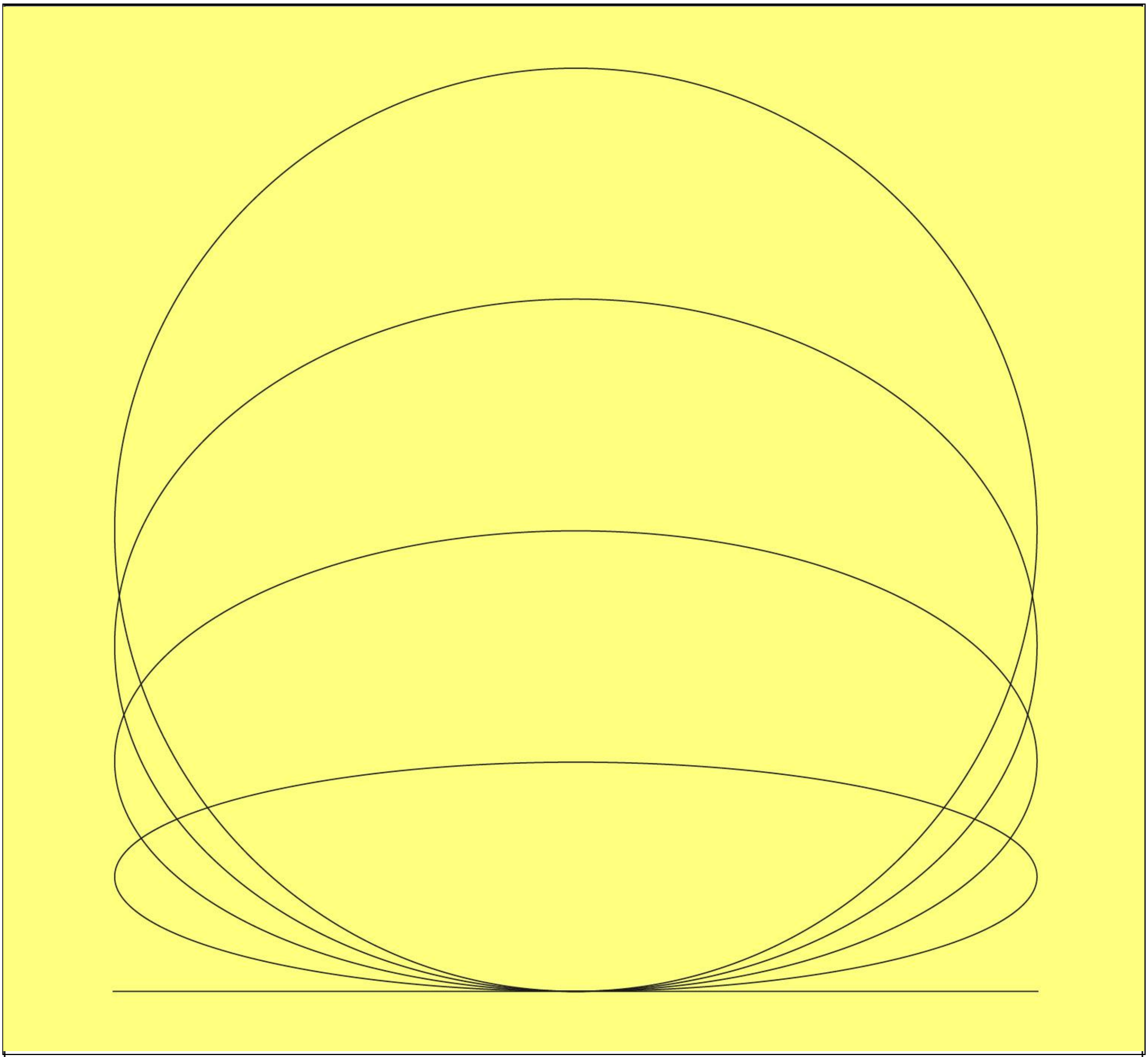

Technical Report – Deliverable 5.1

Define FC System and HRP, ejector, sensor Requirements

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HORIZON-JTI-CLEANH2-2024-03-02

H2UpScale

Clean Hydrogen Partnership

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Dissemination Level (Security)

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Table of Contents

1 Acronyms

BoP – Balance of Plant
FC – Fuel Cell
HRP – Hydrogen Recirculation Pump
PEMFC – Proton exchange membrane fuel cell
PCV – Proportional Control Valve
WP5 – Work Package 5
WP2 – Work Package 2

2 Summary

This report details the requirements for the fuel cell hydrogen loop, based on the FC stack and application requirements. Due to the complexity of hydrogen loop flow dynamics, an in-depth model would be required to accurately define specific operating conditions. Various assumptions have therefore been made to allow for the initial requirement definition for the key hydrogen recirculation components, and these assumptions are called out where relevant.

The focus for H2UpScale WP5 is the hydrogen recirculation components and the hydrogen leakage sensor capability. Components which focus on fresh fuel delivery, prior to the recirculation loop, are out of scope and are not intended for design optimization and upscaling. The same is assumed for the water separator and purge valve as they are also not within scope for design optimization and scaling. It is important to note that this scope allows a demonstration of scaled recirculation and leakage components but limits the amount of system optimisation that can occur. From a system perspective, changes to fresh fuel delivery, purge scheme or water separation will change the recirculation requirements.

The report first gives an overview of WP5 objectives and then leads to a literature review for recirculation components. The requirements translation section is then given, explaining the requirements translation approach, assumptions where needed and then individual recirculation component requirements. Finally, an overview is given of the technical scoping which has been conducted for WP5 task 5.2.

To support the system requirements from WP2 for a 350kW net power node, the hydrogen recirculation loop will need an ejector capable of delivering 29.15g/s total recirculated flow, with a total entrainment ratio of 3.93 (H_2 entrainment ratio of 0.67) at the stack peak power condition. Whilst the ejector needs to meet recirculation requirements at peak power, the design optimization should be focused at a mid-to-low power condition to extend the operating window. The loop also requires a hydrogen recirculation pump capable of supporting the recirculation pressure rise where the ejector is not capable in the lower 30% of the operating range. A motor power of 2.4kW is recommended to support pressure rises of up to 15kPa.

3 Introduction & Objectives

3.1 Hydrogen Recirculation

Hydrogen recirculation in proton exchange membrane fuel cell (PEMFC) systems is key to increasing system efficiency and reducing hydrogen waste. As PEMFC technologies continue to advance, hydrogen recirculation capability will need to scale alongside it to ensure the technology is sustainable, efficient and cost effective.

