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WP1 – "FC Gensets Specifications"
D1.3 – "EVERYWH2ERE Gensets Enabling Technologies (FC and H2 Storage) Assessment Report"

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CO	Confidential	
PU	Public	**X**

Executive Summary

EVERYWH2ERE "D1.3 Gensets Enabling technologies (FC and H2 Storage) Assessment Report" has the aim of providing a technological and commercial assessment of the state of the art when it comes to fuel cell and hydrogen storage technologies towards the identification of the most suitable ones for the realisation of the EVERYWH2ERE gensets. The assessment starts with the existing technical datasheets provided by literature and the technology manufacturers of the consortium who will take care of the wider research evidence for the technologies, highlighting the relative strengths and weaknesses. All the subcomponents that compose the EVERYWH2ERE gensets will be analysed to benchmark the state of the art on this field with the EVERYWH2ERE innovations. Focus will be given to the proposed technologies from LINDE, PCS, MAHY, GEN, and SHSA.

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Abbreviations and acronyms

PEM	Proton Exchange Membrane: a type of fuel cell
BOP	Balance of Plant: all electrical components excluding the fuel cell stack
CAPEX	Capital Expenditure
CAN	Controller Area Network: a digital communication protocol developed for, and commonly used in the vehicle industry.
TPED	Transportable Pressure Equipment Directive (2010/35/EU)

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ECU	Electronic Control Unit.
SotA	State of the Art: the leading technologies in a given field

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1. Introduction

This report was prepared within the framework of Work Package 1: FC Gensets Specifications, and contains a technological and commercial assessment of the state of the art fuel cell and hydrogen storage technologies towards the identification of the most suitable ones for the EVERYWH2ERE gensets realisation.

This assessment has been realized under the responsibility of PCS with the supervision of RINA-C as WP1 leader and coordinator as well as with GENP and SHSA support, who have already started an effective collaboration towards the identification of a Balance of Plant list of material needed by their gensets. This activity has been beneficial for the realization of this deliverable and it has been initiated to start a common procurement of components in order to reduce costs. LINDE's role has also been relevant for what it concerns the assessment of standard solution related to hydrogen and special gas handling technologies, as well as MAHY support who provided relevant insights about their pressurized composite hydrogen tanks.

The assessment will start with the existing technical datasheets, independent studies and field trial reports provided by literature and the technology manufacturers of the consortium who will take care of the wider research evidence for the technologies, highlighting the relative strengths and weaknesses. All the subcomponents that compose the EVERYWH2ERE gensets will be analysed to benchmark the state of the art on this field with the EVERYWH2ERE innovations. Focus will be given to the proposed technologies from LINDE, PCS, MAHY, GEN, and SHSA and will present them and their potentialities in the context of the different chosen test sites. Analysis will focus on the potential CAPEX reduction and how to increase the gensets lifetime and consider the frequent intermittent and partial load operation typical of temporary generators. Relevant inputs for the present deliverable have been collected both via direct interaction with consortium members and from technical catalogues.

The main objective of the project is to develop two plug-and-play gensets with the maximum output power being 25 kVA for the smaller genset and 100 kVA for the larger one. These gensets will have zero emissions and zero noise, be cost effective, have logistical and technologically viable solutions, and will be capable of being deployed across the EU. The gensets will be based on already existing solutions to minimise development required and will allow the focus to be on increasing lifetime and reducing costs.

Considering the final application of the gensets, PEM fuel cell stacks operating on compressed hydrogen were deemed to be the most appropriate technology to meet the core requirements for intermittent/plug-and-play power based on their ability to provide fast and reliable response. The consortium will rely on the expertise of EU core industrial players providing State-of-the-art technological components and focusing on the integration of these BoP components in first of their kind transportable remarkable power size gensets more than on the further development of the performances of the single component.

The integrated gensets scheme will be based on previous partners' expertise in the integration of hydrogen storage and FC Systems in automotive and back-up power solutions both equipped with pressurized hydrogen tanks, as the gensets application, purpose, functioning, control logic is an effective mix of these two applications.

The targets of the gensets are listed in the table below:

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Table 1-1. Targets of the EVERYWH2ERE Gensets.

Characteristic	2023 EVERYWH2ERE Targets
Lifetime	15 years
Durability[a]	10,000 hours
Energy efficiency[b]	55%
Mean time between failures	5 years
Ambient temperature range	-20 to 40°C
Noise	50 dB at 1 m
Start-up time[c]	45 s
Availability	97 %
Equipment cost[d]	2,000 €/kW
Annual maintenance cost[d]	20 €/kW
Annual TCO[e]	300 €/kW

a) Time until 10% voltage degradation when operated on a backup power duty cycle
b) Ratio of DC output energy from the genset to the lower heating value of the fuel input (hydrogen) averaged over the duty-cycle.
c) Time indicated is start-up time for the fuel cell. The backup power system, including hybridised batteries, is expected to provide uninterruptible power.
d) Excluding tax credits and subsidies.
e) Annual cost of ownership, including cost of capital equipment, installation, operation and maintenance, fuel, and fuel storage. Based on a 5-kW system with a 10-year lifetime.

The gensets design is strictly connected with the logistic of the hydrogen distribution and with the overall operation costs. Two possible general architectures or "philosophies" will be evaluated for the gensets; the first being a "one-box" approach where all components are integrated into a single container where the main pros and cons are:

+ Simplified installation, only one box to transport and deploy
+ No floating pipes or cables
− Hydrogen refill only available onsite

The second approach separates the hydrogen storage and the genset in two containers. The main pros and cons of this design are:

+ Flexibility on refilling; either onsite or swap an empty storage module for a full one
+ Scalability of the hydrogen storage design to increase capacity
+ Only one kind on containerised hydrogen storage needs to be designed
− More complex installation due to the floating hydrogen pipe which presents a safety and operational issue

Another important issue to be evaluated also referring to refuelling logistics and regulation (i.e. the current SotA pressure level of pressurized hydrogen transported by gas tanks or the pressure level of distribution systems different than hydrogen refuelling station) is the pressure of the storage: this will be a key parameter also to optimize CAPEX and volume of the hydrogen storage as well as minimize the number of re-fuelling during the operation and related logistic/OPEX issues.

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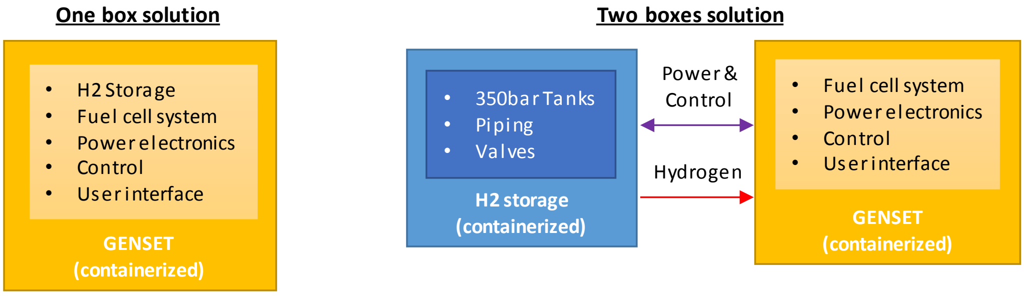

Figure 1-1. The two different options for how the gensets are containerised: a one box solution where all components are in one container (left) and a "two-boxes" solution where the hydrogen storage is in a separate container (right).

In each approach the genset itself is quite similar in terms of general design and control strategies and it makes sense to think one as the older brother of the other and vice versa. To reduce design and realization costs, it is possible to identify parts, components and control software that are valid for both the 25kW and the 100kW genset. The following figure shows the general layout of the gensets:

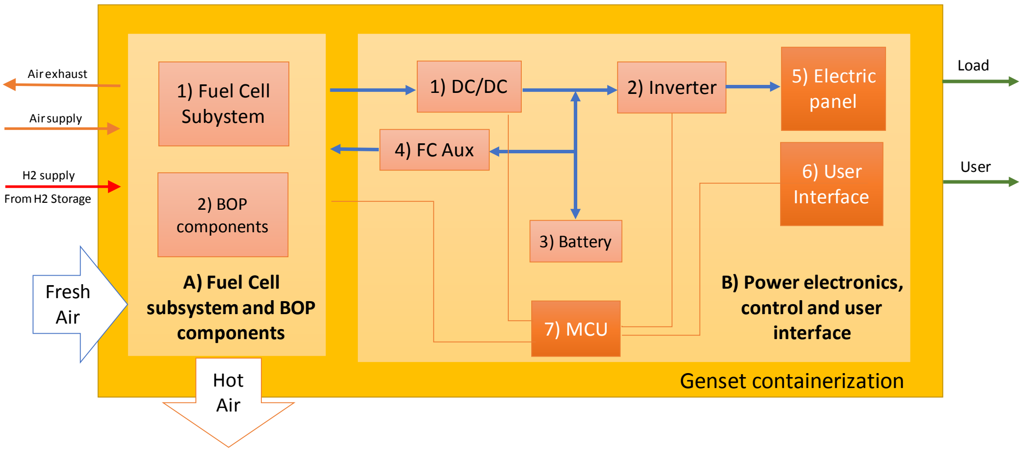

Figure 1-2. The modular approach of the fuel cell support subsystem and the power electronics, control, and user interface.

In the end two important issues raised up during first months of EVERYWH2ERE project to be faced and discussed during this phase of design of the gensets:

1. Air Filtering of the FC system: particularly related to application in construction sites. This aspect could be crucial particularly towards the identification of a not expensive, long lifetime filtering solution which has no inefficient effects on the FC genset performances

2. Power electronics and electric architecture of the genset in case of their use in off-grid modality, if connected with other generators in a sort of microgrid, if connected to local distribution grid etc.

