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Specification report

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1 Introduction

1.1 Summary of project scope

The objective of the project is to develop and demonstrate a compact and highly efficient micro combined heat and power (CHP) system based on high-temperature proton exchange membrane fuel cell (HT-PEMFC) technology and a novel two-stage methanol reformer consisting of a aqueous phase reformer and a steam reformer. The developed micro-CHP system is intended as a back-up solution for sequential or simultaneous cogeneration of electricity and thermal energy in rural areas with unstable or zero grid availability. A core focus on thermal integration and waste-heat recovery enable high fuel utilization, high electrical- and CHP efficiency, and dynamic load response and fast start-up for flexible integration with intermittent renewable energy sources. The main project goals and expected impacts are summarized below.

Table 1 – Expected project impacts and KPIs

Expected impact	KPI
Decrease system cost for small-scale CHP	CAPEX < 3000 €/kW
Decrease system size	System volume power density 30 W/L
Increase system lifetime	Degradation < 0.4 % / 1000h
Increased system efficiency	System electric efficiency > 50%
Fuel processor efficiency at BoL	> 85% fuel processor efficiency at BoL
Proved scalability of system and components	Design study of 50 – 100kW system
Flexible operation and RES support	Start-up time < 10 minutes

1.2 Purpose of the document

This document describes technical requirements and specifications for the micro-CHP system developed during the EMPOWER project. This includes a description of intended use and general functionality of the complete micro-CHP system and integration between sub-systems. The micro-CHP system is described on a system-level displaying an overview of major subsystems and components. The micro-CHP system's operation modes and functionality is further described in a State Machine diagram, which is used for ensuring correct and safe use of the developed system. Finally, this document presents an initial safety analysis of the micro-CHP system.

2. Product description and functionality

2.1 Micro-CHP product description

The micro-CHP system is designed to address multiple customer segments representing different needs for sequential and simultaneous cogeneration of heat and power. The intended use of the micro-CHP system is supplying heat and electricity in backup- and off-grid applications. In an off-grid installation or during grid outages, the micro-CHP system provides a highly efficient and dynamic power source, and the system is designed for integration and support of renewable energy sources such as wind and solar etc. The intended applications for the system are in industrial- or residential installations where the generated electricity is used for powering utilities and the waste-heat generated by the HT-PEMFC is used for space heating and preparation of domestic hot water for cooking, laundry, showering etc. Cogeneration promotes high system efficiency, but the system may operate in heat only- and power only mode when necessary.

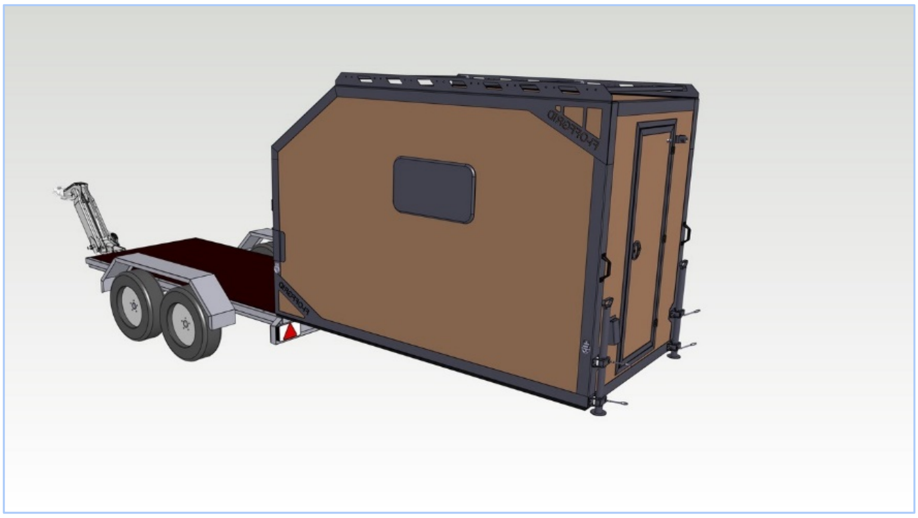


Figure 1 - initial micro-CHP container design

The CHP-system is integrated into a trailer mounted container constituting a mobile workspace (see figure 1). The container is easily loaded and unloaded from the trailer for quick deployment. The micro-CHP system provides heat for the mobile workspace and for external heat demands. During ongoing discussions with customers, the proposed design has been validated for complying with initial customer and use case requirements. Different identified customer / use cases are:

- **User 01** / Raw water test pumping. Raw water test pumping cycles can be up to 1 month long and currently use diesel generators. The basic pump size is 5.5kw, so the power supply should be 6kW. Pump should have a frequency converter, which makes the starting current (of the pump) lower, and if necessary, the frequency converter can be used to adjust the water flow of the pump. The 5.5kW pump operates at 400V and takes about 11.2A of current when running at full capacity. Purity, “no fear of contamination”, and silent operation unlike diesel generators are some of the advantages of a methanol-powered micro-CHP.

- **User 02** / RES power (electricity and heat). The goal is to generate backup power and heat source for 100-150m^2 house. According to calculations, an older house needs 50W/m^2 of heat. In newer houses, 40W/m^2 is enough. In this scenario, the micro-CHP is connected to the circulating water system of the house and to the production of domestic hot water. The 5kW system can maintain one property for several weeks. The same device generates electricity and house / water heating. Simple, quiet, and environmentally friendly. This use case can have two different user situations. One is emergency power where electricity and heat are produced for at least 72 hours. The other operating situation is the connection of the fuel cell device to the water-air heat pump system. This gives the ability to generate electricity and heat in such (a day and year period) when they are particularly expensive. In Finland there is approx. 3 weeks in every winter when temperature drops under -20^{o}C. The required running time could be approx. 500h.

- **User 03** / Mobile hospital heater and electricity device. Using a fuel cell system as a mobile field hospital heater and power generation unit. This would mean that the electricity generated by the fuel cell would be diverted to three different uses. For heating, lighting and electrification of various devices. Space heating would be produced by air heat pump and fuel cell system "wasted heat”. The 5kW system can be split for example 2kW electricity to the lighting and electrification of various devices and 3kW to the air heat pump. Air heat pump can create 10-12kW heating power.

During the EMPOWER project, the system is demonstrated in one of these installation cases.

3. Sub-system functional description

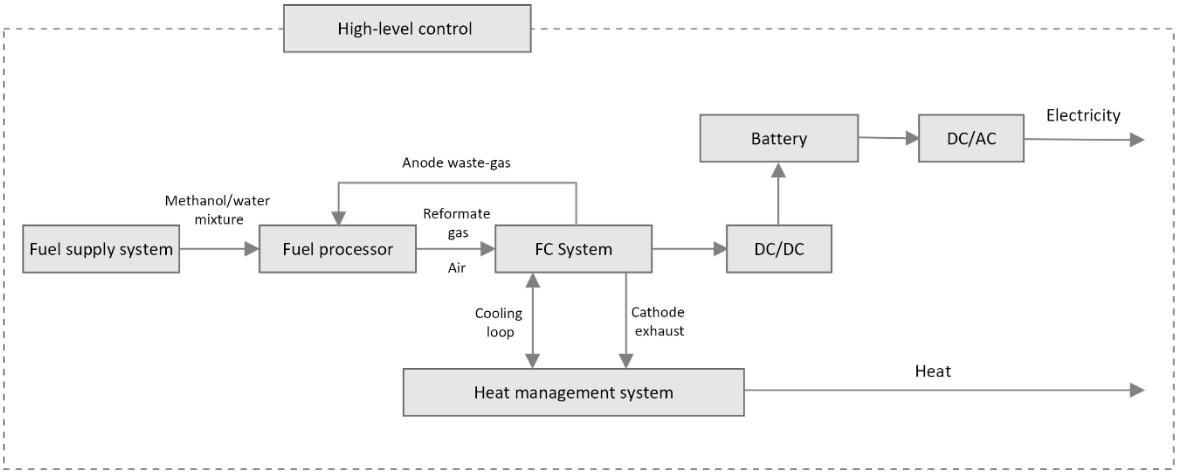


Figure 2 - EMPOWER micro-CHP schematic

The system consists of five main sub-systems: 1) Fuel supply system, 2) Fuel processor system, 3) FC system, 4) Heat management system and 5) High-level control system. The sub-systems are installed in a 19” rack. The 19” rack is integrated and installed into the container presented on figure 1. The major subsystems are described below and the high-level control system is described in section 4.