PEMFCs typically operate with excess levels of hydrogen where more hydrogen is supplied to the cell than is needed for a given operating condition. This helps to prevent anode starvation which can damage the cell, ensures performance consistency and aids with water management [1]. This practice benefits the fuel cell performance but means hydrogen is not fully consumed at the anode and leads to some waste hydrogen leaving the system. This hydrogen can be released to the atmosphere using a dead-end anode architecture or can utilize hydrogen recirculation to prevent hydrogen waste. Hydrogen recirculation re-directs wasted hydrogen from the anode outlet back into the anode inlet, using recirculating components to aid mixing with fresh supplied hydrogen and increase flow pressure. The benefits of hydrogen recirculation include avoiding excessive hydrogen waste to the environment and improving fuel economy, but comes with the trade-off of increased BoP complexity, packaging constraints and material cost.

There are multiple methods to effectively recirculate hydrogen but two of the most common methods consist of hydrogen ejectors and/or hydrogen recirculation pumps (HRPs). There are variations on component and sub-system H2 loop architecture, and there are studies within the industry which assess the trade-offs between these options, considering factors such as efficiency, range of operation and cost [2] [3].

3.2 Task 5.1 Objective

H2UpScale scope considers multiple different power nodes for fuel cell systems, considering 350kW, 700kW and 1050kW net power nodes, which would all require a scaled balance of plant (BoP) to support the system requirements. WP5 prioritizes the 350kW node requirements, where 700kW and 1050kW nodes can then utilize multiples of the 350kW BoP as needed.

The objective of this task was to define the sub-system level requirements by translating the application and system level requirements from WP2. The key elements to this include the HRP, ejector and leakage sensor requirements to allow component design and optimization as needed. Other elements in this work include defining hydrogen loop architecture and outlining a number of trade-off architecture studies to be conducted in task 5.2.

Initial architecture assumptions were made to enable up-front requirements to be determined for the HRP and ejector. As the architecture studies mature, during task 5.2, these assumptions will be revisited and refined. It was assumed that the hydrogen loop would follow a hybrid architecture, combining HRP and ejector in series, and that the HRP would operate where the ejector was not sufficient alone to drive the recirculation requirement for the FC system.

4 Literature Review of Hydrogen Recirculation Components

A literature review was conducted to provide further understanding and awareness of hydrogen recirculation components and architectures. Various studies were assessed, and the learnings were used to guide architecture decisions for trade-off studies to be conducted in task 5.2.

4.1 Literature Review – Ejector Architectures

Hydrogen ejectors are a frequently mentioned component in FC system literature due to their ability to entrain recirculated hydrogen and mix with fresh hydrogen to meet stack anode requirements. A basic, conventional ejector, otherwise called a passive ejector is a useful component due to its simple design, lack of parasitic load, ease of manufacture and, therefore, low cost [4].

A generic passive ejector is shown in Figure 1. The primary flow is high pressure fresh hydrogen which passes through the primary nozzle and creates a local pressure drop as its velocity increases. The secondary flow is the unused hydrogen from the anode, which flows into the low pressure region in the suction chamber, and mixes with the primary flow. This mixing can be very efficient due to the shearing effect, where the two gases are moving with different velocities, promoting turbulence and momentum transfer [3] [5]. The mixed flow pressure then increases as the gas slows in the diffuser section of the ejector approaching the outlet.

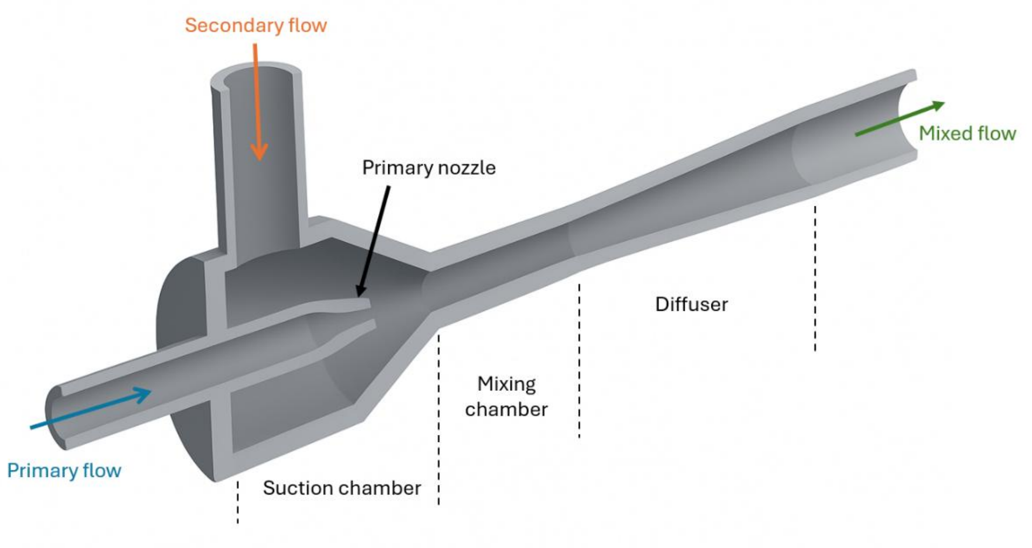


Figure 1: Generic passive ejector architecture, where secondary flow is entrained by primary flow to allow for passive hydrogen recirculation in FC systems.

Although passive ejectors offer a benefit in that they are static components with no parasitic load, the same characteristic also limits their usefulness because they cannot meet a wide operating range. Passive ejectors are typically designed for higher stack power conditions thus they will most effectively entrain secondary flow at that condition. The ejector performance will decrease as primary mass flow decreases and will stop entraining once some threshold condition is reached, dependent on the ejector design [4]. This characteristic of passive ejectors has prompted research into different ejector architectures in attempt to improve entrainment ratio across a wide operating range.

One study evaluates this research in depth in a large-scale literature review [3]. The study presents a comprehensive review of passive ejectors versus double ejectors, bypass ejectors, pulsed ejectors, multi-nozzle ejectors and variable geometry ejectors, focusing mostly on the technical development of each, rather than including cost and manufacturability as a key metric. Most of the ejector variations include some level of geometry variation depending on operating point. For example, the double ejector implements two passive ejectors in the same system, both optimized for different conditions and utilizing a solenoid valve to switch between the two ejector paths [6]. An alternative, the multi-nozzle or nested nozzle ejector adds an element of flexibility by using two inlets for secondary flow, allowing the operating load to determine which inlet is used hence which nozzle geometry is activated [7]. The variable geometry ejector operates with the same principle, by varying nozzle or throat geometry depending on load, however, the variable geometry ejector includes moving parts which adds design complexity where the multi-nozzle ejector is a fixed geometry but with the use of solenoid valves to control inlet flow and prevent back flow [3] [8]. The pulsed ejector design operates on a different principle, instead using pulsed primary flow to promote vortex formation and turbulence to improve mixing and entrainment at lower power operating points, whilst a continuous flow mode, similar to a standard, passive ejector, meets the recirculation requirement for the mid-high power operating points [9]. Finally, the secondary bypass ejector is reviewed which has been designed to include a bypass valve to introduce secondary flow further downstream in the ejector to recover momentum at high primary pressure (high power operating conditions) where energy losses within the ejector are the largest [10].