Furthermore, it is worth to state that all the technological assessment here below presented has to be validated with the eyes of Permitting/safety application and Regulation and standards of different contexts where EVERYWH2ERE gensets will have to operate: from regulation related

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to the transport on trucks of special gases technologies, to the use of hazardous gases in construction sites etc.

The following assessment has been redacted referring to consortium partners' industrial expertise, on-the-shelf technical catalogues from the consortium industrial manufacturers and literature review.

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2. Power Generation

The core of the gensets is the PEM fuel cell stack that generates the raw power that is ultimately conditioned and delivered to the external user at the main electrical interface of the system.

PEMFCs, also known as polymer exchange membrane FCs have been developed during the last 20 years. Hydrogen is split into protons and electrons at the platinum covered anode. The protons pass the solid membrane. PEMFCs show very high reactivity, and due to the low operation temperature cold start is possible. Together with its high energy density, they are most suitable to be used in fuel cell electric vehicles (FCEVs) as well as for transportable application/intermittent functioning solutions such as EVERYWH2ERE gensets where PEMFCs will be designed according to a “mix purpose” gathering beneficial insights from both stationary and automotive stacks. To date, stationary PEMFCs have rather low efficiencies of around 32% to 49% (HHV) and CAPEX are still high (in the range of 3 000 -4 000 €/kW). For stationary application, current life times (up to 60 000 hours) are targeting at least 80 000 hours on average (always larger than traditional automotive lifetime of 5000 hrs but with significant efficiency up to 60%).
The two gensets have different fuel cell stacks which are optimised for the different power output ranges; these are the PowerCell S2 (up to 35 kW) and the S3 (up to 130 kW) fuel cell stacks. The fuel cell stacks require a support system that consists of three sections; the anode (hydrogen), the cathode (air), and the cooling subsystems. PowerCell has already integrated a S2 fuel cell stack with a support system and Swiss hydrogen has done the same with the S3 fuel cell stack. These existing solutions will be the basis of the two gensets and will undergo developments to meet the overall targets of the EVERYWH2ERE gensets. Each of these systems is discussed further in the following sections.

2.1 25 kW Genset Fuel Cell Stack

The 25 kW Genset will be based on the PowerCell’s S2 fuel cell stack (see Figure 2-1) which has been designed for efficient power generation in the range of 5 to 25kW with state-of-the-art PEM technology for superior performance in many applications. PowerCell S2 is optimized to run on reformate gas but performs equally well on pure hydrogen.

Parameter	S2-264C
Voltage output	150-250 V
Current output	10-234 A
Maximum power output	35 kW
Size, mm (approximate)	W:155 x L:490 x H:459
Weight	36 kg
Cathode inlet pressure	0,75 bar(g)
ΔP cathode @ max power	99 mbar
ΔP anode @ max power	25 mbar
Stack maximum temperature	< 85°C
Ambient temperature	-30 to 70°C

Figure 2-1. PowerCell’s S2 fuel cell stack and key technical properties.

The maximum power output of the S2 stack can be increased to 35 kW by pressurising the cathode to 750 mbar(g). This higher pressure increases the concentration of oxygen in the stack

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which results in higher cell voltages and hence, higher output power. Further power increases are possible but these must be balanced against the higher compression power requirements needed to supply the higher air pressures.

The hydrogen consumption for the stack at maximum current is 431 NLPM (0,65 g/s) and the anode recirculation is approximately 329 NLPM (dry basis) at a stoichiometry of 1,5 with an estimated 85% hydrogen concentration at the stack inlet. The maximum operational air flow is 2050 NLPM (44 g/s) at a stoichiometry of 2,0 and this air needs to be filtered with filters of at least MERV 12 rating to remove fine particles. The air also needs to be humidified (maximum 85% relative humidity) to prevent the membranes drying out which will lead to decreased performance and potentially irreversible damage.

The user manual recommends that when the current drawn from the stack falls below 60 A, the flow should be fixed to the value calculated at 60 A; taking this into account the minimum flow is a quarter of the maximum flow (60/234 ≈ 0,26) so the compressor or system need to be able to handle this turn down ratio. At the rated output power of the stack, roughly 50% of the hydrogen will be converted into electricity and the rest converted into heat; towards the end of life, as the stack ages, the heat generation can increase by 15%.

It is recommended to keep the stack inlet temperature and differential temperature constant regardless of the power output. This can be achieved by controlling the cooling rate as well as coolant flow rate. The inlet temperature should be set somewhere in the range 70 to 80°C and the differential temperature should be below 10°C.

2.2 25 kW Genset Fuel Cell Support System

The 25 kW Genset PowerCell will integrate the S2 fuel cell stack in an updated version of the prototype system for mobile applications (MS-20). The MS-20, shown in Figure 2-2, is based on a 250-cell S2 stack and has been successfully tested in a passenger car, light truck, and is currently integrated into a heavy forklift truck.

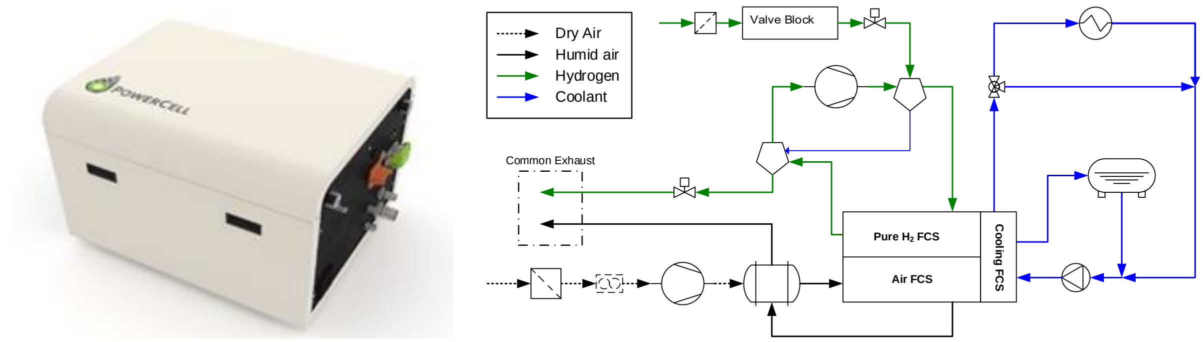

Figure 2-2. PowerCell's MS-20 fuel cell system: CAD rendering and simplified layout.

Due to the market need for 30 kW fuel cell systems and higher, an investigation to increase the power output of the S2 platform was started. During the EVERYWH2ERE project, PowerCell will upgrade the current MS-20 with a larger 264-cell S2 fuel cell stack and raise the cathode pressure to levels that allow a maximum output power of 35 kW, which will allow a net output of 25 kW to the customer. The system can be broken down into three independent subsystems: the anode, cathode, and cooling loops. The main components of the anode and cathode sections are discussed below and the cooling section is discussed in Section 4.

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Anode Support System

The major component of the anode system is the recirculation pump which increases the gas velocity in the stack by recirculating gas from the outlet to inlet. This helps disperse hydrogen evenly across the individual cells and remove any liquid water on the cell surface; both features improve the stack performance and stability.

The MS-20 uses a hydrogen version of the Busch MA0018, which was originally designed for heavy off-road machinery such as excavators and earth-movers; as such the mechanics of the compressor is very overdesigned for its purpose in the MS-20. Internal testing at PowerCell has shown that this compressor is able to deliver up to 500 NLPM of hydrogen at a stack pressure of 850 mbar(g) which is well sized for the 25 kW Genset. At the maximum flow conditions of the 25 kW Genset, this compressor will consume an estimated 140 W of power.

As there are very few compressors in this size range that are compatible with hydrogen, it is difficult to find an alternate compressor that is more appropriate for this fuel cell system; so, VTT has proposed an ejector solution that can be applied to the MS-20 to reduce costs and BOP power consumption. A major challenge for using ejectors in PEMFC systems is to obtain correct ejector dimensions so to enable their sufficient performance over the entire system power range. To overcome this problem, three solutions have been suggested: two or more different-sized ejectors in parallel, a variable geometry ejector, and a hybrid system comprising an ejector and a mechanical compressor in parallel. Regardless of which approach is applied, the search for optimal ejector sizing involves trial-and-error by modelling and experimental measurements unless accurate sizing tools are available.

Cathode Support System

The cathode support system has two main components; a compressor which forcefully drives the air flow through the stack, and a humidifier which recycles water into the stack. The MS-20 uses a FISCHER EMTC-150k Air turbo compressor to supply air to the stack. This compressor is free of oils, particles, grease, and hydrocarbons, which makes it suitable to use in fuel cell systems. Due to this strict requirement of no contaminants, many compressors are unsuitable to use in fuel cell systems and within the required flow and pressure range, there are few options to choose between.

