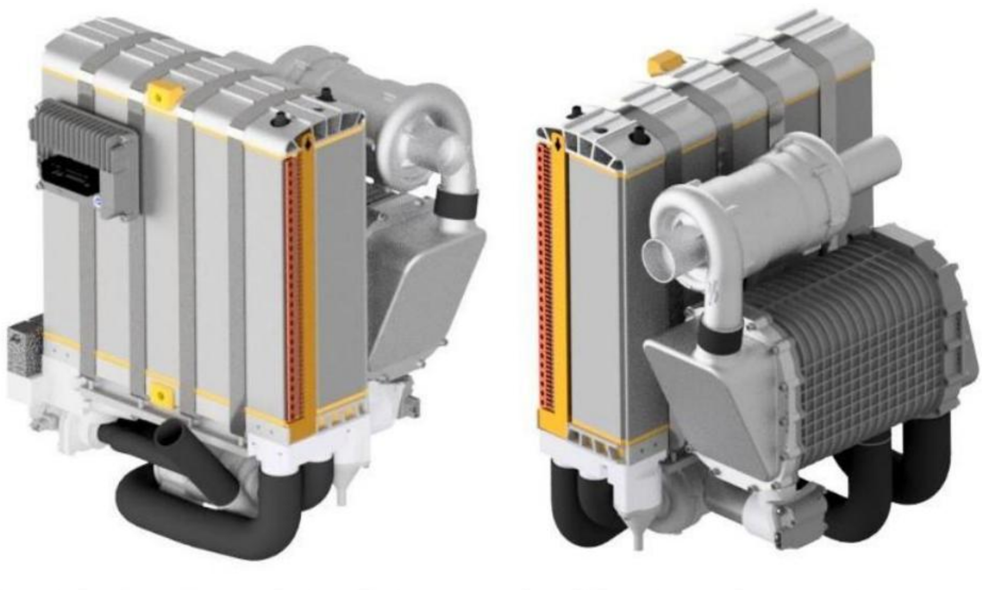
- Chapter 2: reviews the State-of-the-Art of high-power installation designs;
- Chapter 3: outlines and analyses the identified gaps and challenges;
- Chapter 4: describes the defined system architecture blueprints;
- Chapter 5: provides concluding remarks;
- Annexes A-D: contain a summary of the State-of-the-Art and selected Process and Instrumentation Diagrams (P&ID)

2 State-of-the-Art of high-power fuel cell installations

This chapter presents a State-of-the-Art review of publicly reported high-power fuel cell systems. A summary of the reviewed systems, outlined advantages and drawbacks can be found in Annex A: Summary of high-power installation State-of-the-Art.

2.1 EU Maranda

The Fuel Cell System (FCS) developed for the EU Maranda project was based on the 96,9 kW system from Swiss Hydrogen SHA-100-E module, which had been first used in an FC electric truck [1]. The module includes an FC stack, cathode subsystem (air compressor, charge air cooler, cathode drain valves), anode subsystem (proportional valves to control flow rates and pressures, purge valve, hydrogen cyclone, heat exchanger for pre-heating feed hydrogen), primary cooling loop (plate heat exchanger, coolant pump, by-pass valves, coolant reservoir, ion exchanger), and a programmable automotive Engine Control Unit (ECU). A 3-D model of the SHA-100-E is illustrated on Figure 1.



Not shown: air filter, air mass flow meter, brackets, wiring harness, covers, heat shields, coolant reservoir, compressor inverter

Figure 1. Swiss Hydrogen SHA-100-E module [1].

This platform was used to develop the FCS for maritime and stationary applications in the Maranda project, and it **used a single-stage compressor instead of the compressor/expander unit**. The motivation behind this change was the reduction of system power from 100 kW in the truck application to 85 kW, as well as the challenges around water management and operation and, finally, start up from/at freezing conditions which were not completely solved in the truck project.

The cooling is provided through a **two-circuit layout**, with the primary cooling loop consisting of a purpose-made, non-conductive ethylene-glycol water (EGW) coolant circulating through the FC stack and the primary heat exchanger (HEX). The secondary coolant circuit contains a technical-grade fresh water coolant and connects to the vessel's Waste Heat Recovery (WHR) system. The P&ID of the adapted system can be found in Annex B: P&ID – EU Maranda SHA-100-E.

The system installed onboard the vessel in the Maranda project contained **two identical systems**, which could be **operated independently from one another**, which ensured redundancy and enabled studying various operating profiles [2].

2.2 EU BRAVA

The EU BRAVA project investigated preliminary FCS design concepts for aviation applications. Besides looking into improvements in stack performance through usage of advanced catalysts and membranes the project studied innovative air supply, hydrogen supply, and cooling loop architectures towards optimising the overall FCS architecture.

Two concepts were evaluated for the anode path as alternatives to the current recirculation concept [3]. The findings indicate that the passive recirculation concept was seen to not be compatible with liquid hydrogen feed systems. On the other hand, the **dead end concept** (i.e., no recirculation) shows promise in terms of reducing the number of components involved. On the other hand, since there is no constant flow of gas, water can accumulated in the anode and can only be removed by purging. This results in possibility of degradation due to hydrogen starvation caused by the liquid water accumulation. The purging related control challenges can be overcome by design optimisation of the FCS. Therefore, the dead end concept was chosen for further refinement.

For the cathode path, potential options to simplify the path were examined [4]. One of the options evaluated was a cathode recirculation concept which showed limited benefits with added complexity and therefore was not considered further. Another alternative that showed more promise is the complete **elimination of the humidifier**. This would eliminate a component but would also lead to drop in performance especially at higher temperatures. To ensure sufficient performance while meeting the objectives at idle power, the project proposed a non-humidified concept together with low lambda control.

A novel **2-phase cooling (2PC) system** using methanol was evaluated against the conventional liquid cooling system using EGW. The results showed that 2PC concept would reduce the overall weight of the cooling system by 26% (including accumulator) or by 58% for a system without accumulator [5], while maintaining the required cooling capacity. This concept has additional benefits, e.g., it enables the effective heat up of liquid hydrogen with the waste heat from the fuel cell. In a traditional EGW system this would not be challenging due to the high freezing point of EGW and low heat transfer coefficient at low temperatures. On the other hand, usage of methanol as coolant poses challenges in terms of storage and safe handling.

2.3 EU NEWBORN

The EU NEWBORN project focuses on the development and demonstration of a ground demonstrator of the overall propulsion system for aviation applications. The FCS used for these evaluations consists of 1 MW modules that can be integrated in parallel (each module contains 3 submodules of ~300kW).Figure 2 shows a 3-D view of the mechanical integration of the FCS in the aircraft envelope. As the figure shows, the 3 stacks each have a dedicated recirculation loop with a centralised air supply subsystem.

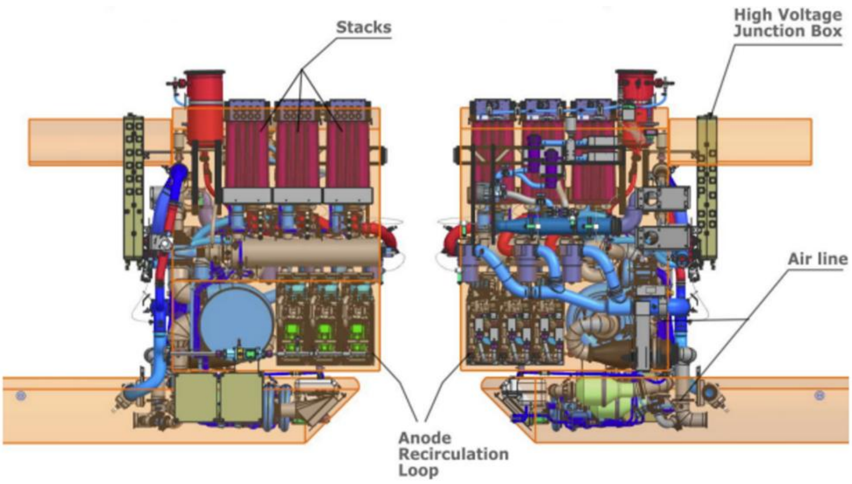


Figure 2. FCS integration in aircraft envelope [6]

2.4 EU GRASSHOPPER

The EU GRASSHOPPER project designed a 1MW Fuel cell power plant based on learnings from a 100 kW module pilot plant. The layout of the FCS used in the pilot plant is shown in Figure 3. The plant included several identical stacks supplied by a central air and hydrogen supply system. Exhaust hydrogen is recirculated using a liquid ring compressor. Both the air and hydrogen supply are humidified using dedicated humidifiers.