3.1 Fuel supply system

The fuel supply system ensures adequate flow of a pre-mixed methanol / water fuel consisting of 45 - 55% weight of methanol in water. The fuel supply system is comprised of the fuel tank, fuel pumps supplying fuel for the aqueous-phase reformer and catalytic start-up burner. The catalytic burner provides thermal energy for heating up the complete system during the start-up phase. The fuel supply system is controlled by the Master Controller (described in section 4), which measures fuel level and fuel quality in the fuel tank and detects potential leakages to avoid hazardous events. The fuel tank is enclosed / placed above a spill tray preventing leakages to the external environment.

The back-up duration of the micro-CHP system is defined to >72 hours. With a threshold fuel consumption of maximum 0.9 l/kWh, the fuel tank capacity is >325 litres of premixed methanol and water to conform with the back-up duration.

3.2 Fuel processor system

The fuel processor system consists of an aqueous-phase pre-reformer, a steam methanol reformer, evaporator, mixer devices, heat exchangers, isenthalpic reformer, WGS reactor and electric heater. The fuel processor system is responsible for converting the liquid methanol / water mixture into a hydrogen-rich reformate gas used in the FC system.

3.3 FC system

The FC system converts the supplied methanol reformat gas from the fuel processor into electric and thermal energy. The FC system consists the high-temperature PEM fuel cell stack and DC/DC power conditioning. The system generates electricity at 48V DC with a maximum rated power of 7.5kW. The FC system supplies electricity for balance of plant components including air supply, fuel- and cooling pumps etc. resulting in a minimum net electrical power output of 5kW during normal operation. The HT-PEMFC stack is designed with efficient cooling channels enabling fast heating and cooling to realize a start-up time below 10 minutes. A 4.8kWh battery pack is connected in parallel with the FC system. During start-up (~10 minutes), the battery supports balance of plant components and any external load. Hybridization enables instantaneous power for the user.

3.4 Heat management system

The heat management system is comprised of multiple components responsible for heating the system during start-up and transferring waste-heat from the HT-PEMFC to other thermally integrated elements, sub-systems and supplying heat for external demands. The micro-CHP system is liquid cooled.

4. Operational functionality and state-machine description

The system is operated in four different modes, standby, start-up, operation, and shutdown. The working principles are described below.