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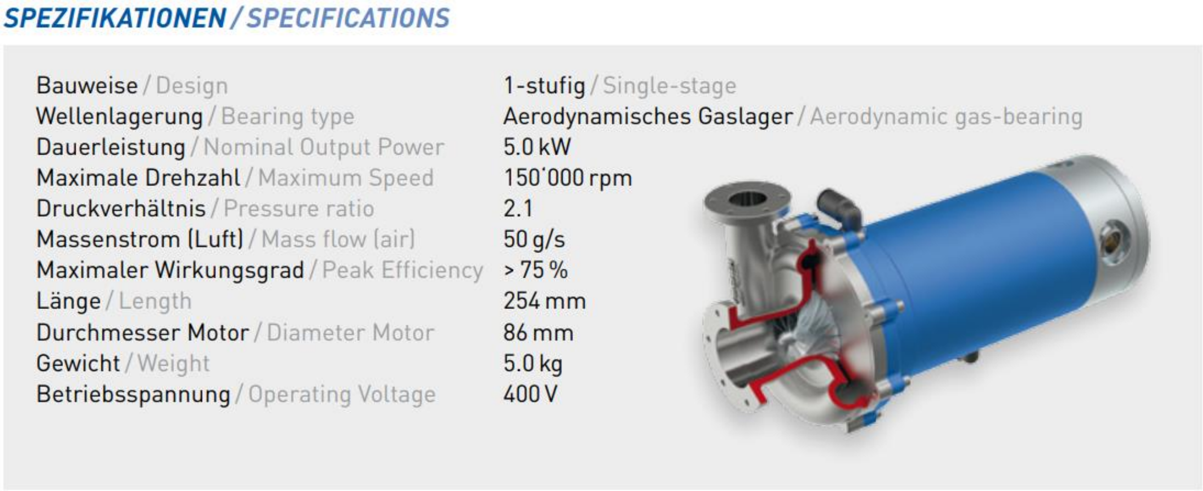

SPEZIFIKATIONEN / SPECIFICATIONS

Bauweise / Design	1-stufig / Single-stage
Wellenlagerung / Bearing type	Aerodynamisches Gaslager / Aerodynamic gas-bearing
Dauerleistung / Nominal Output Power	5.0 kW
Maximale Drehzahl / Maximum Speed	150´000 rpm
Druckverhältnis / Pressure ratio	2.1
Massenstrom (Luft) / Mass flow (air)	50 g/s
Maximaler Wirkungsgrad / Peak Efficiency	> 75 %
Länge / Length	254 mm
Durchmesser Motor / Diameter Motor	86 mm
Gewicht / Weight	5.0 kg
Betriebsspannung / Operating Voltage	400 V

Figure 2-3. The datasheet of the Fischer EMTC-150k Air micro turbo compressor.

The use of this compressor presents its own challenges with regards to operating the compressor. At the minimum flow requirements of the Genset, the compressor has a limited operating zone with respect to outlet pressure (see Figure 2-4), and at pressures above ~220 mbar(g) the compressor will be operating in its surge zone; this is where flow patterns become unstable and will likely result in damage to the compressor. As the stack requires a pressure of 750 mbar(g) at its maximum operating point, the system needs to dynamically adjust the air pressure depending on the system output power; this adjustment needs to be properly tuned so that under no circumstances the compressor operates in the surge zone and the system operates as efficiently as possible.

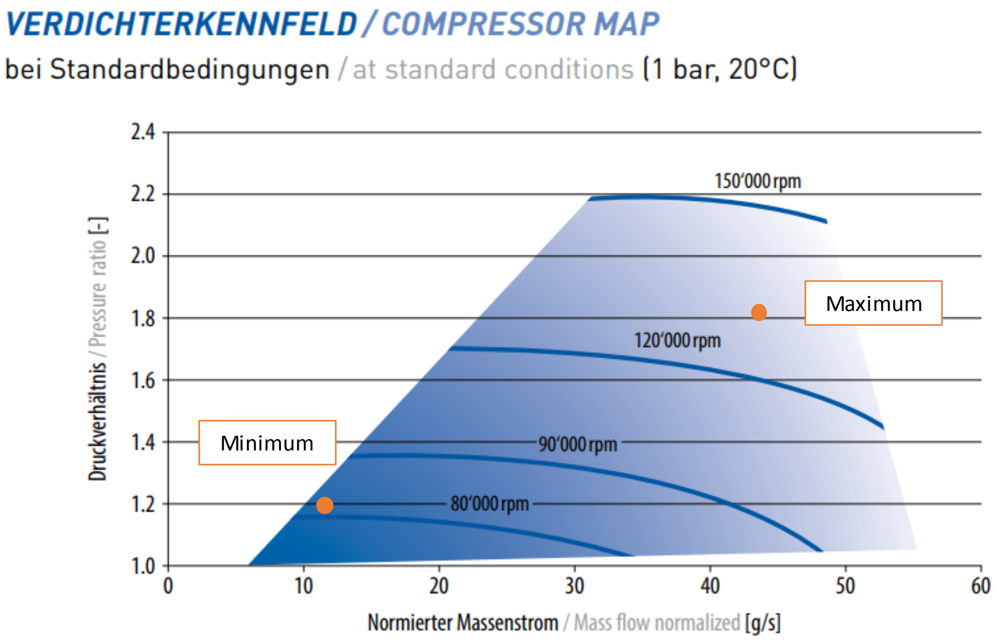

Figure 2-4. The operating window of the Fischer EMTC-120k Air micro turbo compressor and the maximum and minimum operating points in the 25 kW Genset system.

The Fumatech Ecomate® H20 is used as the cathode humidifier which is designed to use in 30 kW fuel cell systems. This has a guaranteed life time of at least 10,000 hours, ideal for a

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stationary fuel cell system; and importantly is rated for temperatures in the range -40 to 110°C. The datasheet of the humidifier is displayed below in Figure 2-5 which states that the dewpoint approach temperature, a measure of efficiency, is between 4 and 15°C depending on operating conditions.

Properties	Ecomate® H20
Fuel Cell Power	~30 kW
Rated air flow	1200-2500 SLPM
Weight (dry)	5 kg
Volume (without end caps)	7 L
Connection method	Ø1.5" clamps
Lifetime	>10,000 hours
Environmental temperature	-30 to 110°C
Operating pressure	≤3 bar(g)
Humidification efficiency (Approach dew temp.)	4 to 15°C
Total pressure drop	<10 kPa @ rated flow

Figure 2-5. Key technical properties of the Fumatech Ecomate® H20 humidifier.

2.3 100 kW Genset Fuel Cell Stack

The 100 kW genset will be based on the PowerCell's S3 fuel cell stack which has been designed for efficient power generation in the range 20-100 kW. The choice of industrial components that are suitable for volume production has proved particularly successful and currently PowerCell has developed a dedicated manufacturing line for this stack.

A first prototype of the 100 kW FC system (realized by Swiss Hydrogen with the support of PowerCell) has been developed and implemented in a heavy-duty truck in autumn 2016. This system provides a very high power density and efficiency (>52%) and the durability was predicted to be at least 5000 hours at a dynamic load and road profile, including automotive start/stop cycles.

Model Code	S3-455C
Voltage output	280-440 V
Maximum current output	450 A (overloading allowed for <30 s)
Maximum power output	130 kW
Size, mm (approximate)	W:156 x L:420 x H:568
Weight	43 kg
Gas pressure	<3 bar(abs)
ΔP cathode @ max power	<200 mbar
ΔP anode @ max power	<120 mbar
Stack maximum temperature	90°C
Ambient temperature	-30 to 70°C

Figure 2-6. PowerCell's S3 fuel cell stack and key technical properties.

The hydrogen consumption of the S3 stack at maximum current is 1427 NLPM (2.14 g/s) and the anode recirculation is approximately 2650 NLPM (dry basis) at a stoichiometry of 1,5 with a 70% hydrogen concentration at the stack inlet. The higher inert gas concentration at the stack

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inlet helps facilitate efficient water droplet removal from the stack. With a cathode stoichiometry of 2,0 the maximum air flow is 6115 NLPM (131 g/s) which needs to be humidified to around 50% relative humidity for optimum stack performance. When the current drawn from the stack falls below 60 A, the flow should be fixed to the value calculated at 60 A which corresponds to a compressor turn-down ratio of 7,5.

The stack temperature should be maintained at a constant value in the range 70 to 80°C regardless of the stack output power, and the differential temperature should be maintained around 12°C for optimal stack humidification. The stack has resistive heaters integrated into the end cells which are used to maintain an even temperature throughout the stack and to assist the start-up. A suitable heater control strategy is to heat them to the same temperature as the coolant outlet temperature using their built-in temperature sensor.

At the rated output power of the stack, roughly 50% of the hydrogen will be converted into electricity and the rest converted into heat; towards the end of life, as the stack ages, the heat generation can increase by 15%.

2.4 100 kW Genset Fuel Cell Support System

The 100 kW Genset will be based on the already existing SHA-100-E fuel cell system, developed by Swiss Hydrogen, which uses 120 additional cells compared to an earlier design. The increased number of cells in the SHA-100-E system allows the stack current to be reduced while maintaining the same power output, which increased the efficiency and durability of the stack. The system efficiency (from Hydrogen in to DC out) will be above 50% at beginning of life due to the large stack, optimised compressor, and careful selection of components that have a minimal power consumption. The support system will be controlled by a free programmable automotive ECU or PLC and will contain a hardwired safety loop that can safely shut down the system in the case of a major controller malfunction. The system will be freeze capable down to -20°C which will be achieved by a combination of shut-down and start-up procedures and some local electric heating. Automotive components will be used wherever possible to improve the system reliability and to reduce the BOM cost. The system does not contain an internal cooling loop, instead cooling will be handled directly by the genset heat rejection system.

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FC system technical data	SHA-100-E
Number of cells	455
Max. continuous net power	100 kW
DC net out at max. cont. power	332 V; 300 A
System pressure (at full load)	2.6 bar_{abs}
Voltage range (Peak Power EOL .. OCV BOL)	250 .. 500 V
Coolant flow (pump integrated)	150 l/min
Coolant outlet temperature	80 °C
Waste Heat	82 kW
System Efficiency (LHV H2 in to DC stack out)	52 %
Dimensions (H x W x D) [1)]	750 x 750 x 520 mm
Weight [2)]	98 kg

Figure 2-7. The Swiss hydrogen SHA-100-E fuel cell system (left) and some key technical data of the SHA-100-E fuel cell system (right).