These ejector architectures factor into the selection of architectures for further study in task 5.2 and highlight the variability of research in this area, where ejectors are still relatively new for hydrogen applications compared to well established industries such as refrigeration and chemical engineering. Further scoping of ejector architectures for simulation is given in section Hydrogen Loop Architecture Selection6.

4.2 Literature Review – Hydrogen Recirculation Pump

Hydrogen recirculation pump (otherwise referred to as a hydrogen recirculation blower) is a sub-system component which requires a motor to drive some mechanical components to do work on and increase the pressure of wasted hydrogen from the anode outlet. HRPs can be used alone in the H2 recirculation loop, or in combination with a hydrogen ejector.

There are many types of HRPs available and under research for PEMFC systems, including but not limited to: claw, scroll, roots, regenerative (also known as side-channel) and centrifugal pump designs. The references cited in this section contain visual representations of the discussed HRP designs, which cannot be presented in this paper due to copyright rules. It is recommended to visit the mentioned sources directly for further understanding and visualization of the technologies discussed in the following paragraphs.

The claw pump design uses two claw shaped rotors to first create a vacuum to pull hydrogen into the flow domain, then drive the gas into a smaller volume which compresses the gas before it is directed through the outlet [11]. A claw pump design relies on precision machining for precise clearance control to improve performance [12]. A scroll pump also uses decreasing flow volume to compress the gas but instead using an orbiting scroll against a fixed scroll to vary the chamber volume. The roots pump operates similarly by volume displacement but doesn't utilize the same volume compression method as the claw and scroll [2].

The above mentioned are all examples of volumetric compressors, whereas the side channel and centrifugal pump designs are examples of rotary-vaned compressors and involve a rotating impeller. With any rotating impeller design, the generic function will be to transfer kinetic energy to the gas, to then be converted to pressure energy though the static pump geometry. As gas flows into a side-channel compressor, it flows in a spiral pattern between the impeller vanes as the impeller rotates and the gas pressure gradually increases [4]. One of the key benefits of a side-channel design is that it can provide higher pressure increase at low flow conditions, relative to other pump designs [13]. A centrifugal compressor is another design with a rotating impeller and involves a diffuser region where the gas pressure increases. Although more efficient, centrifugal compressors typically operate at higher speeds for a given output power in comparison to side-channel compressors, which increases complexity and cost.

Each pump design has trade-offs between noise, manufacturability, cost, efficiency, durability and electrical power consumption [2, 4] . This project will use a side-channel pump for design and optimization due to the baseline pump already available within Cummins Ltd, but this literature review gives an overview of the HRP architectures available and can be used for future research and PEMFC systems.

5 Requirements Translation

This section details the translated sub-system requirements for the hydrogen loop components, using the application and stack requirements provided through WP2. The requirements translation has been conducted using the end-of-life stack data.

5.1 Baseline architecture for requirements translation

To allow for requirements translation, it was assumed that an ejector and HRP hybrid architecture may be needed for this FC system, given in Figure 2. In reality, and as will be explored in task 5.2, an ejector only architecture may be adequate for the system requirements. A baseline hybrid architecture for task 5.1 gives the starting point for component design and optimization for both ejector and HRP, which is conducted in parallel with architecture studies and optimization.

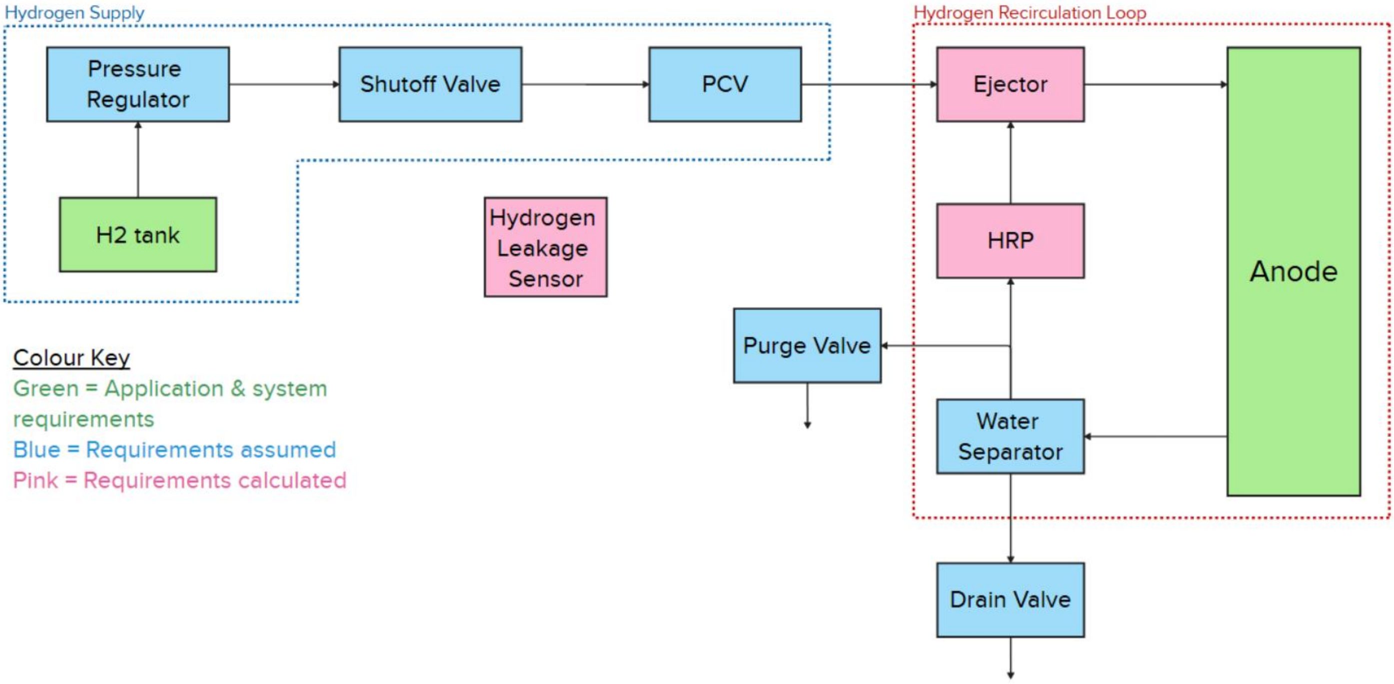


Figure 2: Baseline hydrogen loop architecture for requirements translation. Components are colour coded to demonstrate what requirements have been dictated by the application/system, assumed or calculated.

Data for the assumed components was taken from literature and/or current product knowledge because they are not in scope in WP5 for further component design and optimisation.