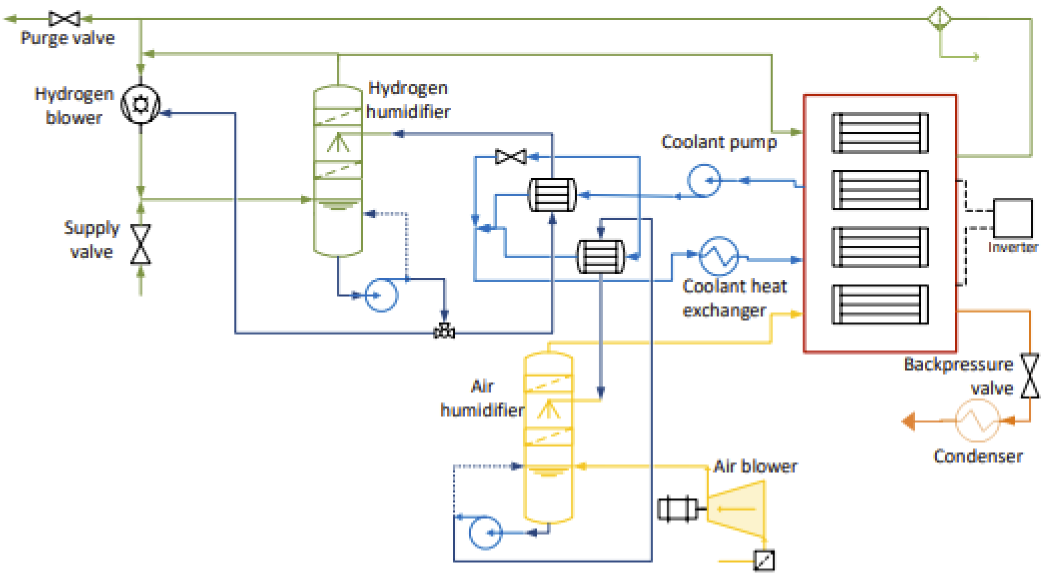


Figure 3. Layout of FCS in 100kW pilot plant [7].

One of the key findings from the pilot plant was that perfect control of the air stoichiometry was not possible by only varying the rotational speed of the blower. This is especially pronounced at low loads where a fraction of the compressed air had to be purged to limit the air stoichiometry, resulting in increased parasitic consumption. The effect of compressor sizing is studied by simulating 3 different compressors, namely, a solution with a single large compressor, a solution with two smaller compressors in parallel, and a third solution with three smaller compressors in parallel. The results showed that there was no significant difference in the electrical power consumption between the studied solutions, therefore **the choice of number of compressors is driven by economic considerations, packaging constraints and the control accuracy.**

2.5 Scientific literature on multi-stack fuel cell system design

The scientific literature extensively explores the concept of Multi-stack Fuel Cell Systems (MFCS) for high-power applications (>200 kW). Compared to single-stack systems, MFCS paired with effective Energy Management Systems (EMS) offer enhanced system scalability, operational flexibility, higher resilience, efficiency gains and extended lifetime — at the same time introducing the drawback of increased system-level complexity, cost and integration burden.

Ultimately, design choices are made by trade-off decisions that balance performance and resilience versus cost and complexity (Table 1). In terms of the design, the process can begin with determining stack-rated power based on application requirements in terms of maximum power and power rates, as well as application constraints. Stack number and size are set accordingly, followed by the design of fluidic, electrical, and thermal architectures (Figure 4 [8]), relevant aspects of which are described in the following sections.

Table 1. Trade-offs to be considered in MFCS design.

Strategy	Efficiency	Redundancy	Cost/Complexity
Shared BoP (compressors, humidifiers, pumps, etc.)	Moderate	Low	Low
Per-stack BoP components	High (fine control)	High	High
Hybrid (e.g. shared + limited local control)	Balanced	Balanced	Moderate
Self-regulating subsystems (e.g. self-humidifying)	Variable	High	Lower (if effective)

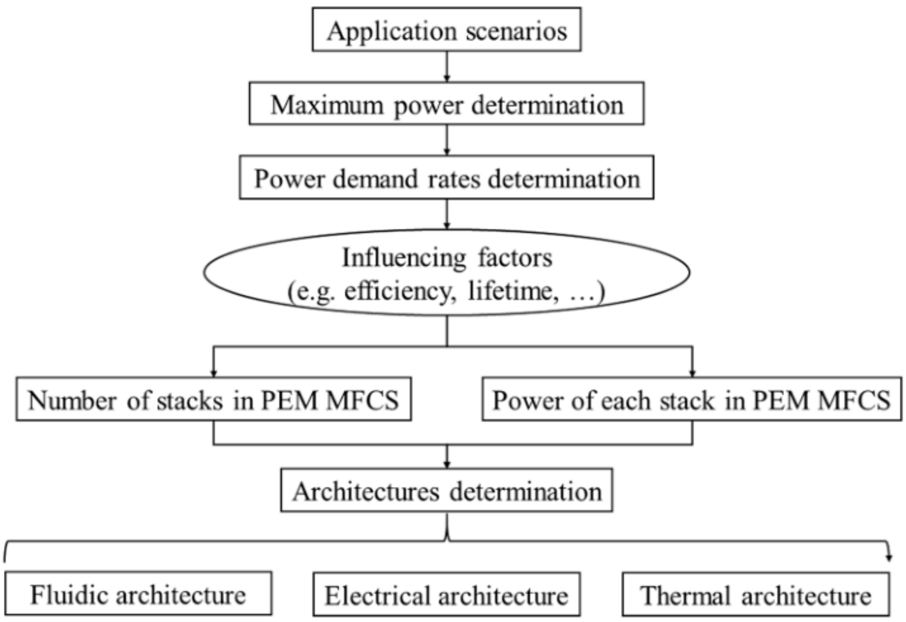


Figure 4. Example workflow of designing a MFCS [8].

2.5.1 Qiu et al.

One of the primary degradation mechanisms of a PEMFC are linked to fuel starvation, suboptimal water and thermal management (including e.g. membrane drying, channel flooding, local hotspots, hygrothermal cycling leading to membrane stress), and chemical degradation of PEMFC components (e.g. platinum catalyst dissolution and agglomeration or carbon support corrosion). Ensuring sufficient reactant supply under high-power demand is essential for both dynamic performance and lifetime. Well-designed and fault-proof fluid supply architectures are key to enabling reliable high-power output [9]. A generalised architecture of a MFCS consisting of several stacks and multiple BoP has been illustrated in Figure 5.