Anode Support System

Hydrogen recirculation will be driven purely by an ejector in the 100 kW Genset system, where the geed gas is used to drive the recirculation. Swiss hydrogen has developed an ejector specifically for their SHA-100-E systems which has the desired performance over the entire operating range of the fuel cell stack. To better handle freezing condition, the hydrogen feed line will pass through a heat-exchanger to preheat the anode gas before it enters the stack. This will prevent excessive water condensation when the feed gas temperature is sub-zero and allow the stack to maintain its optimum humidity levels. In addition to the preheater, small heaters will be attached to the anode water drains to prevent water freezing and blocking the purge water and gas lines. Custom water traps have been designed that integrate into the fuel cell stack end plates that remove and collect liquid water from the cathode loop.

Cathode Support System

The single most important support system component is the cathode air compressor which consumes over 90% of the system supply power. It is critical that this compressor is matched correctly to the fuel cell stack to ensure optimum performance of the entire genset. Swiss Hydrogen is currently evaluating a micro-turbo-compressor from Fischer Engineering to assess its suitability to use in the EVERYWH2ERE genset. This compressor is expensive in the context of the Genset but it is very compact and efficient compared to other compressor designs.

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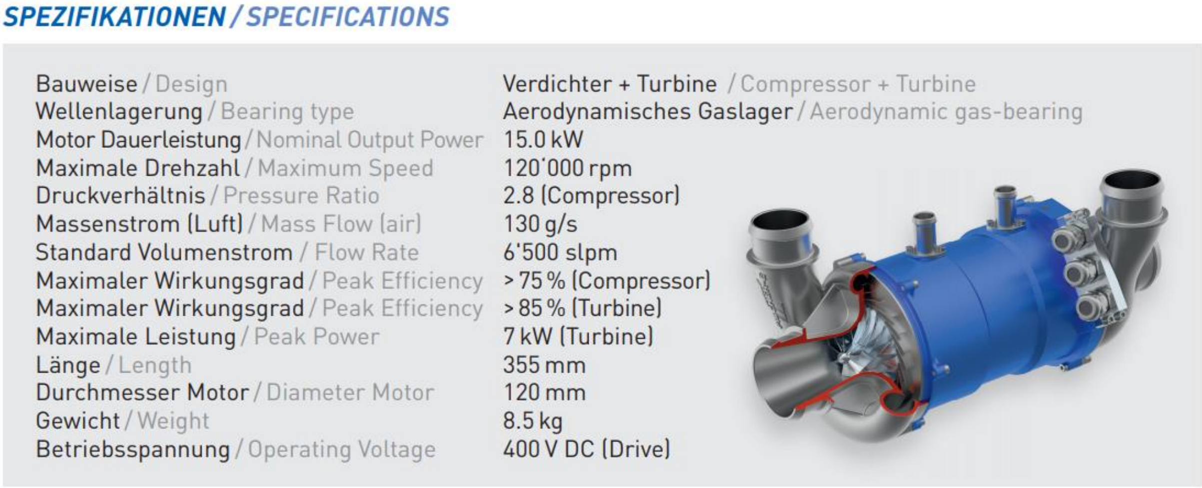

SPEZIFIKATIONEN / SPECIFICATIONS

Bauweise / Design	Verdichter + Turbine / Compressor + Turbine
Wellenlagerung / Bearing type	Aerodynamisches Gaslager / Aerodynamic gas-bearing
Motor Dauerleistung / Nominal Output Power	15.0 kW
Maximale Drehzahl / Maximum Speed	120'000 rpm
Druckverhältnis / Pressure Ratio	2.8 (Compressor)
Massenstrom (Luft) / Mass Flow (air)	130 g/s
Standard Volumenstrom / Flow Rate	6'500 slpm
Maximaler Wirkungsgrad / Peak Efficiency	> 75 % (Compressor)
Maximaler Wirkungsgrad / Peak Efficiency	> 85 % (Turbine)
Maximale Leistung / Peak Power	7 kW (Turbine)
Länge / Length	355 mm
Durchmesser Motor / Diameter Motor	120 mm
Gewicht / Weight	8.5 kg
Betriebsspannung / Operating Voltage	400 V DC (Drive)

Figure 2-8. The datasheet of the Fischer EMTCT-120k Air micro turbo compressor.

This compressor has a built-in turbine to recover compression energy that is otherwise wasted in the cathode exhaust stream and can offset almost half of the original compression energy. The downside to this turbine is that the compressor has a very narrow operating range, as can be seen in Figure 2-9, which places high dynamic requirements on the cathode back pressure control.

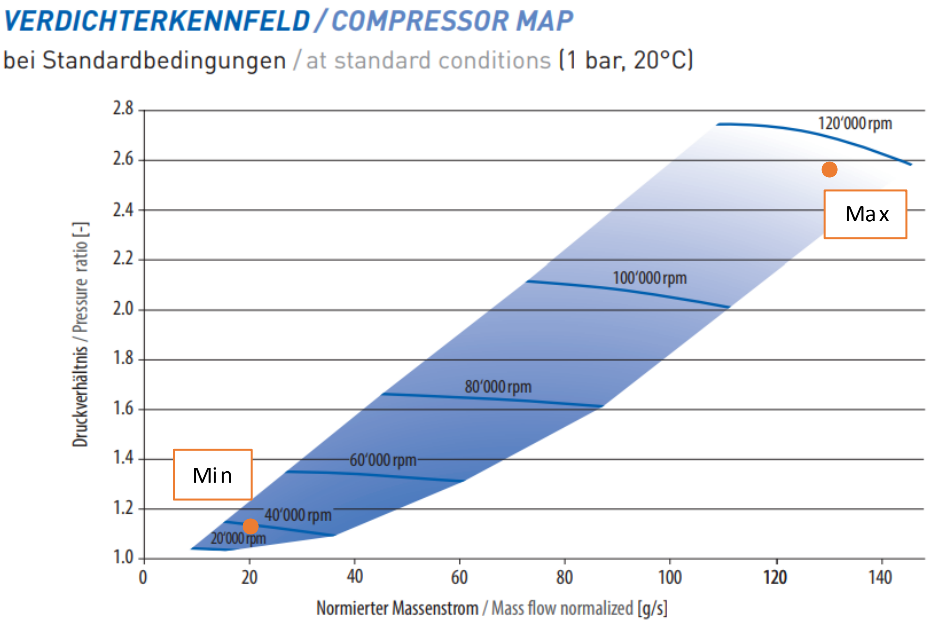

Figure 2-9. The compressor map of the Fischer EMTCT-120k Air micro turbo compressor and the maximum and minimum operating points in the 100 kW Genset system.

The chosen humidifier in the cathode loop in the Fumatech Ecomate H50, which has been proven to work in the support system and is a compact and effective solution, despite it being rated for lower powered fuel cell stacks. This has been fitted with a custom air cooler from API Heat Transfer to cool the exhaust air form the cathode compressor, this is critical to prevent damaging the humidifier membrane. This component is mated to the current humidifier model for a very clean, compact integration as shown in Figure 2-10. Alternative options depend on

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the choice of humidifier and the space requirements; it may be possible to lower the cost by using a standard design but the downside would be a more complex integration.

Properties	Ecomate® H50
Fuel Cell Power	~70 kW
Rated air flow	2000-4000 SLPM
Weight (dry)	6 kg
Volume (without end caps)	11 L
Connection method	Ø2″ clamps
Lifetime	>10,000 hours
Environmental temperature	-30 to 110°C
Operating pressure	≤3 bar(g)
Humidification efficiency	4 to 15°C
Total pressure drop	<16 kPa @ rated flow

Figure 2-10. The Fumatech Ecomate® H50 humidifier with the custom API Heat Transfer charge heat exchanger attached (left) and some key technical data of the humidifier (right).

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3. Power Conditioning

Power electronics and power conditioning systems are relevant components to convert power produced by the FC system into power required for delivery to the end-user according to its requirements/standards.

The power that is generated by the fuel cell stack indeed is not directly useable by the external user and needs to be converted into 230/400 Vac, 50 Hz which is standard across the EU. With reference to Figure 1-2 the power electronics of both the genset can be designed with a layout that includes:

1) DC/DC Converter
2) DC/AC Inverter
3) Battery Pack
4) Fuel cell subsystem auxiliary supply

Such an electric architecture (whose cost is normally between 10-25% of the FC stack CAPEX) allows the slow power dynamics of the fuel cell to be separated from the power dynamic of the external load, that in principle is unpredictable. In this configuration the battery plays the role of an energy buffer that can act as a supply or sink of energy when the power generation does not match the power output. In this setup the DC/DC converter will be controlled with at least three parallel control loops:

1) Stack current control loop
2) Battery current control loop
3) Battery voltage control loop

The best configuration for the DC/DC is a non-insulated switching step down (buck) or step up (boost) converter. The choice between buck and boost is determined from the design of the DC backbone that connects the output of the DC/DC converter to the battery pack and the inverter, that in turn depends on matching the specifications of the battery pack voltage and the inverter input range. The three components need to be considered together when searching for product off the shelf or quasi-off the shelf to reduce costs and enhance reliability.

During the last decade the power electronics and battery components benefited from the growth and the development of the PV (Photovoltaic), BESS (Battery Energy Storage Systems), HEV (Hybrid Electric Vehicle) and PHEV (Plug-In Hybrid Electric Vehicle). For the converters, in addition to the cost benefit led from the mass volume production, a significant improvement of the efficiency from 90-94% to 96-99% has been observed. This result is mainly connected with the deployment within market products of SiC (Silicon Carbide) semiconductors and multiphase converter architecture. In SiC switching semiconductors, the commutation losses can be significantly reduced with the additional benefit of allowing the PWM frequency to be increased and to reduce the size of filtering components (capacitances and inductors), leading to an overall efficiency improvement. Furthermore, the implementation of multiphase interleaved architecture contributes to multiply this positive effect by further increase the aggregate PWM frequency.