Component Definitions:

1. **Anode** – The electrode in a fuel cell where oxidation occurs (loss of electrons).
2. **H2 Tank** – A storage container for high pressure hydrogen fuel.
3. **Pressure Regulator** – A pressure reduction device using mechanical spring-loaded valves to lower hydrogen fuel to a more appropriate pressure for FC use.
4. **Shut-off Valve** – A solenoid valve for electronically controlled fuel supply shut-off.
5. **Proportional Control Valve (PCV)** – A solenoid valve to regulate mass flow per operating point, electronically controlled by FC system.
6. **Ejector** – A static hydrogen recirculation device using the venturi effect to promote mixing of fresh and recirculated hydrogen.
7. **Hydrogen Recirculation Pump (HRP)** – A mechanical pump to increase the pressure of hydrogen from the anode outlet before being re-directed back to the anode inlet.
8. **Water Separator** – A device to remove liquid water from hydrogen loop, to prevent damage to components or anode flooding.
9. **Purge Valve –** A solenoid valve for electronically controlled purging of gas from the hydrogen loop when increased levels of water vapour and nitrogen degrade the fuel cell performance below a certain threshold (determined by the system).
10. **Drain Valve** – A solenoid valve for electronically controlled purging of liquid water from the water separator.

Within the hydrogen recirculation loop itself, the balance of ejector vs pump must be approximated before requirements translation. An understanding of pressure variation within the recirculation loop is also needed to correctly scope the assumed and calculated component requirements. Figure 3 gives a conceptual breakdown of the pressure variation across each component in the loop. As the figure shows, the anode only makes up a small proportion of the total pressure drop, with the water separator, fuel mixing and pipework making up the remaining pressure drop. A recirculation device (or combination) must therefore be able to recover this total pressure drop.

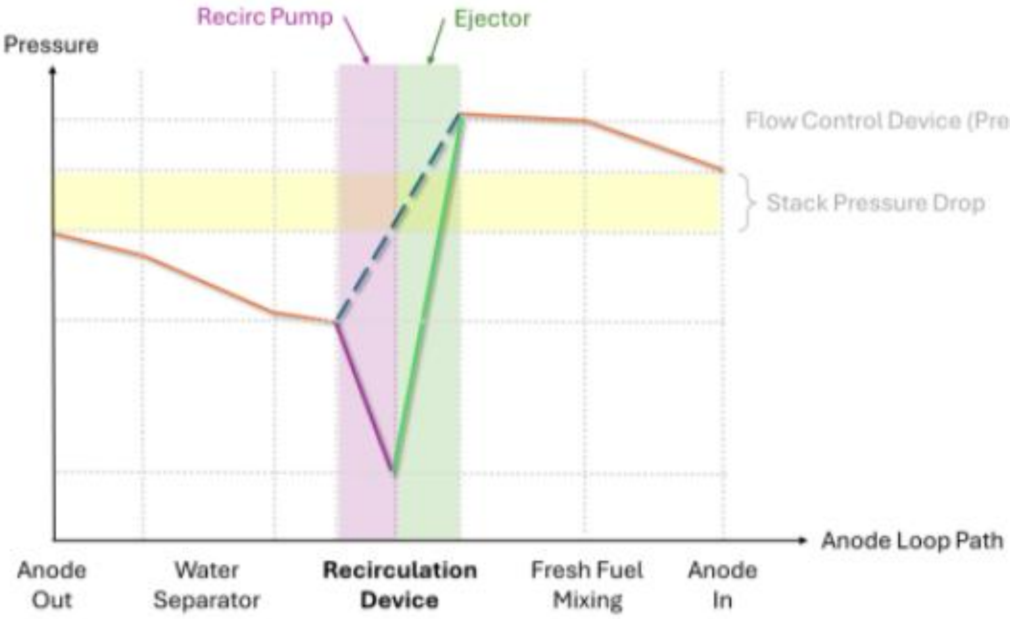


Figure 3: Pressure variation within the hydrogen recirculation loop, for an ejector/HRP hybrid architecture.

Figure 3 represents two cases in the hydrogen loop. The first is when the HRP and ejector are operating together, the blue dashed line represents the pressure increase that is needed from the combination. The second is when the HRP isn't operating so causes a restrictive pressure drop (the purple line) and the ejector must compensate for this in addition to the baseline pressure requirement (the green line). As is shown in Figure 3, the restrictive pressure drop can be significant compared to the other elements of the hydrogen path, however, it will depend heavily on the HRP design.

5.2 Assumed Hydrogen Supply Component Requirements

The key output from task 5.1 is to define the hydrogen loop components and the requirements for the HRP, ejector and leakage sensor. The scope does not include development and optimization of all other hydrogen loop components (blue components as highlighted in Figure 2) because these existing technologies are more readily scalable for higher power PEMFC systems. This section, therefore, details the assumptions that have been made on these components to ensure adequate boundary conditions are available for the ejector and HRP requirements calculations, and to ensure that a realistic hydrogen path BoP is considered. All assumptions have been made from Cummins' experience within the industry on PEMFC systems.

The pressure regulator, shut-off valve and PCV have been classed as the hydrogen supply components for the purposes of this report. These components are responsible for delivering an appropriate working pressure to the ejector, with a controlled hydrogen fuel mass flow as per the stack requirements.

Pressure regulators for fuel cell systems are typically two-stage to allow for more precise and reliable pressure reductions from the hydrogen fuel tank. Hydrogen fuel is stored at very high pressures, in this instance up to 750bar, whilst fuel cell operation is within the range of 1-3bar, so a large pressure reduction is essential for fuel cell operation. The pressure regulator is also intended to maintain output pressure at a constant level as the hydrogen fuel tank depletes. The PCV controls the mass flow into the ejector, depending on the operating point for the FC stack. The PCV will have some pressure drop, which will vary depending on required mass flow and pressure further downstream.

Pressure and mass flow variation in the hydrogen loop is a complex model which is impacted by many factors like component and stack performance. It is therefore optimal for requirements translation to work 'backwards' from the anode, i.e. to define the ejector and pump performance first, and then to optimize the PCV and pressure regulator accordingly. For the purposes of this work, an assumption was made for the PCV outlet pressure based on engineering experience, to allow for the ejector requirements definition. This is presented alongside the recirculation component requirements in Section 5.3.

The water separator is designed to remove liquid water from the hydrogen loop to avoid anode flooding, damage to the recirculation components and improve cell performance [14] [15]. A pressure drop across the water separator is assumed to be 3~10kPa in this system, based on engineering experience, where the pressure drop increases proportional to mass flow.

The purge valve is required to purge the flow in the recirculation loop when the hydrogen concentration drops below a certain level, determined by the system controls. This is a difficult event to model, with the frequency and duration of purge being closely linked to system performance. An assumption has therefore been made about the overall mass flow loss due to purge of ~3%.

Pipework pressure losses should also be considered, although will be highly dependent on the system packaging, pipe size, length and roughness. For the purposes of this work, pressure loss has been approximated using a quadratically proportional relationship against mass flow rate, with a maximum pressure drop of 10kPa.