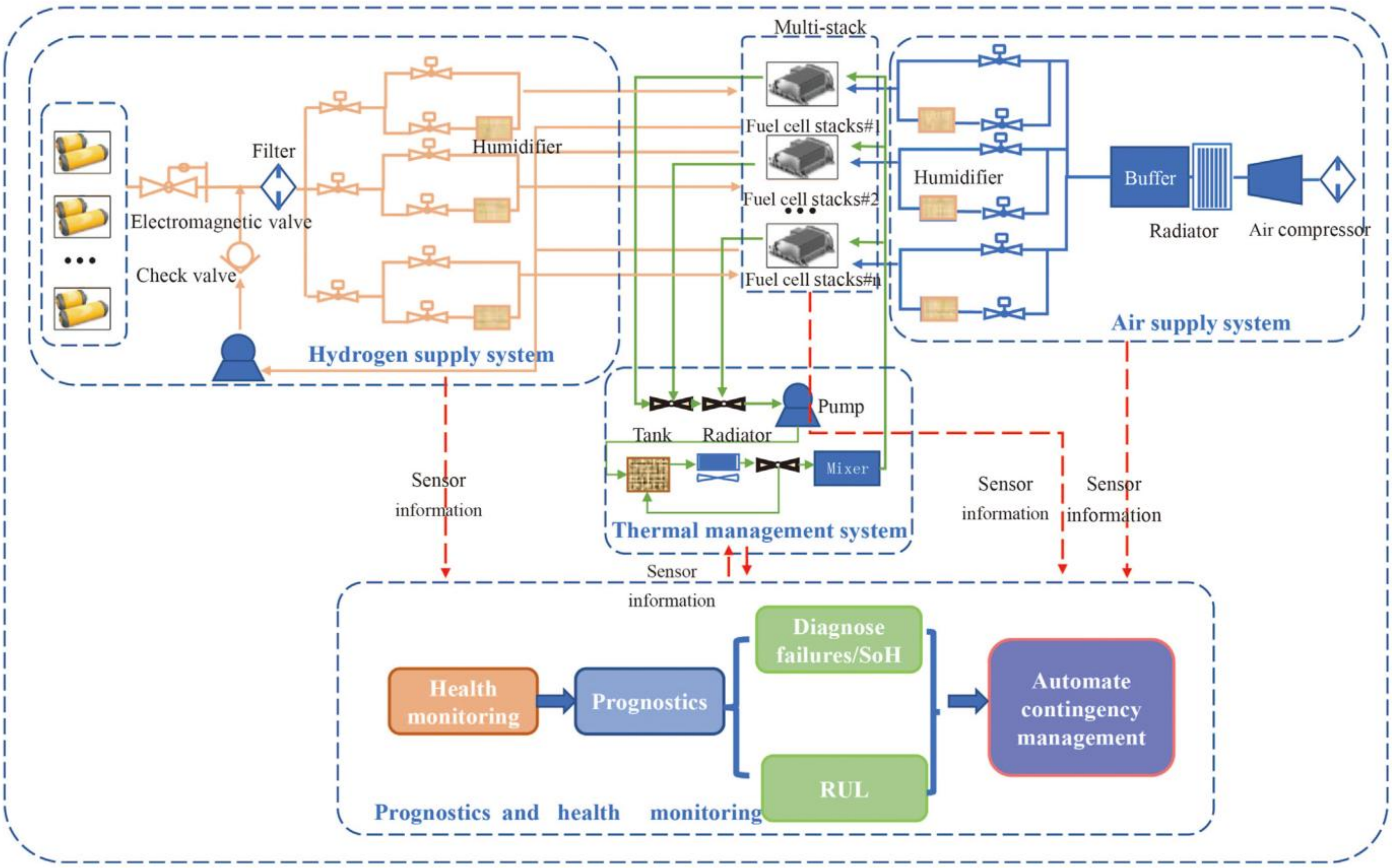


Figure 5. Example structure of a MFCS [9].

For hydrogen management, **hydrogen recirculation can effectively improve efficiency and improve gas flow velocity by using a Hydrogen Recirculation Blower (HRB) or hydrogen ejector.** In terms of high-power fuel cells, excessive hydrogen supply usually is provided to avoid hydrogen starvation and provides a more uniform voltage drop distribution. Moreover, the **parasitic power of the recirculation pump cannot be ignored,** especially in high-power scenarios.

Maintaining proper pressure, mass flow, humidity, and temperature in MFCS air subsystems requires more auxiliary components, increasing complexity and cost. **To reduce reliance on airflow sensors and lower parasitic losses, observer-based methods are proposed to estimate oxygen concentration.** While fast dynamic response is essential in high-power applications to prevent voltage drops, oxygen starvation, and membrane damage from air-hydrogen supply delays, **an integrated air supply system** (illustrated on Figure 11) **can significantly reduce power consumption**.

The advantages and drawbacks of four MFCS fluid supply variants are given in Table 2. These four types are illustrated in Annex C: Hydrogen and air supply architectures.

Table 2. Comparison of variants of MFCS fluid supply architectures [9].

Type	Advantages	Disadvantages
Series	Simple structure	High air compressor power consumption; low fault tolerance
Parallel	High fault tolerance; lifespan improvement	Complex structure
Independent	Power consumed reduced by air compressor	High cost; bulky; complex system
More stacks	High fault tolerance	Complex system

In MFCS, water management is essential to prevent both membrane drying and flooding, which directly affect performance and durability. Passive strategies, such as internal humidification, use product water to self-regulate humidity, reducing system complexity, while active water management, relies on dedicated components like humidifiers, valves, and control loops to maintain optimal hydration conditions. The latter, while more precise and adaptable to variable loads, adds to the cost of the system, its complexity, and parasitic power consumption. The choice between passive and active systems reflects a trade-off between simplicity and control. **For high-power MFCS, especially in dynamic applications, active management is generally preferred for its robustness.** However, further integration and optimization are still needed to balance efficiency, responsiveness, and subsystem redundancy.

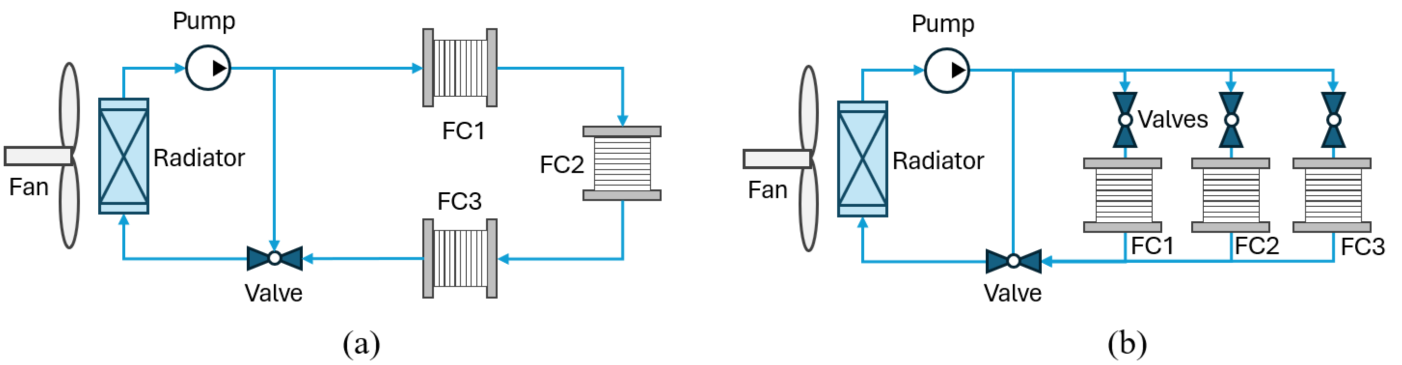


Figure 6. Thermal system architectures. (a) series; (b) parallel. Schematic adapted from [9] with pump placed before the by-pass.

Thermal management in MFCS is critical for maintaining stack performance, durability, and uniform operating conditions. Here, two primary approaches can be distinguished: series and parallel (Figure 6). In the series type, coolant flows sequentially through stacks, offering simpler design and effective control under steady-state conditions but risking uneven temperature distribution and thermal degradation in downstream stacks. Excess heat produced by the upstream stack could be used to preheat the downstream stack(s), reducing start-up soon times, when properly controlled by the thermal management system, potentially leading to the benefit of energy saving [8]. Parallel cooling supplies coolant to all stacks simultaneously, ensuring better temperature uniformity and faster dynamic response, but requiring more complex plumbing, sensors, and controls.

To regulate and control the electrical output of MFCS, various topologies connecting FC stacks with DC/DC converters are proposed. These allow independent stack control, improving dynamic response and system reliability, especially under partial failure conditions. However, they introduce higher cost, increased weight and maintenance needs. **Cascaded converters and modular designs are highlighted as promising solutions to reduce voltage stress and enhance scalability.** Ultimately, the choice of architecture depends on the requirements of the target application for fault tolerance, efficiency, and control precision, balanced with cost and weight/volume limitations.

A comparison of four MFCS electrical architectures with DC/DC converters are given in Table 3, and are illustrated on the schematics in Annex D: Electrical architectures of MFCS and DC/DC converters.

Table 3. Comparison of variants of MFCS electrical architectures [9].

Type	Advantages	Disadvantages
Series	Simple structure; low cost	Low lifespan; fault tolerance
Parallel	Degraded mode operation; high durability and fuel economy	High cost; not easily controlled
Series-parallel	Reliability configuration	No disadvantage
Cascaded	No stress on the converters	Complex structure

Despite higher initial cost and system complexity, MFCS parallel and cascading architectures offer superior control flexibility and fault tolerance, allowing for partial operation in case of individual component degradation or failure, when compared to single-stack topologies.

2.5.2 Zhou et al.

More reflections on the comparison of different MFCS - DC/DC association types were done by Zhou et al [8], summarised here in Table 4.

Table 4. Comparison of different association types for MFCS with DC/DC converters.

Type	Benefits	Drawbacks
Series	All stacks are connected to the DC bus through only one converter; This structure uses a low gain converter which generates less stress on converter switches; This architecture is the simplest and cheapest.	Each stack cannot be controlled individually; The failure of one stack leads to the failure of the entire system without a bypass circuit.
Parallel	Each stack is connected to the DC bus through one converter; This architecture provides redundancy and enables the individual control of each stack; This architecture allows the system to operate in degraded mode.	This structure uses several high gain converters which generate higher stress on switches and larger passive energy storage components; This architecture is complex and the most expensive.

Series-parallel	The voltage-elevation ratio is smaller compared with the parallel architecture; This architecture enables power-sharing between different series associations and brings more redundancy through the parallel association; This architecture can individually control each stack and is the most reliable.	No disadvantage.
Cascaded	Each stack is connected to the DC bus through one converter; The global voltage is divided between different stacks and this division leads to lower stress on converter switches; This architecture can individually control each stack and the cost is lower.	The failure of one stack leads to the failure of the entire system.