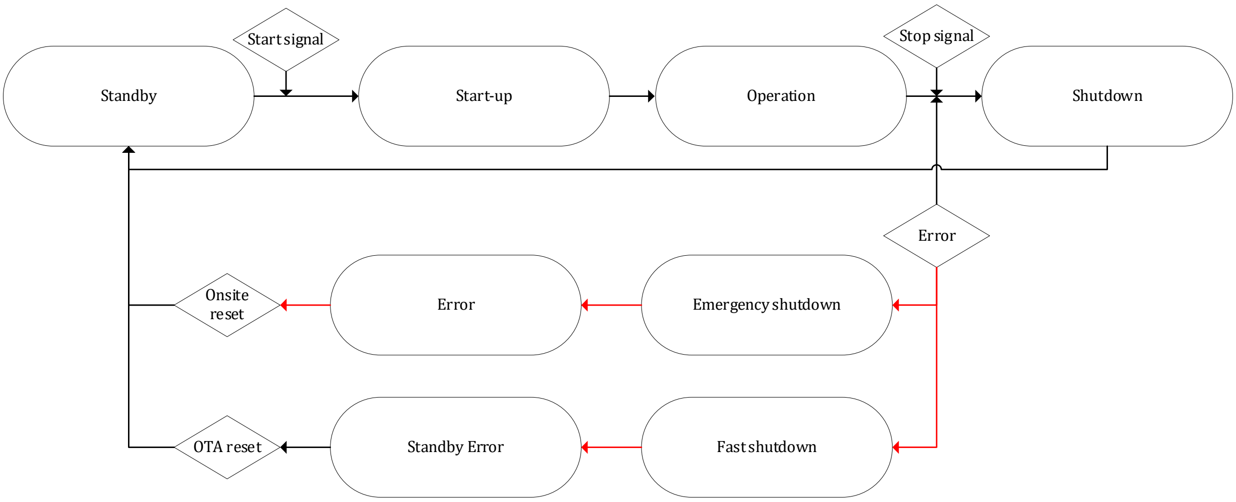


Figure 3 - Simplified state-machine illustration

4.1 Standby

The complete system can be placed in standby / idle mode, where the sub-systems are kept heated for fast response to load changes. Before entering standby mode, the FC system charges the battery. The reformer system operates at minimum load (20% of rated load) when the HT-PEMFC is disconnected. In standby mode, the air flow is adjusted to keep the reformer burner at stable temperature.

4.2 Start-up

During the start-up phase, the battery powers balance of plant components including fuel and coolant fluid pumps, electric heaters, air compressor etc. The electric heaters are used for preheating the HT-PEMFC stack, aqueous phase-reformer, and the methanol steam reformer. The temperature gate for the HT-PEMFC stack to proceed for producing power is 120ºC and the maximum dT is 15ºC. When the stack reaches a temperature above 120ºC, hydrogen-rich reformate gas is supplied at the anode and air is supplied at the cathode for a 5A load. When the OCV is around 1V per cell current is ramped up with 0.2A/s.

4.3 Operation

When the system is fully heated and the HT-PEMFC stack temperature reaches 160ºC flexible changes to demand are possible. The maximum operation temperature of HT-PEMFC stack is 170ºC. At this point, the power produced by the HT-PEMFC stack is sufficient for powering balance of plant components and the external load with a 5kW electric output and an additional thermal output. The primary reformer (steam methanol reformer) produces and feeds the HT-PEMFC stack with methanol reformate gas. The reformer operates at <500°C and the reformer burner operates at ~750°C.

4.4 Shutdown

In normal shutdown conditions, the HT-PEMFC output current is decreased with 1A/s. The reformer ramps down the supply of reformate gas and cathode air is ramped down accordingly. Fans and radiators start cooling the complete system. The fuel supply from the aqueous phase-reformer to the main reformer is turned down and finally stopped alongside the reformate flow and catalytic burner. At temperature of 120°C the current output of the HT-PEMFC stack goes to 0 and at a temperature of 60°C the complete system is considered OFF and active coolant stops. The complete system is then completely shut down or enters the standby mode and awaits new start signal.

4.5 Emergency Shutdown

In case of unexpected failure and hazardous situation, the system immediately stops delivering power and the load is dumped. The fuel supply to the main reformer via the APR system is instantaneously shut-off and the main reformer is isolated from further fuel supply. Air is supplied at maximum to quickly bring down the system temperature. The system enters a “Error” mode. When in “Error” mode, the system is unable to restart itself and must be given a manual and onsite restart signal from the operator after inspection.