As was discussed in section 5.1, the HRP causes a restrictive pressure drop when it is not operating. The HRP restriction pressure for different flow conditions is difficult to estimate without modelling or test results and heavily depends on the HRP flow domain design. Therefore, an assumption has been made to align the HRP pressure drop to that shown in Figure 3. A pressure drop up to 20kPa has been assumed, varying proportionally to anode outlet mass flow. As the HRP design and hydrogen path modelling progress, the pressure restriction across the pump when it’s not operating should be considered more closely to ensure this is factored into the ejector design.

5.3 Hydrogen Recirculation Components Requirements

5.3.1 Balance of Ejector vs HRP

Some outline of where the ejector vs HRP will operate is needed before defining component requirements. Figure 4 shows the three main regions of operation that are expected for a hybrid recirculation loop. These regions are:

1. The pump is working alone to recirculate hydrogen. The ejector is not entraining secondary flow due to the low primary flow. Flow still passes through the ejector.
2. The pump is supporting the ejector. The ejector operates in the sub-critical mode where secondary flow is proportional to the primary flow.
3. The ejector is working alone. The ejector is operating in critical mode where the secondary flow rate is high and doesn’t see a lot of variation as the primary flow increases. Flow still passes through the pump and there is a restrictive pressure drop across the pump.

(Regions estimated from [4]).

The ejector should be optimized for the stack current density point 1.88A/cm^2 and is expected to operate alone at the mid-to-high stack power operating points. The ejector performance is expected to degrade as the primary mass flow reduces, and this is where the pump needs to support the ejector. At low flow conditions, the ejector will stop entraining secondary flow and the pump will be required to sustain recirculation alone.

It is important to note that this is the target usage for the ejector and HRP, to limit the use of the HRP as much as possible to reduce the parasitic load. The design phase for the ejector will determine if this is feasible for a larger power stack, and if not, the pump will need to support across a wider range. The ejector and HRP design teams will need to work together closely to determine if any changes need to be made to this proposal.

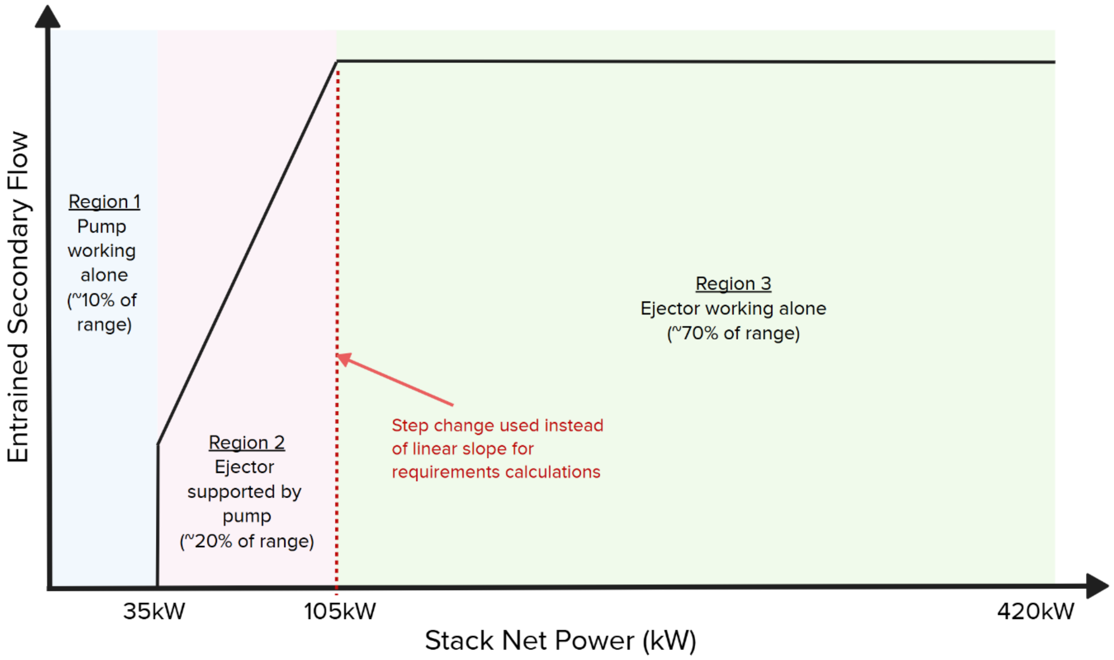


Figure 4: Entrained secondary flow through the ejector across stack operating range, indicating where the pump must support recirculation.

5.3.2 Ejector Requirements

Ejector requirements include:

- Primary mass flow rate
- Primary pressure range (same as PCV outlet pressure)
- Primary flow temperature
- Secondary flow pressure
- Secondary flow temperature
- Secondary composition (H2, N2, H20) (same as anode outlet composition)
- Outlet pressure
- Target secondary flow (both total and H2)
- Target entrainment ratio (both total and H2 only)
- Target design optimisation point

Assumptions:

- Pressure drop across water separator 3-10kPa
- Mass flow loss due to purge ~3% anode outlet flow
- Primary flow 100% hydrogen
- Purging only impacts mass flow, impact on gas composition is ignored for this work to simplify the ejector design
- Isothermal assumption so there is no condensation in the hydrogen loop
- HRP restriction pressure has been assumed 6-20kPa

Table 1 shows the calculated ejector requirements and highlights the expected operating range for the ejector to function without the HRP. At the lower operating conditions, it has been assumed that the HRP could provide a 15kPa pressure increase if needed, which has been considered in the secondary pressure requirement.