2.5.3 Gao et al.

Gao et al. [10] proposed an optimized stack power allocation for a MFCS (210 kW), considering economy and dynamics to establish integrated subsystems with added functional components. The results show that an MFCS consisting of a 3 individual stacks with distributed powers of 20 kW, 70 kW, and 120 kW are most optimally fulfilling the requirements of a load profile of a heavy commercial vehicle and satisfy lifetime and efficiency factors and. The architecture of the MFCS is shown in Figure 7.

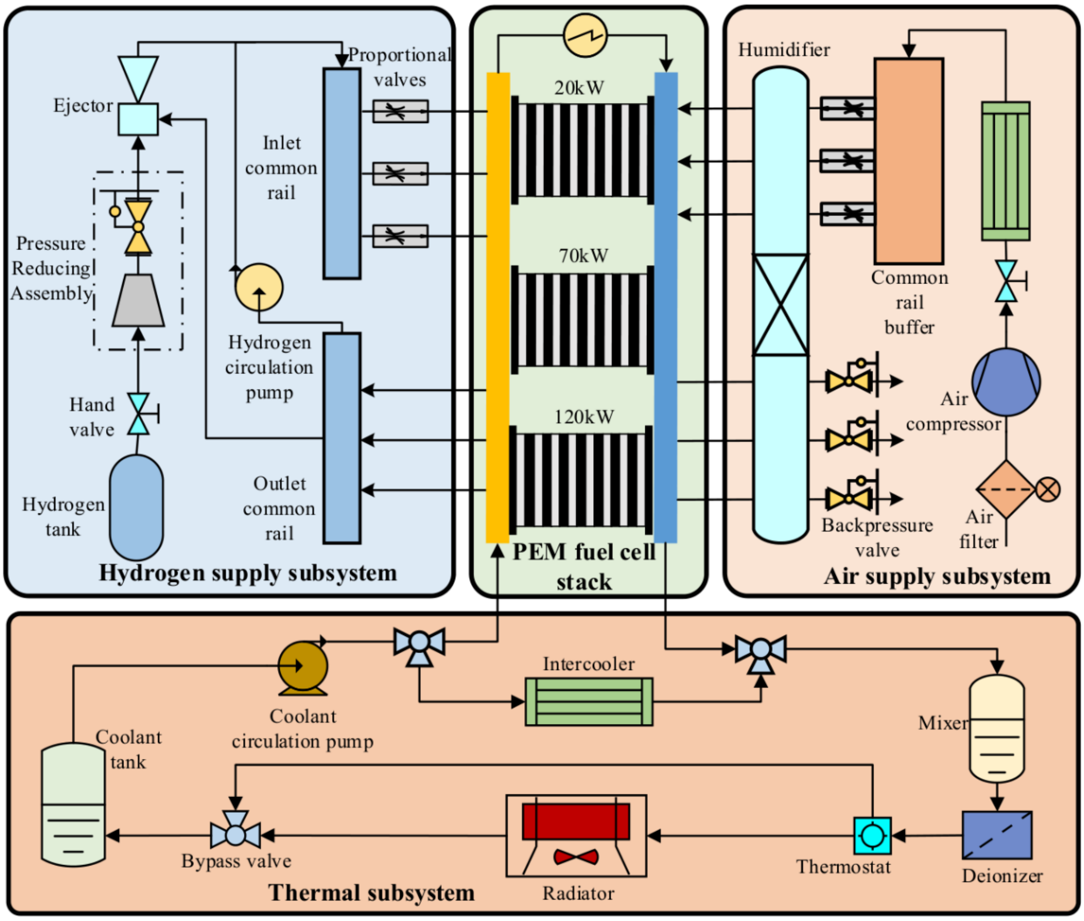


Figure 7. Structure of a 210 kW MFCS using a common rail approach and 3 stacks with different power outputs.

One of the key features of this system was the use of a **common rail buffer**, inspired by engine common rail technology. This isolated the air compressor from the fuel cell air demand, **enabling one set of pressurized air supply equipment to serve multiple stacks**. It stabilizes pressure, buffers demand fluctuations, and stores air to supplement supply during compressor shortages or highly variable and peak loads. The common rail also supports humidification by recycling water vapor from cathode exhaust for thermal recovery. Results show that the buffer volume affects compressor energy consumption, maximum power, as well as its own pressure drop. For a 210 kW MFCS, a 200 L buffer is identified as the optimal volume, while compressor power sizing remains flexible. The compressor accounts for a major parasitic load (15–20% of MFCS output), making its selection and the buffer's optimization critical for efficiency.

Similarly to the air supply subsystem, the hydrogen subsystem used a common rail – here both for the inlet and the outlet of the 3 stacks – enabling hydrogen supply and exhaust gas recirculation for all stacks through one integrated system. The inlet common rail stabilizes inlet pressures, diverts flows, and isolates stack demands, while the outlet common rail converges anode exhaust gases and ensures equal circulating pressure using a single hydrogen circulation pump. **The integrated hydrogen supply subsystem improves hydrogen utilization and reduces parasitic power**.

The thermal subsystem uses a single coolant supply and circulation system to manage multiple stacks, with diverter valves and mixers enabling integrated control. Heat is carried by the coolant to an air-cooled radiator for dissipation, with radiator performance calibrated under standard temperature conditions. An intercooler in the loop also serves the air supply subsystem. **Compared to a distributed thermal subsystem, the integrated approach offers no performance gain in thermal management, but is structurally simpler.** A closer coupling between coolant pipelines of different stacks helps in sharing heat more effectively during low temperature operation, which is a notable advantage e.g. for cold starts.

2.5.4 Zhou et al.

Air supply devices for MFCS need to provide appropriate air to each stack to obtain highest system efficiency, Typically this is done by having a dedicated air supply unit per stack, however this adds to the overall weight and cost of the system. This can be tackled by the use of a central air supply device which is investigated by this paper. The central air supply devices (filter, compressor and intercooler) feed a buffer volume that then supplies each of the stacks with the appropriate air as seen in Figure 8. The benefits of such as system is simulated on an automotive drive cycle, namely, the China World Transient Vehicle Cycle (C-WTVC). This is done by simulating 3 sets of FCS (140, 210 and 280kW) as part of both a single stack and multi stack system. The results reported show that the **peak electrical power demand and overall energy consumption of the auxiliary devices are strongly influenced by the relative size of the stacks in the multi stack setup and the control strategy** chosen for the buffer volume.

Using a constant control scheme (controlling the buffer pressure to a certain preset value) leads to an increase in overall energy consumption by the auxiliary devices compared to a single stack system while there is a 30% decrease in the peak power demand. On the other hand, a hybrid strategy **where the buffer is maintained at a lower preset value, unless the stack demand exceeds, is shown to reduce the overall energy consumption by up-to 20%**, while the peak demand is maintained in comparison to the single stack system. Additionally, an optimal stack distribution of 1 small stack and a large stack is shown to have reduce the overall energy consumption compared to an average distribution (e.g., 2 stack of 70kW for a 140kW system).

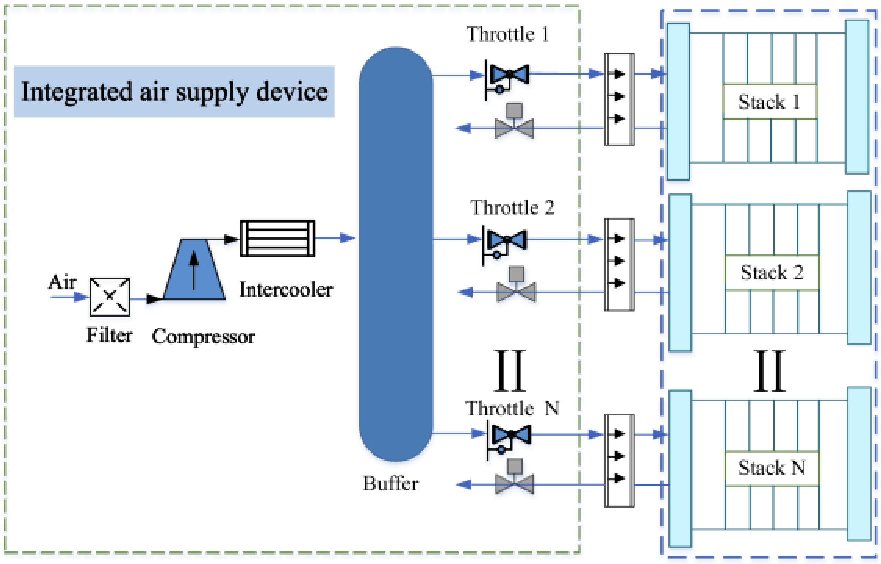


Figure 8. Integrated air supply device for MFCS from [12]

2.5.5 Massaro et al.

Storage (liquid hydrogen) and cooling systems have a significant impact on the overall weight of the electrified system, accounting for approximately 26% and 54%, respectively [11]. The required sizes of both storage and cooling systems are correlated to the stack efficiency, therefore the weight of the electrified propulsion system varies with the FC stack design working point (defined as a percentage of its nominal power). At low operating points, oversizing stacks increases total system weight, while near nominal loads, lower fuel cell efficiency demands larger hydrogen storage and BoP components. The optimal trade-off occurs at intermediate loads (~50% load, ~64% on-design), where oversizing stacks slightly below nominal rating improves efficiency (illustrated on Figure 9).