As far the DC/DC is concerned, the choice falls between product developed for BESS, HEV and PHEV where bidirectional buck bust has been widely developed. Two alternatives are:

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	MSC 200DCDC750DE	Tame Power COMET series
		
Voltage In	35-700V	150-450V
Voltage Out	200-800V	500-700V
Power	30 kW	36 to 60 kW
Max Efficiency	97%	97%
Cooling	Liquid	Liquid

Figure 3-1. Two alternatives for the main stack DC/DC which converts the variable fuel cell stack voltage to a stable voltage required by the battery pack and DC/AC inverter.

The first choice for the DC/AC inverter would be a PV inverter, but these types of inverters are normally designed to be directly connected to the PV field and needs to implement MPP (Maximum Power Point) algorithms. This makes it difficult to connect a battery pack to the input which is very likely to be required in the gensets. In addition, asking the main industrial manufacturers for customizations is not a viable option due to the limited scope of supply. As a result, alternatives should be searched in the UPS (Uninterruptible Power Source), ESS and Microgrid. The following is an example from ABB:

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ESI-S	
Maximum power at $400V_{AC}$(3-phase)	Up to 85 kW in one unit
Battery voltage range	585-830 V_{DC} at 400 V_{AC} (3-phase) 120-830 VDC at 240 VAC (single-phase)
Connection method	3-phase/3-phase + neutral/single-phase
Inverter range	725 V_{DC} (585 V – 830 V) 400 VAC (380 V – 415 V)
Modularity	Maximum 8 inverters can be combined. S-type: 4 inverters
Efficiency	$\geq$ 97% at P_{Nom}

Figure 3-2. The ESI-S inverter option from ABB which is designed as an energy storage inverter (ESI).

The battery pack should provide energy for start-up shut-down routines and peak shaving; thus, it will be a "power battery pack". The key characteristics of this type of battery is the capability to deliver current in the range 2C to 4C to keep the size small as possible to reduce capital costs. The main battery chemistries to evaluate are Li-NMC, LiFePo4 and Lead acid. The Li-NMC and LiFePO4 types have the advantage of having high discharge capabilities (2C to 25C), high number of charge cycles, a wide temperature range, and high power and energy density. The disadvantage is that they are expensive, require a sophisticated BMS (Battery Management System) to safely operate, and it can be difficult to find products off the shelf with the voltage range required by the EVERYWH2ERE gensets. Lead Acid batteries are more flexible in terms of scalability (connecting them in series and in parallel) and are cheap but have the disadvantages of having low power-energy density, being sensitive to temperature, and have a reduced number of charge cycles. Lead Acid batteries can also discharge hydrogen during charging, and this must be carefully evaluated in the context of the genset. Example of battery product are:

	AKASOL 15 AKM	**NorthStar NSB 12-170RT**
		
Technology	Li-ion NMC	Lead Acid
Type	Battery pack with BMS and cooling	6 cell module
Energy	35.3kWh	40Wh/cell
Voltage Max	756V	2.28V/cell
Voltage Min	486V	1.75V/cell
P max (continuous)	60kW	160W/cell

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Figure 3-3. Two examples of different type of batteries that each have their own advantages and disadvantages in relation to the EVERYWH2ERE gensets.

Alternatively, the feasibility of two other fuel cell stack/power electronics interfaces will be evaluated: (1) linear DC/DC converter and (2) fuel cell directly connected to the DC/AC inverter. Both options can potentially simplify the electronics design and lower the costs but with the potential disadvantage of decreasing of the efficiency or reducing of the fuel cell lifetime.

Lastly the fuel cell auxiliary's converter will be selected accordingly to the needs of the subsystem. Generally, they will be insulated DC/DC, AC/DC connected to the AC output of the inverter, or direct connection to the DC bus for the auxiliaries that accept the battery voltage.

Table 3-1. Preliminary sizing for the main electrical components for the two gensets.

	25 kW Genset	**100 kW Genset**
DC/DC Converter	30 kW Vin = 150 to 300 Vdc Vout = 120 or 650 Vdc Imax = 230 A	120 kW Vin = 280 to 560 Vdc Vout = 200 or 650 Vdc Imax = 450 A
DC/AC Inverter	30 kVA 230/400 Vac, 50 Hz true sine	120 kVA 230/400 Vac, 50 Hz true sine
Battery	6 kWh capacity 120 or 650 Vdc Lead acid or LiFePO	30 kWh capacity 200 or 650 Vdc Lead acid or LiFePO
Auxiliary Supply	24 Vdc and 400 Vdc for a cumulative 4 kW	Up to 10 kW of cumulative power

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4. Heat Rejection

In each of the gensets the fuel cell stack will be cooled through a high temperature (~70°C) cooling loop that takes heat directly from the stack and rejects it to the atmosphere. The most important item in this cooling loop is the coolant itself as fuel cells have requirements that the coolant must meet, most significantly it must have a very low electrical conductivity. As the coolant directly contacts the cells in the S2 and S3 fuel cell stacks, it has the potential to create an internal short circuit which will cause irreversible damage to the cells. In addition, normal vehicle coolants contain additives such as corrosion inhibitors and dyes that are incompatible with fuel cells.

Several companies produce coolants specifically designed for fuel cell applications, such as Glysantin's FC G20 and Dynalene's LC and FC series. As the fuel cell stack and other components continuously releases ions, coolants such as the FC G20 and LC series require ion traps to be installed into the coolant loop to maintain their low conductivity. One option for the ion filter is the Dynalene IC-093-04 high temperature ion exchange resin, although lower-cost, higher-capacity alternatives are being sought after.

The Dynalene FC series is unique as it does not require ion traps to be installed, instead it maintains its low conductivity by containing nanoparticles that have a surface charge that scavenge rouge ions directly from the coolant. The relative advantage and simplicity of not requiring ion traps are balanced by the increased cost of the FC series coolant. In any case, it is difficult, if not impossible, to calculate how long each option will last before the ion trap or coolant needs replacing so it is necessary to continuously or periodically monitor the conductivity.

Table 4-1. Relative advantages and disadvantages of the different fuel cell coolants.

	Glysantin RC G20	Dynalene LC series	Dynalene FC series
Advantages	Lowest conductivity	Cheap and easy to obtain	Does not require ion traps
Disadvantages	Requires ion traps	Requires ion traps	Most expensive

Each genset will also contain a low temperature (~45°C) cooling loop that is used to cool the cathode compressor and any other components the need liquid cooling. As this loop does not contact the fuel cell stack there are no requirements on conductivity so a generic glycol coolant can be used, although the same coolant may be used across both coolant loops to keep the genset maintenance simple.

Two alternatives for the coolant pump are the AVID Technology WP29 and the Pierburg CWA400, which are both cheap and reliable automotive pumps. Technical properties of the two pumps are compared in Figure 4-1, where the main difference is that the WP29 pump can deliver up to 110 LPM (suitable for the 25 kW genset), while the CWA400 can deliver up to 220 LPM (suitable for the 100 kW genset).

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Properties	AVID Technology WP29	Pierburg CWA400
Operating voltage	18 to 32 Vdc	8 to 16 Vdc
Operating current	Limited to 15 A	up to 35,5 A (36.3 A max.)
Maximum flow	108 LPM at over 400 mbar pressure	150 LPM @ 850 mbar 220 LPM @ 550 mbar
Control Type	CAN (full speed control and diagnostics)	PWM duty cycle
Weight	2,95 kg	2,15 kg
Temperature range	-40 to 95°C	-40 to 128°C
Life cycle	>10,000 hours	>10,000 hours
Model		

Figure 4-1. Key technical properties of the AVID Technology WP29 and the Pierburg CWA400 coolant pumps.

The chosen pump will be paired with a commercially available aluminium automotive-type radiator with one or two variable-speed fans. This type of product is mass-produced, lightweight, efficient and reliable. Typically, costs will be much lower than a stationary-type air-cooled heat exchanger, which would also be much larger and heavier.

An option for the coolant expansion tank is the MANN+HUMMEL MCR which comes in six different sizes between 1,5 and 8,0 L, has the option of having a built-in level switch, and has a 1,5 bar(g) overpressure valve built into the filling cap with a dedicated overflow port. The MCR has been designed for heavy vehicles such as construction and farm equipment and is already produced in volume which results in easy availability and low costs. It also has a configurable port arrangement which can be changed according to packaging requirements. The main disadvantage of the tank is that the plastic it is constructed from is not fire rated and may need to be protected from fire sources.

Ideally all power electronic components will be air-cooled and reject their heat to the internal compartment; the ventilation fans will then reject this heat to the atmosphere. If required, an additional cooling circuit can be integrated into the genset which specifically cools the power electronics.

A final feature that will be investigated is the option of adding a liquid-liquid heat exchanger into the high temperature coolant loop. This would permit flexible exploitation of available heat energy, either for genset thermal management or for users' temporary combined heat and power (CHP) applications. An example would be the provision of heat and/or hot water during temporary events.

In normal operation, especially in hot ambient conditions, keeping the genset compartment temperatures acceptably low is expected to be a challenge.