	Category	**Data**													
Stack Requirements (WP2)	Current Density	0.10	0.30	0.50	0.70	0.90	1.10	1.30	1.50	1.70	1.88	1.90	2.10	2.30	2.50
	Net Power (kW)	25.3	68.8	106.8	145.1	183.3	217.8	250.5	285.3	320.8	350.4	352.9	377.4	399.5	419.3
	Anode In Pressure (kPa)	130.00	140.00	150.00	170.00	190.00	200.00	210.00	240.00	260.00	280.00	280.00	280.00	280.00	280.00
	Anode Out Pressure (kPa)	129.28	137.80	146.37	165.73	185.39	195.00	204.31	234.20	253.90	273.79	273.72	272.95	272.16	271.34
	Anode In Mass Flow (g/s)	1.79	5.39	9.86	12.89	15.24	17.15	20.28	23.30	26.08	27.83	28.13	31.21	34.32	37.48
	Anode Out (g/s)	1.47	4.46	8.33	10.75	12.49	13.78	16.30	18.90	21.06	22.20	22.44	24.93	27.47	30.05
Application Requirements (WP2)	Hydrogen storage pressure (kPa)	75000.00													
	Hydrogen storage temperature minumum (℃)	-40													
	Hydrogen storage temperature maximum (℃)	85													
Assumed Requirements	Water Separator Pressure Drop (kPa)	3.4	4.1	5.0	5.6	6.0	6.3	6.9	7.5	8.1	8.3	8.4	9.0	9.6	10.2
	HRP pressure drop (HRP not in operation) (kPa)				11.2	12.0	12.6	13.8	15.1	16.1	16.7	16.8	18.0	19.2	20.4
	PCV outlet pressure minimum (ejector primary pressure) (kPa)	300.00													
	PCV outlet pressure maximum (ejector primary pressure) (kPa)	1000.00													
	Mass flow loss due to purge (3% assumed) (g/s)	0.04	0.13	0.25	0.32	0.37	0.41	0.49	0.57	0.63	0.67	0.67	0.75	0.82	0.90
	Pressure drop due to fresh fuel mixing (kPa)	1.00													
	Pressure drop in pipework out of Anode (kPa)	0.02	0.22	0.77	1.28	1.73	2.10	2.94	3.96	4.91	5.46	5.58	6.89	8.36	10.00
	Pressure drop in pipework into Anode (kPa)	0.02	0.21	0.69	1.18	1.65	2.09	2.93	3.87	4.84	5.51	5.63	6.93	8.39	10.00
Ejector Requirements	Primary mass flow rate (g/s)		0.94	1.53	2.13	2.75	3.36	3.97	4.41	5.02	5.63	5.69	6.27	6.85	7.43
	Primary temperature *assumed* (℃)		60.0	68.0	69.0	69.0	69.0	69.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0
	Secondary pressure (HRP outlet pressure) (kPa)		141.21	151.69	147.70	165.67	173.97	180.63	207.64	224.83	243.36	242.98	239.11	235.03	230.70
	Secondary temperature *assumed +2degrees from HRP* (°C)		71.4	77.9	78.8	78.8	79.0	77.2	86.5	86.8	86.9	86.9	87.2	87.5	87.9
	Target outlet Pressure (kPa)		140.21	150.69	171.18	191.65	202.09	212.93	243.87	264.84	285.51	285.63	286.93	288.39	290.00
	Target secondary mass flow (g/s)		4.32	8.08	10.43	12.12	13.37	15.81	18.33	20.43	21.53	21.77	24.19	26.64	29.15
	Target H2 secondary mass flow (g/s)		0.99	1.66	2.09	2.38	2.54	3.01	2.97	3.36	3.72	3.76	4.16	4.56	4.96
	Target entrainment ratio (total)		4.61	5.29	4.89	4.40	3.98	3.98	4.16	4.07	3.82	3.83	3.86	3.89	3.93
	Target entrainment ratio (H2)		1.05	1.08	0.98	0.87	0.76	0.76	0.67	0.67	0.66	0.66	0.66	0.67	0.67

Table 1: Calculated ejector requirements, stack/application requirements and assumed requirements. The colour coding corresponds to the balance of component work shown in Figure 5.

5.3.3 Hydrogen Recirculation Pump

HRP requirements include:

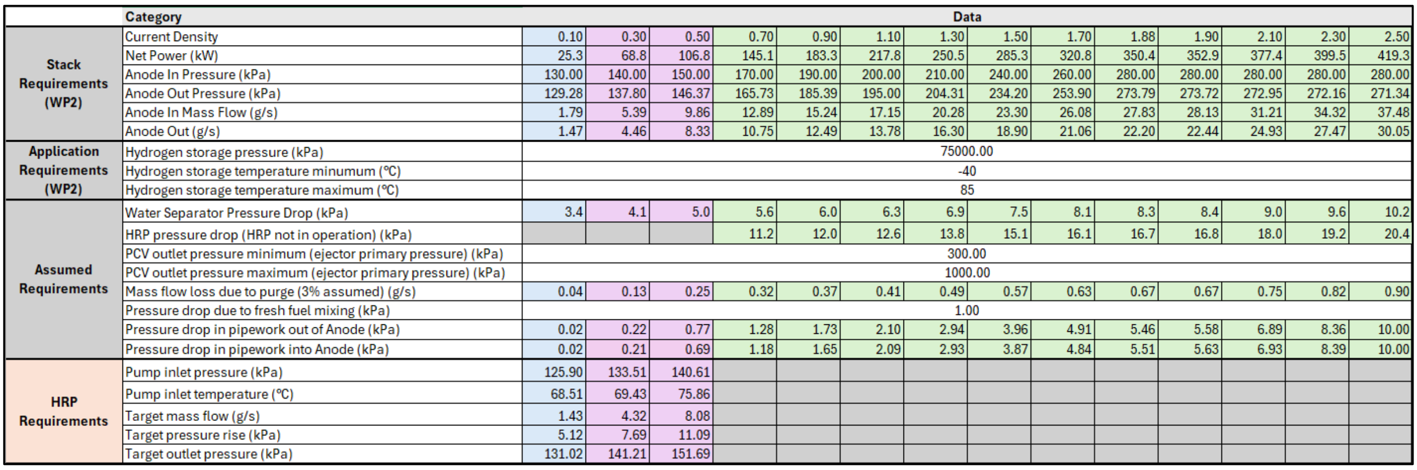
- Inlet pressure
- Target outlet pressure
- Target pressure rise
- Required minimum motor power
- Target recirculated mass flow
- Target design point (optimized operating range)

The hydrogen recirculation pump in this system is intended to be used towards the lower end of the operating range, to limit the use of the motor and therefore the parasitic load on the FC system. However, the higher end of the operating range must still be considered and included on a HRP performance curve to ensure the pump performance can be characterized in that region if needed.

Assumptions made:

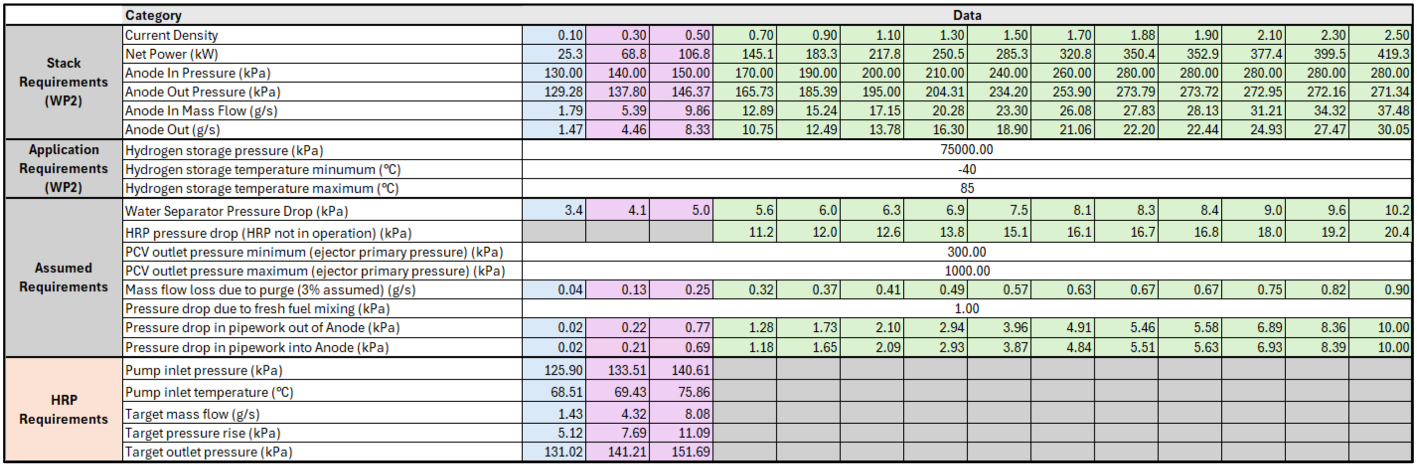
- HRP efficiency ~60%
- Motor efficiency ~ 90%
- Pressure drop across water separator 3-10kPa
- Mass flow loss due to purge ~3% anode outlet flow
- Purging only impacts mass flow, impact on gas composition is ignored for this work to simplify the ejector design