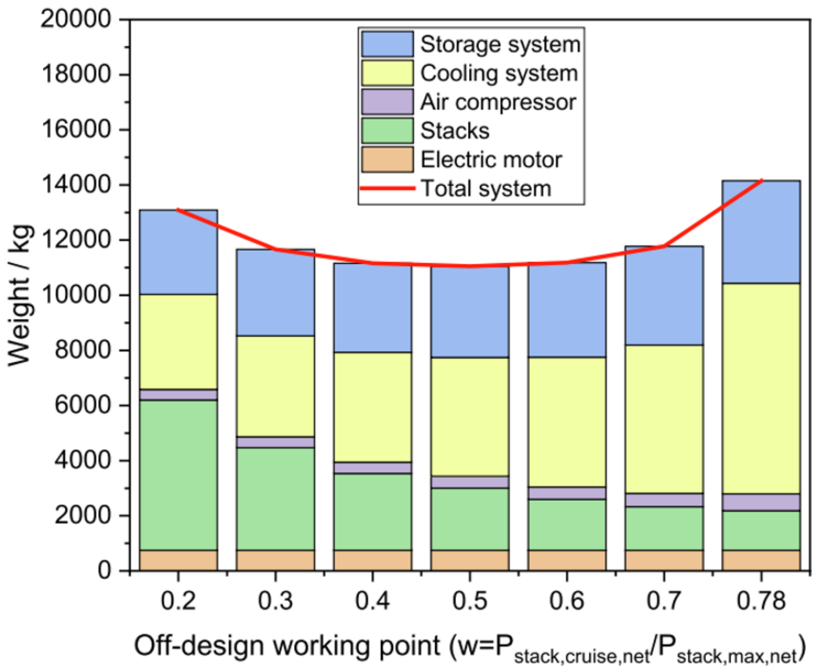


Figure 9. Weight distribution of the components of the electrified propulsion system for different off-design working points [11].

The analysis outlines that **it is advantageous to increase the number of stacks so that the entire FC system operates below its nominal power rating, even under on-design conditions, as this improves overall stack efficiency**. This gain reduces cooling requirements due to lower heat generation, compressors operate with reduced airflow, and hydrogen consumption, thereby lowering the size and impact of these subsystems.

2.5.6 Schröder et al.

The paper utilizes simulation studies to optimize the design of FCS for regional aircraft applications. The expected electrical power demand of 3.12 MW is supplied by 10 identical FCS of 312 kW.

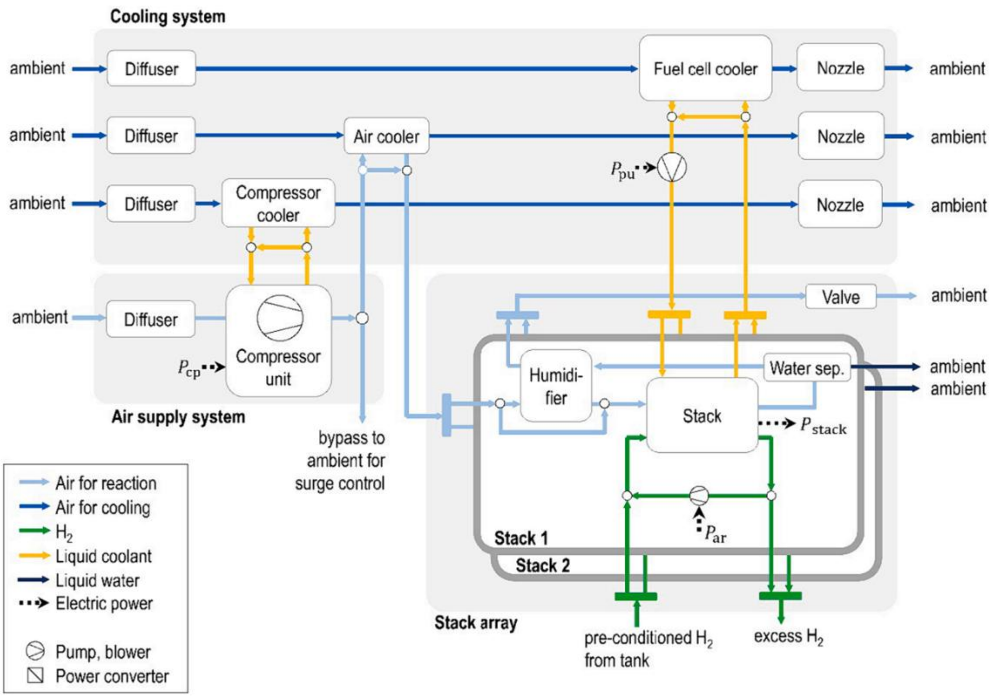


Figure 10. Fuel cell system building block from [13]

Considering that the current generation of fuel cell stacks are typically limited to a power output of 125kW, the proposed 312 kW FCS building block is made of multiple stacks in parallel with Figure 10 showing an exemplary layout containing two stacks in parallel. Each stack has its own **dedicated humidifier and recirculation loop with a centralized air supply and cooling loop** designed for the 312kW system. The cooling system is designed to be passive (i.e. operated without additional fan) and uses air-to-air heat exchangers. A single-stage radial compressor from automotive applications is proposed since currently available two stage compressors are not capable of providing the required mass flow.

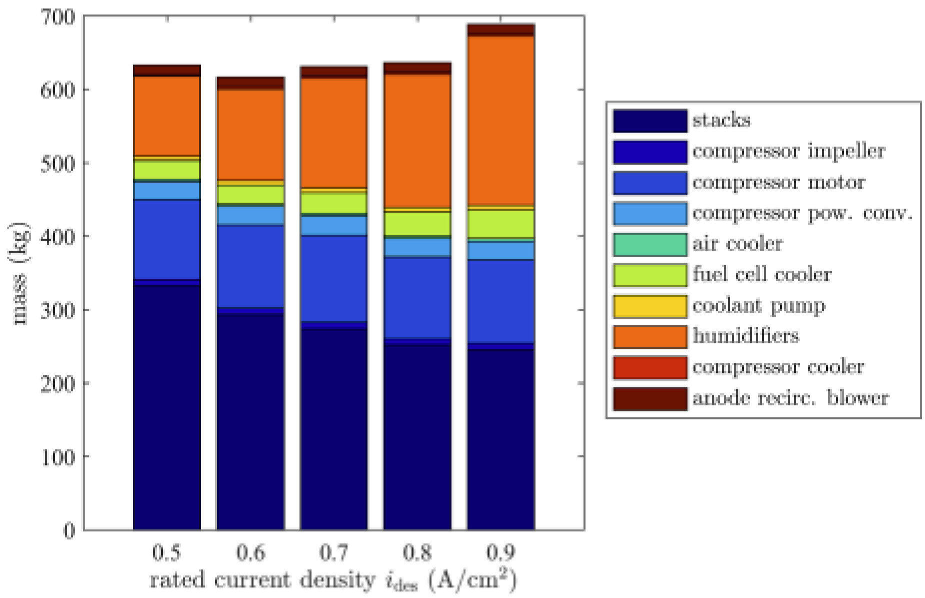


Figure 11. Effect of current density on overall system mass from [13].

On top of the architecture, the paper also investigated the effect of fuel cell operation on the overall FCS mass. This was done by simulating the performance of the FCS at different current densities. The simulation study showed that while high current densities result in decreased stack mass it is not beneficial in terms of overall system mass when stacks operate at current densities above 0.6 A/cm^2 (for the chosen scenario) as seen in Figure 11. The positive effect of the **reduced stack mass was diminished by an increased mass of BoP components** due to lower efficiency of the stack at high current densities.

3 Analysis of identified gaps and challenges

This chapter provides an overview of the requirements for high-power fuel cell systems, drawing both from the Strategic Research and Innovation Agenda (SRIA) [14] and from project-specific definitions. It then summarises the main parameters of current state-of-the-art system architectures, which serve as a benchmark for comparison.

On this basis, the chapter outlines and analyses the gaps and challenges that have been identified in relation to existing designs. The purpose of this analysis is to establish a clear point of reference for the project's subsequent activities, particularly those aimed at simplifying fuel cell system architectures. The ultimate goal is to support the development of solutions that reduce system complexity and cost, while improving efficiency and gravimetric power density, thereby enabling scalable and competitive high-power PEMFC systems.