- In addition to the heat removed by the fuel cell liquid cooling loops, the fuel cell system and the electrical equipment both generate waste heat which will be evacuated from their respective compartments using exhaust fans (see under section 7.3 Fans).
- Along with internally-generated heat, solar heat gain can be a major problem and must be minimized. Some possible strategies are listed below. These must be evaluated according to their thermal effectiveness, cost, robustness and ease of implementation:

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- Container external surfaces painted in a light colour or coated in reflective, low-absorption material
- 2nd skin (fabric or rigid panels, light-coloured or reflective) to block direct solar gain, with an air gap to ventilate the solar-heated air
- Internal insulation on roof and sidewalls (rigid foam panels, spray foam, etc.)
- Active cooling (this is not expected to be an acceptable approach)

Heat Rejection technologies (as ancillary services for heat rejection of power electronics) will be presented afterwards. Nevertheless their role is relevant considering that the increase of their performances could be relevant (from 90 to 95% of efficiency), so it will be important to maybe considering innovative strategy/architecture to combine heat rejection systems for stacks and power electronics in parallel.

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5. Hydrogen Storage

The most common method to store hydrogen in gaseous form is in steel tanks, although lightweight composite tanks designed to endure higher pressures are also becoming more and more common. Cryogas, gaseous hydrogen cooled to near cryogenic temperatures, is another alternative that can be used to increase the volumetric energy density of gaseous hydrogen. A more novel method to store hydrogen gas at high pressures is to use glass micro spheres.

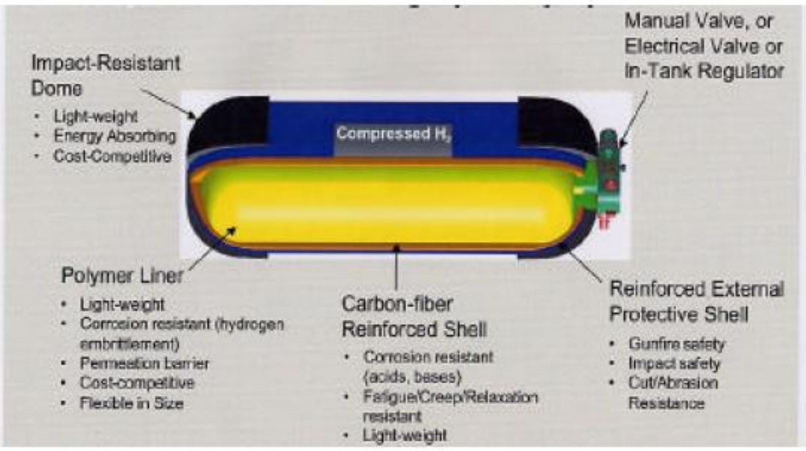

Figure 5-1. Schematic of a typical compressed H2 gas composite tank (Source: Quantum Technologies)

Hydrogen will be stored in the high-pressure tanks developed by MAHYTEC which are four time lighter and two-and-a-half times smaller than the equivalent steel gas cylinder containing the same volume of hydrogen. These tanks have been designed to be used for gas transportation and for refilling stations and are currently on the market in two different sizes: 220 L and 300 L, both designed to fit in the EVERYWH2ERE Genset containers. The tanks are currently in the process of TPED certification and therefore will be able to have a road permit. The 25 kW Genset will have three 220 L tanks while the 100 kW Genset will have nine 220 L tanks; both systems will have a supply manifold that allows refilling, depressurising, and has several layers of over-pressure protection.

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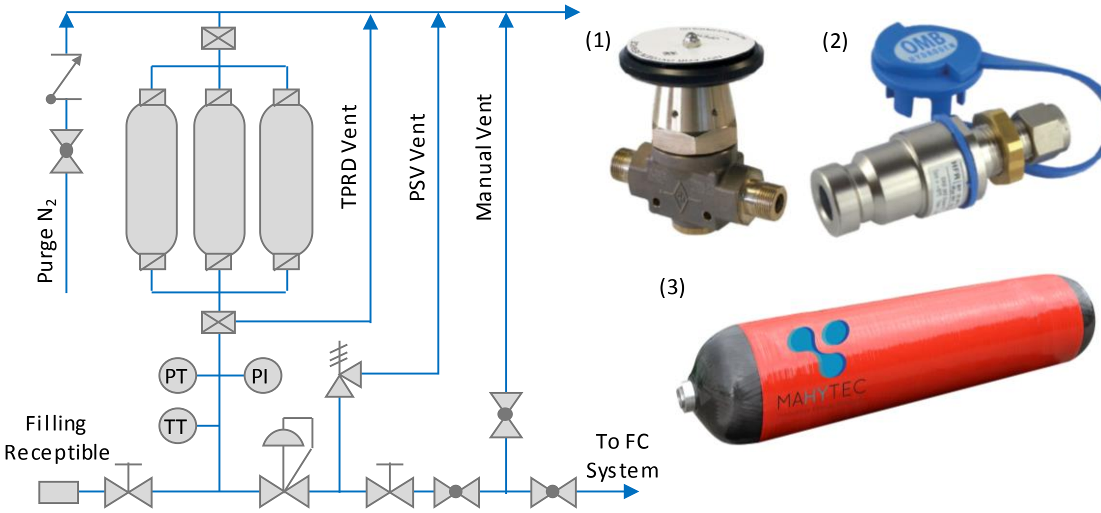

Figure 5-2. The layout of the hydrogen storage system showing three storage tanks (left) and several of the components (right): 1) the Hale Hamilton valve, 2) the 350 Filling Receptacle, and 3) the MaHyTec 220 L hydrogen storage tank.

The main hydrogen supply and feed lines will contain a Hale Hamilton manual valve which is TPED rated and as such is suitable to use as a primary closure for transportable pressure vessels, such as the EVERYWH2ERE Genset. These valves are relatively expensive components (1350€) and the inlet thread have to be adapted to the tank nozzle, but it is essential that the genset has the TPED rating, otherwise the system will not be able to be transported with the hydrogen tanks pressurised. The hydrogen supply line will be fitted with a standard 350 bar filling receptacle (OMB HFR 350) to allow the storage to interface with any existing hydrogen supply system such as mobile or stationary storage facilities or even a mobile hydrogen generator system. In parallel, an industrial connection will be provided to facilitate refilling from hydrogen production plants.

Intermediate pressure hydrogen in the range 3-10 bar, will be delivered to the fuel cell system through a R1100 pressure regulator with a Technical SV 10001 pressure safety valve (PSV) installed downstream for over-pressure protection. The hydrogen the passes through a series of valves, arranged to allow venting of the supply line in preparation for disconnecting the storage from downstream equipment.

Each end of the storage tanks will be connected through a manifold to a temperature-pressure relief device (TPRD) which will protect the tanks for over-pressure and/or over-temperature scenarios. These TPRD's, along with the PSV and manual relief valve, will all be connected to a vent manifold that is directed to a high safe location and a nitrogen purge system will be installed to flush these lines after a pressure relief occurs.

Each of the components in the hydrogen storage system will be certified to use in mobile high-pressure flammable gas systems and will be rated for the full range of environmental conditions to provide a high level of performance and safety.

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6. Control System

The control system of the two gensets will be separated into two sections. An embedded system will control all aspects of the fuel cell stack and support system, as well as the interaction between the fuel cell and DC/DC power converter. The master control unit (MCU) will communicate with power electronics, the hydrogen storage system, the user interface, and the embedded fuel cell system controller. This will allow a common backbone hardware to be developed as the master controller with only minor changes between the two gensets and it will increase the level of safety by having two redundant controllers that can monitor each other.

Datalogging and remote communication for maintenance and monitoring will be provided with GPS module or via LAN if available. Possible supplier for the MCU could be NI (National Instruments) with the NI GPIC board that includes FPGA module suitable for programming high reliability algorithm or hardware in the loop features with loop cycle up to 25ns. GPIC is an OEM product and need conditioning customized boards to properly interface to the field. An alternative control system from industrial automation is the Siemens S7-1200 PLC which has a large set of I/O module to expand the base functionality and BUS modules ready for the connection on the field. The user interface will include an LCD panel where the user can monitor and set the operation of the genset. The electric panel will include electric sockets for 230/400Vac connections with circuit breakers. A suitable example of touch screen LCD from Siemens is SIMATIC HMI KTP400 BASIC COLOR PN.

NI GPIC OEM	SIEMENS S7-1200 series	SIMATIC Basic KTP400
		

Figure 6-1. Examples of some of the control system components.

The MCU will remotely communicate with the project cloud SCADA presumably via MQTT protocol. Both NI and SIEMENS controller have libraries for MQTT.

The control of the MS-30 subsystem is based on the B&R’s X90 hardware which has been designed for use in commercial vehicles, outdoor applications, and other harsh environments. The X90 has four different variants and can contain up to four option boards to expand the functionality of the I/O’s. The controller communicates with external systems with a dedicated CAN bus which allows for message based communication and the ability to set message priorities. The embedded controller of the SHA-100-E (100 kW fuel cell support system) is currently being investigated with a potential option being the automation supplier WAGO. Such a system is currently being implemented in an ongoing containerized fuel cell system project.

GENP and SHSA will realize similar control and communication solutions for the 25 kW and 100 kW gensets also able to remotely monitor (directly via GSM or storing data on a SD card) the performances of the gensets and their position.

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7. Miscellaneous Components

Along with the major components described in the previous sections, there are numerous minor components in each of the gensets. These mainly consist of valves, sensors, fans, and filters and are discussed in the following sections. As many as possible components will be identical between the two systems, although the different flow requirements may necessitate that some components are larger in the 100 kW genset.

In this analysis wiring, connectors, support hardware, and other minor components of the electrical system were not addressed even if it is worth to underline that an optimization of such elements would have a not unremarkable relevance considering that an addition of 10% of BOP cost is normally considered for such components.