The minimum pressure rise across the HRP must encompass the pressure drop across the stack, the water separator, pipework losses and fresh fuel mixing. The impact of ejector performance degradation has been ignored for the purposes of this work because it is not clear what level of degradation would be typical for this system. The calculated pump requirements are given in



	Category	Data													
Stack Requirements (WP2)	Current Density	0.10	0.30	0.50	0.70	0.90	1.10	1.30	1.50	1.70	1.88	1.90	2.10	2.30	2.50
	Net Power (kW)	25.3	68.8	106.8	145.1	183.3	217.8	250.5	285.3	320.8	350.4	352.9	377.4	399.5	419.3
	Anode In Pressure (kPa)	130.00	140.00	150.00	170.00	190.00	200.00	210.00	240.00	260.00	280.00	280.00	280.00	280.00	280.00
	Anode Out Pressure (kPa)	129.28	137.80	146.37	165.73	185.39	195.00	204.31	234.20	253.90	273.79	273.72	272.95	272.16	271.34
	Anode In Mass Flow (g/s)	1.79	5.39	9.86	12.89	15.24	17.15	20.28	23.30	26.08	27.83	28.13	31.21	34.32	37.48
	Anode Out (g/s)	1.47	4.46	8.33	10.75	12.49	13.78	16.30	18.90	21.06	22.20	22.44	24.93	27.47	30.05
Application Requirements (WP2)	Hydrogen storage pressure (kPa)	75000.00													
	Hydrogen storage temperature minumum (℃)	-40													
	Hydrogen storage temperature maximum (℃)	85													
Assumed Requirements	Water Separator Pressure Drop (kPa)	3.4	4.1	5.0	5.6	6.0	6.3	6.9	7.5	8.1	8.3	8.4	9.0	9.6	10.2
	HRP pressure drop (HRP not in operation) (kPa)				11.2	12.0	12.6	13.8	15.1	16.1	16.7	16.8	18.0	19.2	20.4
	PCV outlet pressure minimum (ejector primary pressure) (kPa)	300.00													
	PCV outlet pressure maximum (ejector primary pressure) (kPa)	1000.00													
	Mass flow loss due to purge (3% assumed) (g/s)	0.04	0.13	0.25	0.32	0.37	0.41	0.49	0.57	0.63	0.67	0.67	0.75	0.82	0.90
	Pressure drop due to fresh fuel mixing (kPa)	1.00													
	Pressure drop in pipework out of Anode (kPa)	0.02	0.22	0.77	1.28	1.73	2.10	2.94	3.96	4.91	5.46	5.58	6.89	8.36	10.00
	Pressure drop in pipework into Anode (kPa)	0.02	0.21	0.69	1.18	1.65	2.09	2.93	3.87	4.84	5.51	5.63	6.93	8.39	10.00
HRP Requirements	Pump inlet pressure (kPa)	125.90	133.51	140.61											
	Pump inlet temperature (℃)	68.51	69.43	75.86											
	Target mass flow (g/s)	1.43	4.32	8.08											
	Target pressure rise (kPa)	5.12	7.69	11.09											
	Target outlet pressure (kPa)	131.02	141.21	151.69											

Table 2. The calculated requirements are worst case considering a step change from pump only to ejector only operation, shown in Figure 4. Realistically, the ejector and pump will work together as the ejector performance degrades, and the pump won't need to provide the full pressure rise given in



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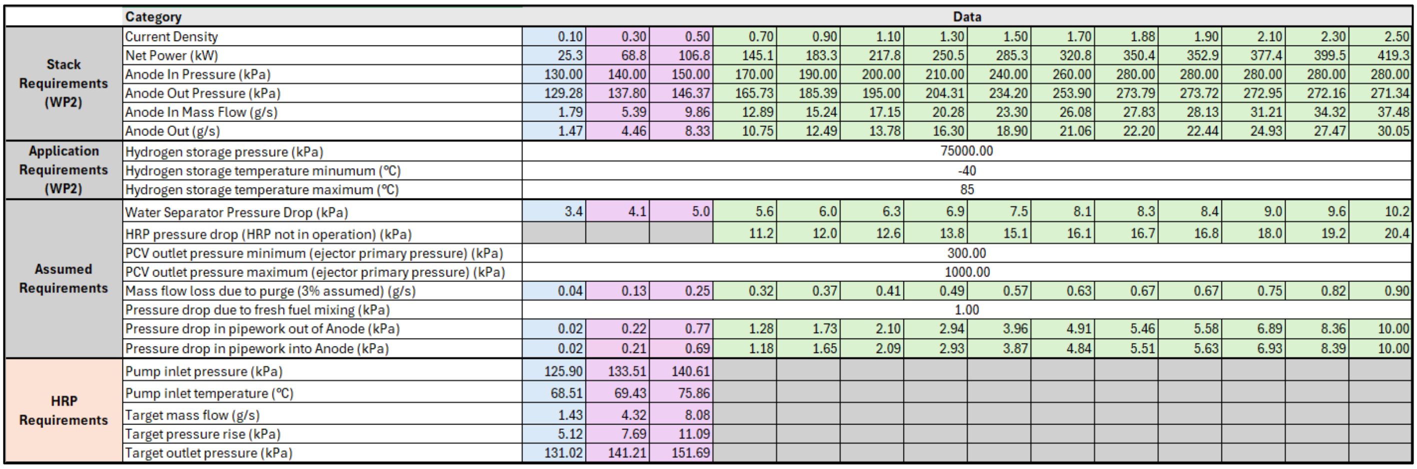

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Table 2: Calculated HRP requirements, WP2 stack and application requirements and assumed requirements. The colour coding corresponds to the balance of component work shown in Figure 5.

In addition to the tabulated requirements, the HRP also requires some estimate of motor power. Figure 5 shows the motor requirement for various pump capabilities from 6-20kPa pressure rise. The 6kPa and 10kPa would not be sufficient to meet minimum requirements for pressure rise for the lower operating points.