3.1 Performance targets

Table 5. Clean Hydrogen JU SRIA targets [14].

	SRIA reference	SRIA KPIs (parameter)	Unit	SoA (2020)	Target 2024	Target 2030	H_2UpScale project KPI (target)
1	Pillar Hydrogen end use: transport applications/ KPIs for Maritime	FC power rating	MW	0.5	3	10	6
2	Pillar Hydrogen end use: transport applications/ KPIs for Maritime	Maritime FCS lifetime	h	20,000	40,000	80,000	>25,000 ("BoP component durability for HD vehicles and aircraft or 60,000 hours for ships")
3	Pillar Hydrogen end use: transport applications/ KPIs for Maritime	PEMFC system CAPEX	EUR/kW	2,000	1,500	1,000	1,300
4	Pillar Hydrogen end use: transport applications/ KPIs for Aviation	FC module durability	h	15,000	20,000	30,000	>25,000 ("BoP component durability for HD vehicles and aircraft or 60,000 hours for ships")
5	Pillar Hydrogen end use: transport applications/ KPIs for Aviation	FC system efficiency	%	43.5	45	50	FC system electric efficiency >50% (incl. a 5% improvement in cold weather scenarios compared to State-of-the-Art 200 kW PEMFCs)
6	Pillar Hydrogen end use: transport applications/ KPIs for Aviation	FC system gravimetric index	kW/kg	0.75	1	2	>2 kW/kg for aviation applications and >1.5 kW/kg for maritime and on-road heavy-duty trucks

In addition to these directly quantifiable targets, other principles guiding architecture design include:

- Simplification of the FC system design (in particular for heavy-duty applications) in order to reduce the number of parts and foster the emergence of standard components, interfaces and system configurations hence improving their manufacturability;

- Achieving BoP components which can be coupled to HD fuel cell stacks or to multiple stacks;
- Durability of up scaled BoP components meet the requirements of application relevant load cycles;
- Contributing to reducing cost for reaching targets expected in 2030 in line with SRIA (Table 5). Impact of manufacturing aspects shall be considered for scaled-up BoP components (techno-economic aspects will be analysed in WPs 4 and 8).

Table 6. Identified high-power state-of-the-art FCS with reported power, efficiency and weight.

	Fuel Cell System	**Application**	**Power [kW]**	**Gravimetric density [kW/kg]**	**Peak Efficiency [%]**
1	PowerCell MS225	Maritime	225	0.184	54
2	Ballard FCmove	Automotive	120	0.48	60
3	Ballard FCwave	Maritime	200	0.2	53.5
4	HDF FC 1500	Maritime	1500	0.21	49
5	HDF FC 1500	Stationary	1500	0.055	49
6	Plug Power	Stationary	1000	0.014[#]	*Not specified*
7	ZeroAvia ZA600[*]	Aviation	200	1.4	55-60
8	ZeroAvia SuperStack Flex	Aviation	150	0.88	*Not specified*

[#] includes weight of container

[*] all parameters reported at stack level

Table 6 shows the state-of-the-art of current FC installations for various high power applications. The primary requirements for these applications in the H_2UpScale project are listed in the public project deliverable **D2.1 “Application-specific requirements”** [15], and are evoked below.

Gravimetric power density requirement

- For **truck and maritime** application the **minimum** required power density is **0.89 kW/kg** and the **ideal** is **1.5kW/kg**.
- For **aviation** application the **minimum** required power density is **0.89 kW/kg** and the **ideal** is **2 kW/kg**.

Comparing the values listed in Table 6 to the minimum requirement from D2.1, the truck and maritime systems the values reported are far off the minimum requirement while the aviation grade system is close to the minimum requirement. Further gains are expected for all systems through material improvement and improved packaging at the stack and system level.

Efficiency at cruise power

- **55%** efficiency for **truck** application **at ~51% load**
- **55%** efficiency for **aviation** application **at ~90% load**
- **50%** efficiency for **maritime** application **at ~82%-90% load**

The efficiency reported in Table 6 are typically achieved between 20-30% load. Further gains are expected through material improvements and optimisation of BoP layout.

3.2 Identified gaps and challenges and relevant observations

In the reviewed literature and identified state-of-the-art high-power systems, air and hydrogen management approaches vary from fully centralised supply systems to distributed loops, with necessary trade-offs between complexity, controllability, fault tolerance, cost, weight and volume. Peak electrical power demand and overall energy consumption of the auxiliary devices are strongly influenced by the relative size of the stacks in the multi stack setup and the control strategy. Overall, design choices are often guided less by vast differences in performance, but more from economic, packaging, and operational considerations.
While the individual FC stack power is pre-determined as specified in WP2 of the H2UpScale project, a very relevant factor to consider is the stack design working point, compared to its nominal power. As was presented in the literature review in 2.5.5 and 2.5.6, it is advantageous to increase the number of stacks so that the entire FC system operates below its nominal power rating, even under on-design conditions, as this improves overall stack efficiency and reduces the requirements for the BoP components.

Hydrogen supply and recirculation path

- Passive recirculation concepts such as dead-end anode operation can simplify design and reduce weight, but introduces degradation challenges due to lower controllability;
- Additionally, passive recirculation was seen to not be compatible with liquid hydrogen feed systems;
- Usage of a HRB and hydrogen ejector can result in more consistent gas flow velocity and reduced parasitic losses thereby improving efficiency though recirculation pump power remains a consideration;
- Integrated hydrogen supply subsystem (one supply and recirculation subsystem + buffers for multiple stacks) improves hydrogen utilization and reduces parasitic power.

Air supply and exhaust path

- Compressor power remains a serious consideration;
- In one case, power consumption differences have not been noticed for various compressor setups (for the same system) – one large, two medium compressors in parallel or three smaller compressors in parallel. The choice of number of compressors might be driven by other considerations, such as required control accuracy, economic and packaging constraints;
- A centralised air supply system (e.g. common rail buffer for a FC system with multiple stacks) system in tandem with an optimised buffer and buffer operating pressures can cut energy use by up to 20%, but results in a higher volume requirement;
- Oxygen concentration measurement using observer-based methods can reduce reliance on airflow sensors and lower parasitic losses.

Water and thermal management

- Eliminating components like humidifiers reduces complexity at the cost of high-temperature performance;
- Especially for high-power dynamic applications, active water management is generally preferred for its robustness – further integration and optimization are needed to balance efficiency, responsiveness, and subsystem redundancy;
- Integrated thermal subsystem (one set of BoP equipment for multiple stacks) and a distributed one (one set of BoP equipment for each individual stack), are comparable in terms of performance, but the former is structurally much simpler. Additionally, a closer coupling between coolant pipelines of different stacks helps in sharing heat more effectively during low temperature operation;
- Innovations in cooling (e.g. 2-phase cooling) can offer significant weight reduction, but introduce challenges depending on the nature and properties of the coolant used (e.g. methanol handling).

4 Definition of system architecture blueprints

This chapter presents the preliminary system architecture blueprints developed within the project (Table 7). These suggested architectures are grounded in insights from the literature review as well as the challenges and gap analysis, and the rationale behind the proposed configurations is discussed. That said, this is a starting point for the follow-up activities to build up upon and further investigate, which might result in blueprint changes as project development bring new insights.

The architectures are based on the assumption of a multi-stack fuel cell system with symmetric stack powers. Other configurations could potentially be explored via simulation to explore their benefits.

Within this framework, two principal degrees of freedom exist for up-scaling:

- Increasing the size of individual components, or
- Increasing the number of components (e.g. several smaller heat exchangers versus one large unit).

Identifying the optimal balance between these two approaches is essential, as each brings its own trade-offs in terms of performance, cost, footprint/mass, and redundancy requirements.

Table 7. Number of BoP components per each power node.