7.1 Valves

Solenoid Valves

Solenoid valves will be used throughout the gensets to programmatically turn on and off different flows according to various control schemes or in accordance with start-up and shut-down procedures. These will be sized for the function and location of the individual valves, although, wherever possible the same valves will be used to minimise the number of valve types. There are many different suppliers of solenoid valves with some large European ones including Burkert, ASCO, Emerson, Parker, and Seitz. Each supplier will be contacted about the valve requirements of the EVERYWH2ERE gensets and the suppliers will be chosen based on factors such as valve performance, lifetime, temperature and pressure range, power consumption, materials, and size. It is expected that the valves will be in the process range 50-100€ mainly depending on valve size.

Electronic Safety Valves

Electronic safety valves are a subset of solenoid valves that conform to various safety and performance standards and as such can be directly relied upon for safety. Valves in this category may have an ATEX rating (suitable for use in explosive environments) or have passed type testing of safety standards such as ISO 23550: Safety and control devices for gas and/or oil burners and appliances. As the requirements of these types of valves are much higher than normal solenoid valves, they are expected to cost significantly more than solenoid valves (i.e. >500€ each) depending on which and how many standards they conform too. The same valves suppliers; Burkert, ASCO, Emerson, and Parker, also have a range of classified valves that may cover the requirements of the EVERYWH2ERE gensets and they will be contacted regarding these valves. Due to the high cost of classified safety valves, they will only be implemented if deemed necessary from the standards and risk analysis of the gensets.

Control Valves

Valves that can control their effective opening between fully open and fully closed are considered control valves and have several uses within the EVERYWH2ERE gensets. These valves will be used to control the back pressure inside the fuel cell stack and to keep the cathode compressor within its pressure-flow operating zone. Three-way control valves will be used to bypass the air flow around the cathode humidifier to control the stack humidity, and will also control a coolant bypass flow which is the main stack temperature control device. These valves are more difficult to source as there are fewer uses for them compared to solenoid valves; two

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alternatives are the IMI Buschjost (origin series 82880) and the Belimo (R2/3... series) 2-way and 3-way control valves. The IMI valves are small and cheap but several may be required in parallel to achieve the desired flow rate, whereas only one Belimo valve would be needed but it is much larger. Other alternatives for 2-way control valves are the spring returned throttle valves used in the automotive industry for the combustion air supply. These valves have the advantage/disadvantage that they do not fully close which is not suitable for a shut-off valve but may be an advantage for back pressure control, as they are unable to completely block the flow at low flowrates. Another control valve application is the use of proportional valves to control hydrogen inlet to the FC system's recirculation ejector(s). These valves' opening is determined by a PWM signal, and is infinitely variable while having a very rapid response.

Pressure Regulators

Two pressure regulator valves will be used in each of the gensets, one to reduce the hydrogen pressure from the storage pressure (up to 350 bar) to an intermediate pressure (3 to 10 bar), and a second to drop the intermediate pressure to the fuel cell stack pressure (0,5 to 2,5 bar). The high-pressure regulator has been chosen to be the R1100 as it has ATEX and Pressure Equipment Directive certification and so is suitable to use in the hydrogen storage system (see Section 5). The low-pressure regulator is installed at the feed to the fuel cell stack and does not have the same certification requirements as the high-pressure regulator. Numerous pressure regulators are available from many different suppliers with varying physical size and performance and so a regulator will be selected during the detailed design when performance requirements are set. One important factor, other than performance, that will influence the regulator choice is the maximum pressure rating; this regulator should be able to withstand the failure of an upstream component that can cause the pressure to rise above its normal operating value.

Relief Valves

Relief valves will be used through the gensets as a final non-electrical over-pressure safety device. One of these will be installed in the high-pressure hydrogen storage system with the current choice being the Technical SV 10001 (see Section 5) as this complies with the Pressure Equipment Directive although it is only rated down to -15°C and so may need to be reassessed. It is currently unknown if a second relief valve is required next to the fuel cell stack and if so, if it needs to be safety certified. The need for this valve will be assessed during the risk analysis of the gensets.

Check Valves

Check valves, otherwise known as one-way valves, will be used in various locations to prevent backflow of gasses into upstream equipment, or to prevent flow circulation if parallel pumps or compressors are installed. In general, the use of check valves will be minimised through the design and layout of the process equipment as they present an unnecessary increase in pressure drop, which when around the fuel cell stack, can result in lower system efficiency due to increased compression requirements.

Excess Flow Valves

These valves are a special type of safety valve that will automatically close if the gas flow rate through them becomes too high. This is achieved by the gas flow pushing against a plug which will block the flow, while a spring holds the plug open. When the gas momentum (i.e. flow) becomes stronger than the force of the spring, the plug closes and blocks all flow; the feed line needs to be depressurised, or the outlet line pressurised, for the valve to reset. The need for

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these valves will be assessed during the risk analysis but they may be avoided as they can present operational issues, especially during start-up and shut down scenarios where gas flows can be large when pressurising different sections. While not technically an excess flow valve, flow restrictors may also be used in strategic locations to limit the maximum hydrogen flow rate. If sized correctly, these can significantly limit the maximum hydrogen leakage rate in the case of a catastrophic failure and have little to no impact on the normal operation of the gensets.

7.2 Sensors

Pressure Sensors

Pressure sensors will be used in the anode a cathode sections of the fuel cell support system as a part of the control strategy as well as the safety strategy. Sensors will also be in the hydrogen storage system to estimate the remaining quantity of hydrogen, and the delivery system to monitor the intermediate hydrogen pressure. Basic versions of these sensors are priced around 100€, but this can rise above 200€ if the sensor requires conformity to specific safety standards. There are numerous pressure sensors suppliers and they will each be compared in terms of accuracy and cost to determine the most suitable component to use in the gensets. The hydrogen storage system will also contain a Bourdon pressure gauge so the storage pressure can be confirmed without relying on the control system.

Temperature Sensors

Several temperature sensors will be installed around the fuel cell stack to measure the anode, cathode, and cooling fluid temperatures, as well as the hydrogen storage system, and various ambient locations in the genset container. These sensors are very cheap with sensors priced around 25€, cheap enough that the sensor housing can cost more than the sensor itself.

Hydrogen Sensors

The performance and functional safety requirements of the hydrogen sensor need to be assessed, in conjunction with the risk analysis, to determine what hydrogen sensors can be used in the two gensets. If performance classified sensors are required, an option would be to use the Dräger PEX3000 fixed gas detector which has EN 60079-29-1 (Performance requirements of detectors for flammable gases) approval. Otherwise a sensor such as the NTM SenseH2 could be used, which has UL and ATEX classification and is CE marked for hazardous locations, but does not have a specific performance classification.

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Figure 7-1. Examples of potential hydrogen sensors: the Dräger PEX3000 (Left) and the NTM SenseH2 (right).

Fire Detectors

The gensets may need to be fitted with a fire detector to meet safety standards; if so the functional requirements will need to be determined and a market search performed to find sensors that meet the requirements.

Flow Sensors

Flow sensors are required in the cathode support system to ensure the fuel cell stack has the correct air flow rate to ensure optimal performance and prevent oxygen starvation. With this component, the EVERYWH2ERE gensets can capitalise on the automotive industry's use of air mass flow meters and suppliers such as Bosch can provide highly reliable sensors for a good price. Additional meters may be needed in the coolant loops to ensure correct coolant flow rate and in this application, vortex flow meters provided by companies such as IFM's SV series or Grundfos's VFS series.

Electrical Sensors

The gensets may also require independent measures of voltages and/or currents for redundancy to ensure safe operation. The need for these sensors will be assessed in the detailed design phase as well as the risk analysis and the components will be sourced based on their individual requirements.

7.3 Fans

Each of the gensets will contain several fans that will provide ventilation to the containers. These fans are critical for the normal operation of the system and fulfil several functions:

- Dilution: the main fans provide a layer of safety during operation by diluting any hydrogen leak to safe concentrations. These fans will be sized during the detailed design of each of the gensets to ensure that they correctly meet the specific ventilation requirements. It is expected that these fans will be premium-efficiency, variable-speed axial fans such as the EMBpapst HyBlade® series of fans. These fans are very light, efficient, quiet, and have excellent corrosion resistance to extreme atmospheric conditions.

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- Start-up dilution: in case of a leak, a dangerous concentration of hydrogen could be detected in the fuel cell compartment at system startup. In this case, the ideal solution would be to dissipate the leak and return to a safe condition via passive ventilation. However, the genset's configuration may not permit this approach. In this case, a small explosion-proof exhaust fan would be required for dilution airflow to permit safe intervention and start-up.
- Thermal management: by exhausting hot air from the compartments, the fans will permit operation in hot ambient conditions. The fuel cell system's primary cooling loop will probably be independent of the compartment air, but the system will produce waste heat which must be evacuated. The electrical compartment (assuming air-cooled equipment) will also be cooled by exhausting the hot air.

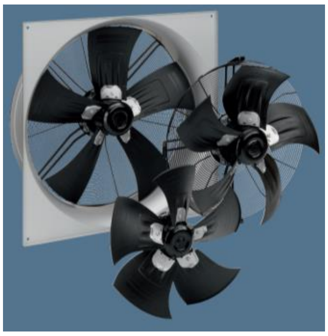

Figure 7-2. Examples of the EBMpapst HyBlade® series of axial fans.

7.4 Filters

The process air filters for both gensets will be from the Freudenberg FC series of fuel cell air filters. These provide high particulate filtration, as well as high adsorption performance of chemicals that are harmful to fuel cells, such as sulphur and nitrogen oxides, toluene, and ammonia. While these filters are excellent for fuel cell applications, they are expensive due to their chemical adsorption properties.

Figure 7-3. Examples of Freudenberg FC series fuel cell air filters showing the closed (left) and half open (right) options.