4.6 Fast shutdown

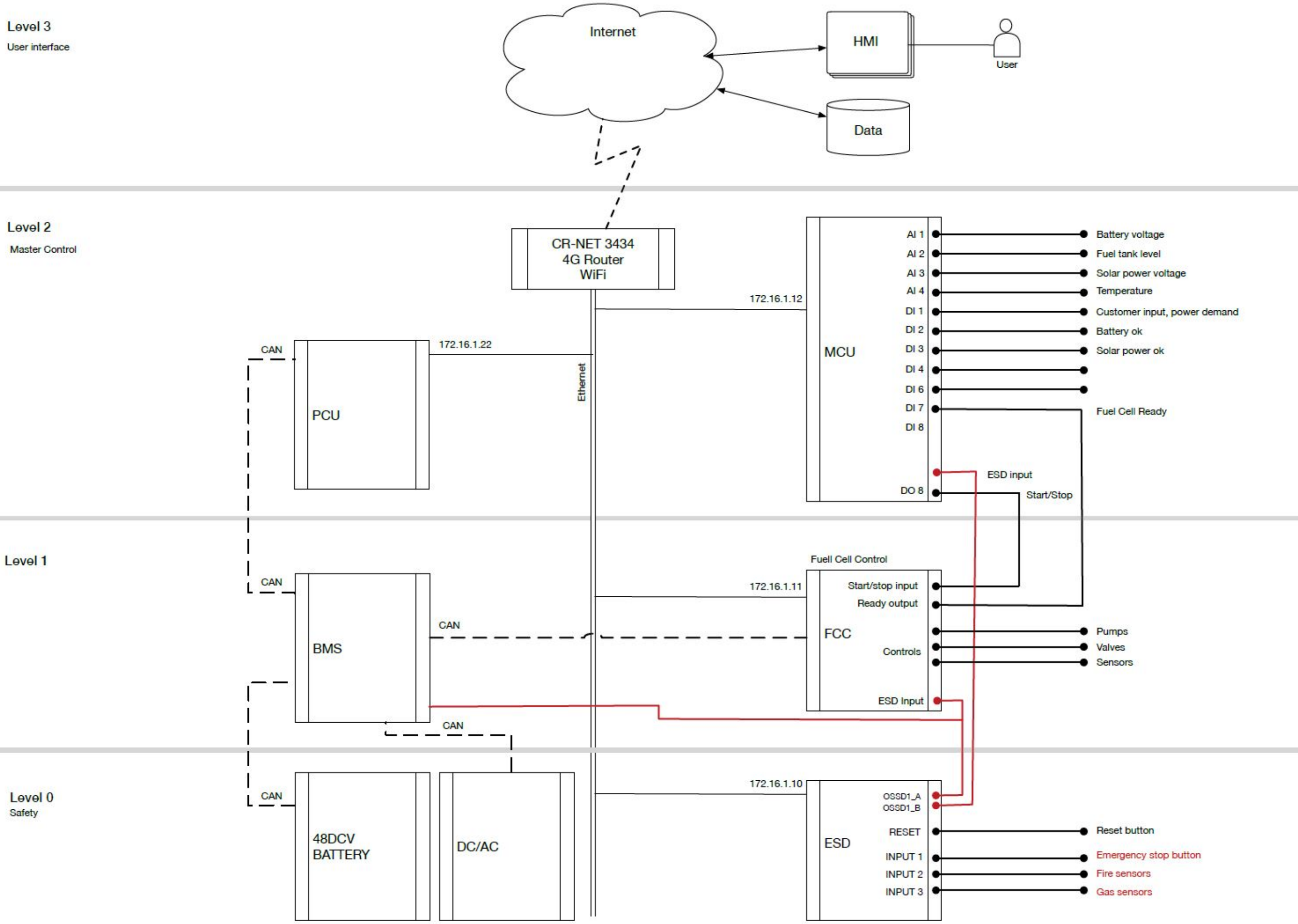
In case of a non-hazardous unexpected failure, the system ramps down and is cooled quickly. The complete system enters a “Standby error” mode where the system is unable to restart itself and needs a restart signal. The restart signal can be given onsite or remote “over the air”. When reset is performed, the system enters normal standby mode and is ready to operate again.

5. Product requirement specifications

	No	Metric	Unit	Value
Performance requirement specification	**HT-PEMFC**			
	1	Rated power @ BoL	kW	7.5
	2	Estimated net power	kW	5
	3	Operating temperature	ºC	160 - 180
	4	Efficiency @ net power	%	> 50
	5	Start-up time	min	< 10
	6	Output voltage	VDC	48
	7	Inlet reformate gas flow rate @ net power	Nm^3/h	6.72
	Aqueous-phase reformer (Pre-reformer)			
	8	Operating temperature	ºC	150 – 220
	9	Operating pressure	Bar(g)	10 – 50
	10	Inlet fuel flow rate	l/h	3.5 – 4.3
	11	Estimated outlet gas composition	%	- 0% CO - 12% CO_2 - 36% H_2 - 18% MeOH - 34% H_2O
	Optiformer (Main reformer)			
	12	Operating temperature	ºC	Ref: 200/550°C WGS:180/230°C Burner: <800°C
	13	Operating pressure	Bar(a)	1 – 1.5
	14	Inlet gas flow rate	Nm^3/h	Depends on APR
	15	Estimated outlet gas compositions	%	- 0.86% CO - 22.2% CO_2 - 68.32% H_2 - 0.37% MeOH - 8.25% H_2O
	Complete micro-CHP system			
	16	Net power output (kW)	kW	5
	17	Net thermal output (kW)	kW	4