Component List	350 kW	700 kW (#1)	700 kW (#2)	1050 kW (Maritime)	1050kW (#1)	1050 kW (Aviation)
Fuel Cell Stacks*	2	4	4	6	6	6
H2 Ejector	1	2	2	3	3	3
H2 Recirculation Blower	1	2	1	3	2	3
H2 Heat Exchanger	N/A	N/A	N/A	N/A	N/A	1
H2 Purge Valve	1	2	2	3	3	3
H2 buffer & common rail	N/A	N/A	1	N/A	1	N/A
Air Filter	1	2	1	3	1	3
Compressor	1	2	1	3	2	3
Turbine	0	2	1	3	2	0
Humidifier	1	2	1-2	3	2	3
Charge Air Cooler	1	2	1	3	2	3
Water Separator	1	2	1	3	2	3
Resonator	1	2	1	3	2	3
Air buffer & common rail	N/A	N/A	1	N/A	1	N/A
Radiator	2-4	N/A	N/A	N/A	N/A	1
Coolant Pump	1	2	2	2	2	3
Cooling Fan	4-6	N/A	N/A	N/A	N/A	1

* - *assuming symmetric stacks of 175 kW electric net power output at End-of-Life (EoL)*

General discussion about blueprints per power node:

- 350kW blueprint – The 2 stacks are assumed to be housed together in one box of 350kW with internal division for the anode and cathode paths. With this base definition, the blueprint is defined to have 1 of each component for the air and hydrogen path. While the turbine would help with energy recovery and therefore boost system efficiency, the integration space and gravimetric power density requirement of a truck application do not favour the addition of a turbine. For the cooling system, a range of multi fan integrated units are available, so a range on the number of radiators is considered.
- 700kW blueprint #1 – This system intended for maritime applications is chosen to represent 2x the 350kW system with the addition of turbines to the air path for energy recuperation. Additionally, due to the requirement of using water-to-water cooling, the system does not require a cooling fan but instead needs an additional pump for the secondary coolant loop.
- 700kW blueprint #2 – An alternative blueprint is prepared for the 700kW system using common rails for the air path and hydrogen paths. Using a common rail and buffer would allow for single large components to be used. A range is provided for the number of humidifiers to account for the possibility of buffering air either before or after the humidifier.
- 1050kW maritime – The 1050kW system for maritime applications uses the 350kW as a base and scales linearly.
- 1050kW blueprint #1 – The alternative 1050kW blueprint utilizes the same principles as the 700kW blueprint #2 in terms of using air and hydrogen buffers and common rails. Owing to the higher overall power, the number for each BoP component is specified as two. This allows for the possibility to have a high power (flow) compressor and a low power (flow) compressor to cover a larger portion of the operation area more efficiently.
- 1050kW aviation – The 1050kW system for aviation differs from the maritime system in not having a turbine (space constraints), using hydrogen heater (feed hydrogen being liquid instead of compressed) and requiring a cooling system for air-to-air cooling.

BoP component specific discussion:

- Compressor for 1050 kW (Aviation):
    - 3 compressors expected enough for sea-level ambient air pressure, but 3 units might be insufficient for ambient pressures at cruising altitude
    - For aviation, multi-staged compressors discarded by Schroeder et al. due to not being able to provide required mass flow at cruising altitude
- Turbine in aviation and truck blueprints:
    - As was commented in the general discussion section, adding the turbine decreases the system gravimetric power density (not a standard BoP component for state-of-the-art FC systems)
    - 50% efficiency at 80% load for maritime; compared to state-of-the-art adding a turbine could recuperate enough energy to improve system efficiency plus space is not an issue for maritime.
- H_2 heat exchanger
    - Assumed 1 needed for aviation due to H_2 storage in liquid form
- Cooling systems
    - Observation on number of components vs. size scaling: 2x 6 fans or 3x 4 fans or 1x 9 fans – all these options are available in market today
    - Terminology: a multi-fan unit (e.g. 4 fans) considered as 1 cooling fan or still multiple fans?
    - 1 pump for truck application based on current flow rate in trucks

- Cooling medium on the application side is a critical factor in component number count (truck liquid-to-air; maritime liquid-to-liquid; aviation liquid-to-air or air-to-air)
- Cooling fan probably not needed for maritime (additional pump necessary)

5 Conclusions

This deliverable has provided a structured overview of the state-of-the-art in high-power PEMFC installation designs and assessed them against both project-specific requirements (WP2) and the SRIA targets. Building on a challenges and gap analysis, a set of preliminary system architecture blueprints has been proposed for three representative power nodes: 350 kW, 700 kW, and 1050 kW. These blueprints are aimed at reflecting different strategies for addressing the trade-offs between increasing component size versus increasing component number, while evaluating implications on criteria such as performance, cost, footprint/mass, and redundancy, and form a conceptual foundation for the next modelling and optimisation activities of WP3.

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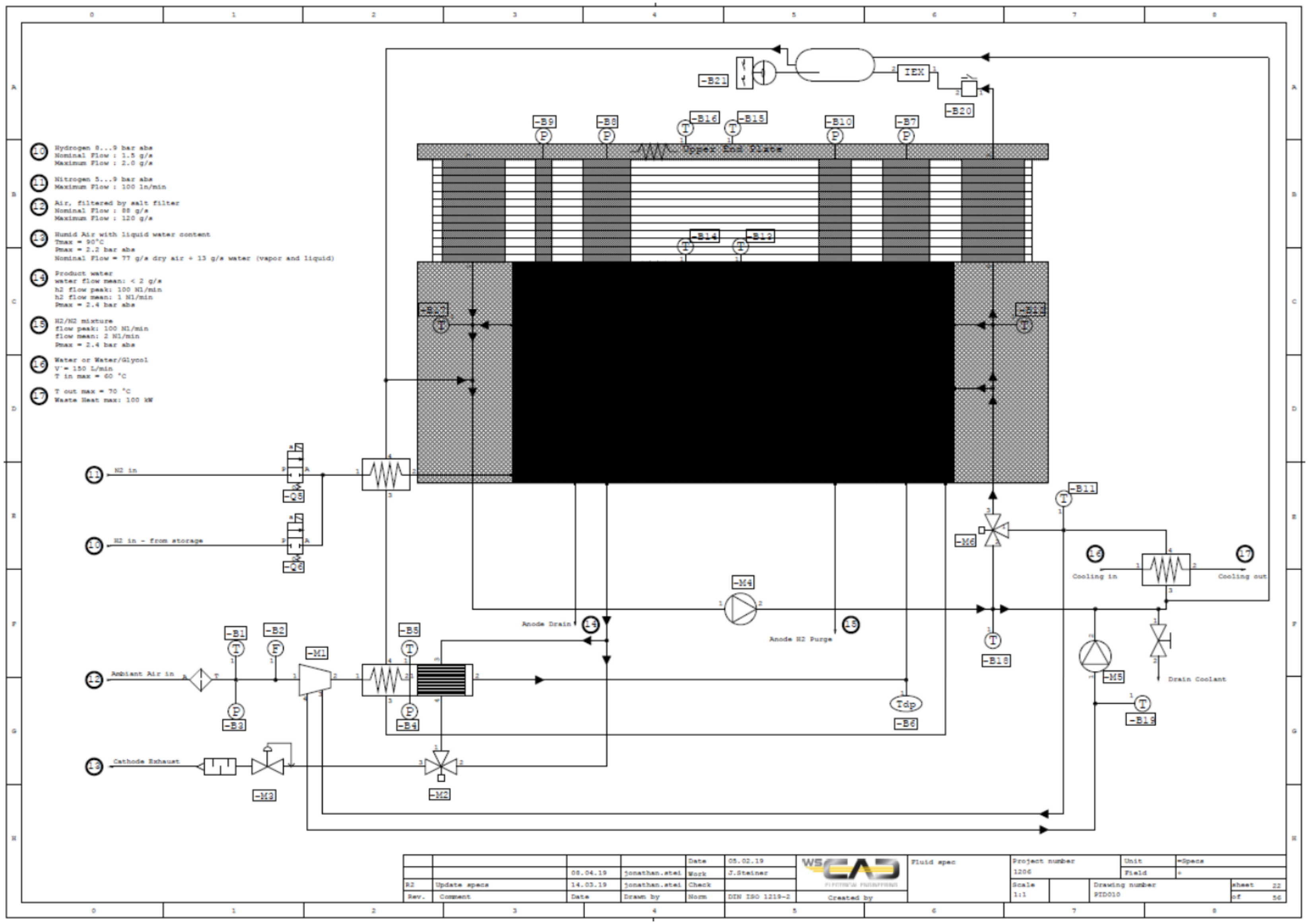
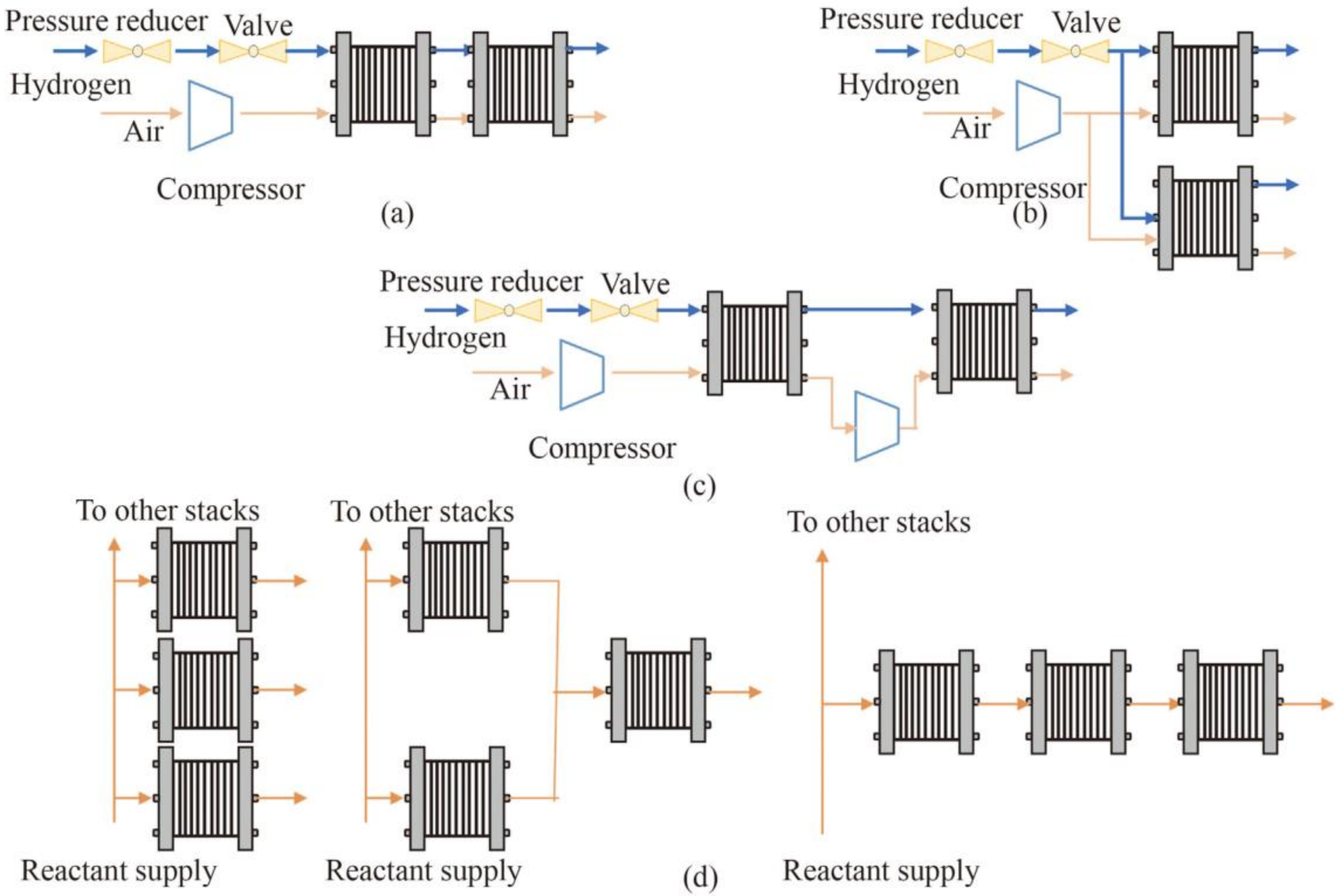
Annex A: Summary of high-power installation State-of-the-Art