The air quality required inside the genset containers will be assessed during the detailed design phase and appropriate filters will be selected that are suitable for the required ventilation flow rate. These filters are likely to be standard building ventilation filters, making them a cheap and

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easy component to integrate into the EVERYWH2ERE containers. The air required for system cooling will pass through dedicated air ducts through the genset container and so only needs to meet the requirements of the radiator and fan. These are likely to be automotive components and so are well suited for a wide range of harsh ambient conditions and will only need to be protected from foreign objects and rain using grilles and louvers.

8. Challenges and Innovation

The realisation of the two gensets proposed by the EVERYWH2ERE project presents several technical challenges that need to be overcome to deliver a robust and reliable product. On the flip side, this project also presents an opportunity to innovate beyond the current state of the art solutions and push the boundaries on how fuel cell gensets are designed and what they can achieve in terms of performance and robustness. Some of the key challenges and innovation potential that have been identified in the early stages of the project are detailed in the sections below.

Challenges

EVERYWH2ERE gensets will rely on robust and already proven FC stacks (PCS) and systems (SHSA, GENP) and hydrogen storage (MAHY) technologies already proven and consolidated particularly in the field of automotive and aligned with the current performances of the State of the Art of Fuel cell and hydrogen technologies. Considering that in EVERYWH2ERE gensets a mix of automotive and stationary applications oriented components will be used, a potential support to an effective enhancement of the performances and widespread of the gensets, will be strongly related to an effective development of FC based vehicles.

Table 8-1. State of the Art of Fuel Cell and Hydrogen Storage technologies used in EVERYWH2ERE

Technology	Power/capacity range	Efficiency	CAPEX	Lifetime	Maturity
Stationary PEMFC	0,5-400 kW	32-49%	1000-3000 €/kW	60000 hrs	Early market
Mobile PEMFC	80-100 kW	Up to 60%	500-1000 €/kW	<5000 hrs	Early market
Pressurized Tank	0.1-100 MWh	~99% (without compression)	5000-8000 €/MWh	20 yrs	Mature

A major challenge of the gensets will be related to increase the lifetime of key components in the context of how a genset is typically operated. The fuel cell stack is one of the most delicate components and the nature of a mobile genset does not present the most optimal operating conditions. The stack will need to undergo numerous start stop cycles, have a highly dynamic and unpredictable electrical load profile, and be able to withstand a wide range of environmental conditions including freezing temperatures. The genset must be able to mitigate these operating and environmental conditions if they are to meet the genset target lifetime and potentially increase it to 15,000 or even 20,000 hours.

The second major challenge is to develop an efficient and low-cost power electronics layout and battery pack that allows maximum genset performance and flexibility towards the end user. The power electronics will need to be capable of managing the fast-electrical dynamics that the external load may experience (second to millisecond) in combination with the slower dynamics of the fuel cell stack (tens of seconds to minutes), and it will need to do this in a way that the end user is accustomed to from the benchmark diesel gensets and expects to find in the EVERYWH2ERE gensets.

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Another challenge is obviously related to the integration of a low cost, reliable and high capacity pressurized hydrogen storage composite tank. The main advantages with such composite tanks (like those ones provided by MAHY) are their low weight (meets targets), and that they are commercially available, well-engineered and safety tested (extensive prototype experience exists), and have codes that are accepted in several countries for pressures in the range 350-700 bars. Composite tanks require no internal heat exchange and may be usable for cryogas. The main disadvantages are the large physical volume required (does not meet targets), the ideal cylindrical shape makes it difficult to conform storage to available space, the high cost (400-500 €/kg H2), and energy penalties associated with compressing the gas to very high pressures. There are also some safety issues that still have not been resolved, such as the problem of rapid loss of H2 in an accident or even the evaluation of "complete emptiness" of the tanks which is often an indirect measurement. The long-term effect of hydrogen on the materials under cyclic or cold conditions is not fully understood either as well as the evaluation of the leakage via the tank material. Hence, there is still need for more R&D, specifically:

1. Research on material embrittlement, using new *ad hoc* fracture mechanics techniques.
2. Development of stronger and lower cost construction materials, especially carbon fibers.
3. Reliable and robust increase of storage pressure towards the development of an efficient, cost effective and clean (without oils) 1000 bar compressor.

Other challenges include the humidification performance of the cathode subsystem, which controls the in-stack water management, and the ability to maintain optimal humidification in a wide range of ambient conditions; to create a simple-as-possible user interface to make the system as user friendly as possible; and to meet all relevant standards and directives to allow the genset to be used in a wide range of situations.

Innovation

Within the EVERYWH2ERE project an innovative and robust pressurized hydrogen storage tank will be developed by LINDE and MAHY with three main objectives, 1) reduce system volume and develop a modular rack mountable solution, 2) reduce CAPEX by using adaptable on the market components, and 3) guarantee the possibility of refilling the storage tanks by multiple different methods. The possibility of adapting LINDE solutions to refill hydrogen (commercial as well as industrial) will be also considered to reduce the CAPEX.

Another innovation will be to review the purpose and need for all minor components and wherever possible components will be removed to reduce the CAPEX of the gensets. The remaining components will also be consolidated to reduce the number of different components in the gensets, which will increase the serviceability of the system and allow the integrators to capitalise on bulk components orders which can significantly reduce unit costs.

Component Cost Analysis

With reference to the challenges and innovation potential of the EVERYWH2ERE genset, a cost analysis of the components has been performed. This is detailed in Table 8-2 below which separates the genset into its main sections. The two gensets can be divided into four sections which each contain approximately a quarter of the overall genset component cost, these are 1) the fuel cell stack, 2) the fuel cell support system (excluding fuel cell stack), 3) the power electronics system, and 4) the hydrogen storage system. The remaining components, the heat rejection system, the control system, and the genset container, account for 5-10% of the overall cost.

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The key components that have the largest influence on the overall genset cost are the fuel cell stack, the cathode humidifier, the DC/DC converter, the DC/AC converter, the battery pack and the hydrogen storage tanks; it is critical that these components are correctly selected and not over specified to minimise the CAPEX. The minor components account for approximately 20% and 10% for the 25 kW and 100 kW gensets respectively, so while they do not have a high individual cost, there are many of these components and the costs add up to be significant.

Table 8-2. Cost analysis of the major components of the two gensets.

Estimated Component Costs (€)	25 kW Genset	100 kW Genset
Fuel Cell Stack + Support System		
Fuel cell stack	26,000	70,000
Anode recirculation system (pump and/or ejector)	1,000	2,000[1]
Cathode compressor	17,000	60,000
Cathode humidifier	4,500	10,000
Miscellaneous valves	100 (x5)	4,000
Miscellaneous sensors	100 (x5)	100 (x5)
Overall	***49,500***	***146,500***
Power Electronics		
DC/DC Converter (est. 0,2€/W)	6,000	24,000
DC/AC Inverter (est. 0,2€/W)	6,000	24,000
Battery Pack	6,000	25,000
Axillary supply system	1,000	2,000
Wiring, connectors, etc.	2,000	2,000
Power Panel	2,000	3,000
Overall	***23,000***	***80,000***
Heat Rejection		
Coolant	50	100
Radiator	100 (x2)	100 (x2)
Fans	100 (x2)	100 (x2)
Expansion tank	100 (x2)	100 (x2)
Pump	300 (x2)	300 (x2)
Heat exchanger	100	2,000
Miscellaneous valves	300 (x2)	4,000
Miscellaneous sensors	100 (x3)	100 (x3)
Overall	***2,250***	***7,600***
Hydrogen Storage		
Hydrogen tanks (est. 1250€/kg of H_2)	17,000	51,000
Filling receptible	420	420

[1] To be considered in the project if foreseeing an ejector or pump solution for 100 kW genset

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Manual isolation valve	1350 (x2)	1350 (x2)
Pressure regulator	1350	1350
TPRD	505 (x2)	505 (x2)
PRV	1350	1350
PSV	455	455
Miscellaneous valves	200 (each)	200 (each)
Hydrogen sensors	1200 (x2)	1200 (x2)
Overall	***27,285***	***61,285***
Control System		
Master controller, LCD user interface	2,000	2,000
Subsystem controller	1,100	1,500
Other Component Costs in the Genset		
Container	5,000 (or 2x3000)	8,000 (or 2x5000)
Fans	150 (x4)	150 (x4)
Filters	200 (x4)	250 (x4)
Sensors (e.g. H2 sensor, fire sensor)	1200 (x2)	1200 (x2)
Overall		
Estimated overall component costs	**113,935 € (~4500 €/kW)**	**310,885 € (~3100 €/kW)**

The aforementioned costs, which are the results of this preliminary assessment, have to be properly optimized (as well as mounting, integration, installation costs) in order to keep tracked the objective costs described in the Grant Agreement

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9. Conclusions and Future Plans

In this report a technological and commercial assessment of the state of the art fuel cell and hydrogen storage technologies was carried out towards the definition of guidelines for the specification of EVERYWH2ERE gensets design. These components were analysed in general and with focus on the components that have already been proposed from the technological partners from systems that have already been designed. This report identified that the fuel cell stack, the cathode humidifier, the DC/DC converter, the DC/AC converter, the battery pack, and the hydrogen storage tanks are the most expensive components, accounting for 70-80% of the overall component costs, as well as being the most difficult components to source. For example, both PowerCell and Swiss Hydrogen have independently decided to use a micro-turbo compressor from Fischer Engineering, as well as the Fumatech Ecomate® humidifiers.

Moving forwards from this report, the project will move into the prototype phase where the detailed design of two gensets will be performed and the first prototypes will be realised. This report provides a starting point for which components are available and which technologies are likely to be the most suitable for the EVERYWH2ERE gensets and it will be the main starting point for forthcoming WP1 activities and technical discussion to be held in M5 Technical meeting in Gothenburg.

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