Focusing on the lower operating points only, where the pump would be required, a 15kPa pump capability would require ~2.4kW motor power, whereas a 20kPa pump capability would require ~ 3.1kW motor power. The latter option would be able to meet the pressure rise requirement for the entire operating range which isn't required in a hybrid architecture where the ejector should be dominant at the higher operating points. This would likely be more suitable for HRP-only hydrogen loop architecture. Ideally, the HRP should be optimized to deliver the pressure rise requirement whilst keeping the parasitic load on the system as low as possible, therefore it is recommended to target a 15kPa pressure rise capability where a 2.4kW motor would be required, for the proposed baseline hybrid architecture. A 2.4kW motor requirement equates to approximately 0.7% of the 350kW stack power.

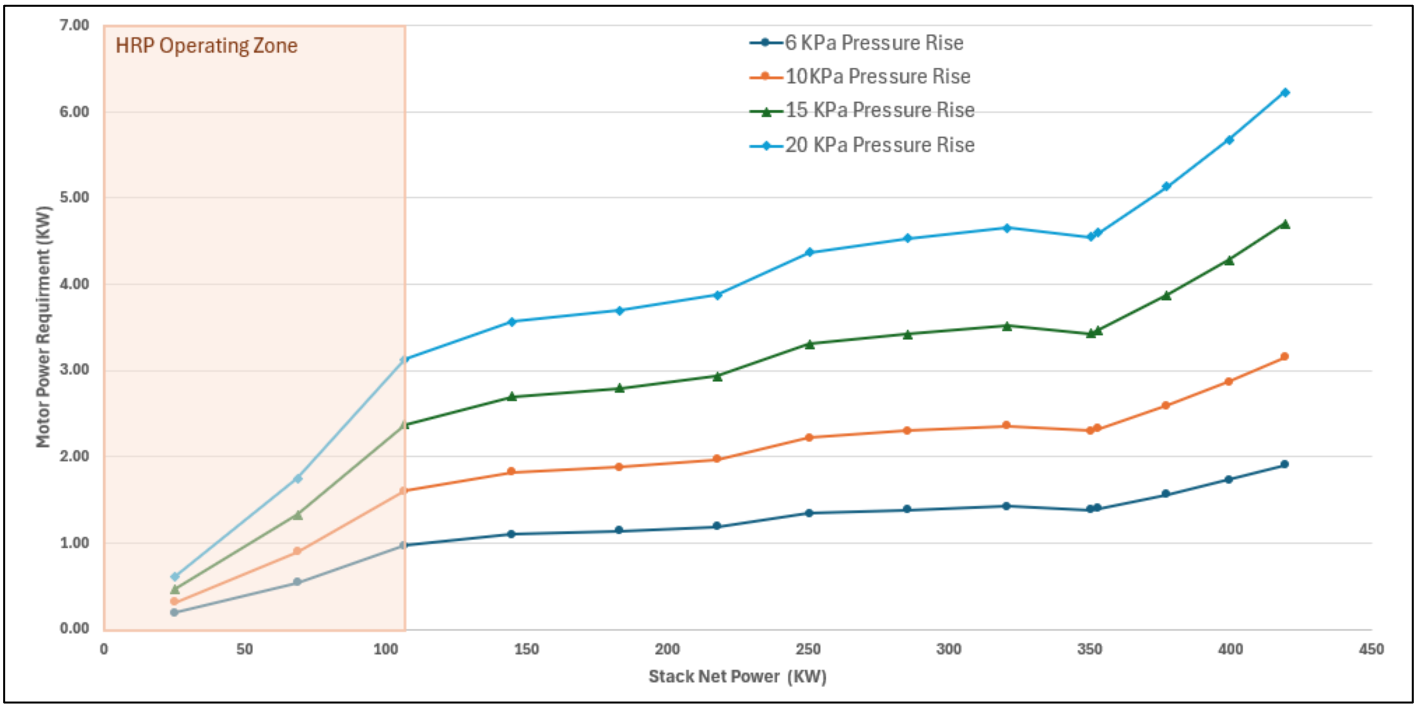

Figure 5: Pump motor requirements for various pump capabilities

5.4 Hydrogen Leakage Sensor Requirements

The hydrogen leakage sensor requirements are mostly independent of the hydrogen loop flow characteristics, except for the temperature of the leakage gas, as shown below.

Hydrogen Leakage Sensor requirements include:

- Hydrogen measurement range 0-4% vol H2 (extended range 0-16% vol H2)
- Temperature range –40 – 105°C
- Relative humidity range 0-100% limited to absolute humidity 200 g/m3 H2O
- Risk classification - FuSa level ASIL B

The measurement accuracy of the sensor is dependent on environmental conditions. Initial safety analysis shows good feasibility against the required risk classification.

6 Hydrogen Loop Architecture Selection

6.1 Objective

This section outlines the selection of 3 hydrogen loop architectures for further trade-off studies in task 5.2. This work leans on the literature review previously discussed in Section 4. Various architectures were ranked against each other for a range of key factors.

6.2 Architecture Ranking & Selection

In preparation for task 5.2, three different recirculation architectures have been selected for further study. The first is passive ejector-only architecture because this is considered an important baseline. The second is a passive ejector and HRP hybrid loop with components in series. Both architectures include pre-existing and commonly used technologies, so they are considered important cases to assess.

The final architecture was selected using a scoring system on the remaining architectures highlighted in the literature review in section 4. This scoring is given in Table 3 and is based on learnings from the literature review as well as engineering judgement. The final architecture for study was selected based on the scoring so is the variable geometry ejector (passive). This benefits from having a wide operating range, scalability and low parasitic load.

	Double ejector	Bypass ejector	Multi-nozzle ejector	Variable Geometry Ejector (passive)	Variable Geometry Ejector (electrically actuated)	Scaling Factor
Design complexity	5	3	4	1	1	1
Parasitic load	4	4	4	5	3	1
Operating range	3	1	3	4	5	1.5
Scalability	3	1	3	5	5	1.5
Responsivity	1	1	3	4	5	1
Cost	5	4	3	3	1	1
Packaging	1	2	3	5	3	1
Score considering weighting	25	17	26	31.5	28	

Table 3: Scored architecture options for hydrogen loop. Scoring was completed according to 1='worst', 5='best'. Not all parameters are considered equally weighted for this project. Operating range and scalability are more important for the scope of H2UpScale, therefore, a scaling factor has been assigned to those characteristics.

Architectures for simulation & further study in task 5.2:

1. Passive ejector only
2. Passive ejector + HRP hybrid
3. Variable geometry ejector (passive)

7 Conclusion

Ejector and HRP requirements have been presented in this report which will allow the design, optimization and procurement of the required hydrogen loop components. The approach taken was for the ejector to meet recirculation requirements for the majority of the operating range, and the HRP to support recirculation at the lower end of the operating range. The hydrogen leakage sensor has fewer requirements dependent on the application and stack. The goal for WP5 is to focus on the 350kW single BoP, and high-power nodes will utilize multiple BoP components, as will be further detailed in WP3.

The next step for WP5 is to complete the recirculation architecture studies using a hydrogen path model, and to continue the design and optimization of the recirculation components.

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