Source	Concept	Application domain	Advantages/benefits	Disadvantages/drawbacks	Other comments	Reference
EU Maranda	2x 96,9 kW single stack, single stage compressor instead of compressor/expander	Maritime & stationary adapted from automotive	Use of twin independent systems offers improved redundancy	More complex system due to an increased number of components	No compressor/expander because of challenges with water management and start-up from/at freezing conditions	[1] [2]
EU BRAVA	Multi-MW system	Aviation	Weight reduction (no hydrogen recirculation and humidifier), usage of waste heat for heat up of fuel (two-phase cooling system)	Loss of performance, higher degradation, large accumulator for cooling system	Non accumulator solution being investigated further	[3] [4] [5]
EU NEWBORN	1 MW system with 3 stack, centralised air supply unit with dedicated recirculation loop	Aviation	Modular solution integrated into aircraft envelope	Increase in dead volume	Reduction of volume through integration of stacks into 1 housing	[6]
EU GRASSHOPPER	100kW demo plant (multi-stack system)	Stationary	Single air and hydrogen loop for all stacks.		Single DC/DC converter dedicated air and hydrogen humidifier	[7]
Gao et al.	210 kW system using 3 stacks with distributed powers (20, 70, 120 kW) with common rail buffer for hydrogen and air supply paths	None specified	Stabilizes inlet pressures, buffers and isolates stack demands, stores supplement reactant for periods of supply shortage or highly variable and peak loads	More complex system due to an increased number of components, more voluminous system due to the use of buffers	Integrated thermal subsystem and a distributed one are comparable in terms of performance, with the former being structurally much simpler	[10]
Massaro et al.	3,7 MW with multiple stacks and LH2 storage (sizing simulation)	Aviation	Oversizing stacks compared to their design operating point and increasing the stack count can lead to reducing overall system weight	More complex system due to an increased number of components	Careful trade-off optimization is needed to balance performance gains with weight constraints.	[11]
Zhou et al.	Multi stack system for different power levels (140, 210, 280kW) with buffer	Automotive	Single air supply subsystem with buffer. Reduction in peak auxiliary power and/or energy consumption	More voluminous system due to the use of buffers	Multi stack system with one small stack and one large stack shows benefit compared to two identical stacks	[12]
Schröder et al.	10x 312kW multi-stack, single stage compressor, integrated air supply and cooling system	Aviation (compressor from automotive)	Modular system with increased redundancy (multiple stacks and systems), weight reduction through use of air-to-air HEX	Added weight and volume due to number of stacks		[13]

Annex B: P&ID – EU Maranda SHA-100-E

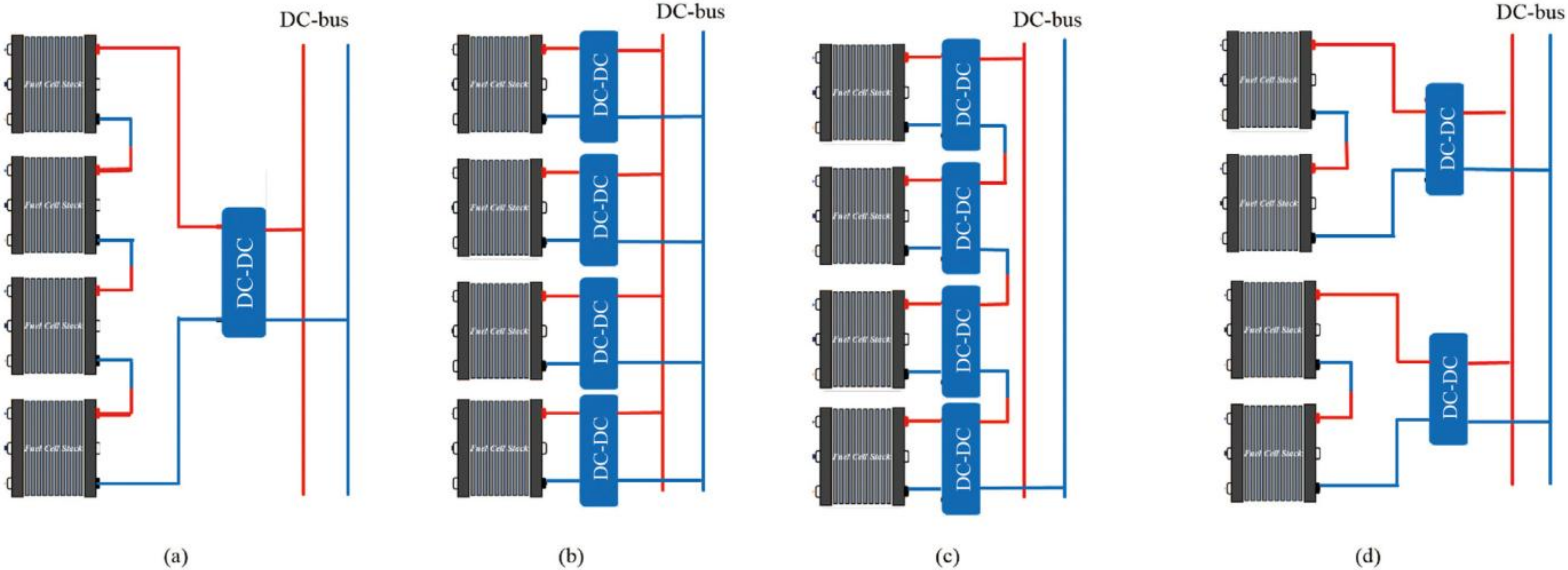


Annex C: Hydrogen and air supply architectures



(a) Series fluid (it could provide reactants from stack 1 to stack 2). (b) Parallel fluid (it provides reactants to each stack simultaneously). (c) Independent air-compressor based on series fluid. (d) Hydrogen and air supply architectures for three or more stacks [9].

Annex D: Electrical architectures of MFCS and DC/DC converters



(a) Series. (b) Parallel. (c) Series-Parallel. (d) Cascaded DC-DC architectures [9].