	18	Electrical efficiency (%)	%	> 50
	19	CHP efficiency (%)	%	> 90
	20	Fuel processor and HT-PEMFC start-up time	Min.	< 10
	21	Voltage output	VDC	3-phase 400
	22	System degradation rate	N/A	< 0.4% / 1000h
	23	Battery capacity	kWh	4.8
	24	Battery charged by RE	N/A	Yes
Physical requirement specifications	25	System dimensions excl. container and fuel	N/A	19” Rack
	26	System weight excl. container and fuel	kg	< 250
	27	Shock resistant	N/A	Yes
	28	Operating temperature	C°	-20 to + 50
	29	Relative humidity	%	0 – 95
	30	Operating altitude	m	< 2000
	31	Sound level	dB	< 65
	32	Location	N/A	Outdoor
Fuel type and storage requirements	33	Fuel type and grade	N/A	Methanol-water mixture (45-55% of methanol on weight basis). (IMPCA methanol and deionized water)
	34	Fuel tank volume	l	> 325
	35	Fuel consumption	l/kWh	0.9
Control, communication and data requirements	36	Monitoring software / GUI	N/A	Yes
	37	Sensors	N/A	Fire, gas, leakage..
	38	Data interface	N/A	CAN
	39	Monitoring interface	N/A	Modbus TCP
	40	Communication converter	CAN	Modbus
	41	Safety PLC	N/A	Yes
	42	Battery Management System	N/A	Yes

6. High-level system control



The micro-CHP system is designed according to the standards: IEC 62282-3-100: Stationary fuel cell pow-er systems – Safety and IEC 62282-3-300: Stationary fuel cell power systems – Installation. Moreover, relevant regulations, national or EU-wide, for handling and storing methanol will be followed. The high-level system control is designed and categorized in four different levels with different priority in terms of equipment selection, installation, and programming. Everything is designed for security from the starting point.

Level 0: Critical layer, safety components, high voltage components
All components that are at level 0 have been selected according to the highest level of requirements. The devices themselves can pose a life hazard. Safe operation of devices is protected by safety logic.

Level 1: Fuel Cell and subsystems
The fuel cell and reformer in controlled based on power demand from the "consumer". It is controlled by a "control platform", managing all the BOP components in the system. The control platform is a "TTtech" automotive grade platform for the early stages, and for mass production, a dedicated development track will ensure that there is a dedicated control platform.

Level 2: Master controls, PCU (Power control unit) and MCU (Master Control Unit)
The components that control and monitor the entire system are level 2. The overall control of the hardware is done from this level independently.

Level 3: Supervisory level, user interface and data collection
Level 3 includes remote user interface control and data collection for cloud computing. The connection to the arrange is 24/7 available locally and remotely.

7. Preliminary safety and system failure analysis

The preliminary safety and failure analysis is summarized in the following section with emphasis on the fuel supply system, fuel processor system, FC system and specifically the HT-PEMFC stack and lastly, the heat management system. The analysis is based on the failure mode and effect analysis approach.

Table 2 – Preliminary safety and system failure analysis

Sub-system	Function	Potential failure	Potential effects	Mitigation action(s)
Fuel supply system	To supply methanol/water fuel to the evaporator and catalytic burner at specified pressure and flow and supply methanol/water mix to the APR at specified pressure and flow with the required quality and mix standard.	Not able to supply sufficient or any fuel to the catalytic burner because of pump failure, fuel hose rupture, low fuel supply pressure and flow rate and / or inlet restriction, contaminated fuel.	System comes to a complete halt or system is unable to start-up within the desired time frame. Degradation of fuel cell output due to fuel starvation	• Leakage sensor • Pressure sensor on fuel line
		Not able to supply sufficient or any fuel to the APR reformer because of pump failure, fuel hose rupture, low fuel supply pressure and flow rate and / or inlet restriction.	a) Complete operation failure as the APR is not able to send reformate gas to the steam reformer b) Heat and power production is reduced and gets delayed	• PWM signal check on pump • Pressure sensor on fuel line

	Storage of required quantity and quality of premixed fuel	1) Leakage of fuel due to cracks in fuel tank or improper connection between fuel tank and sub-systems 2) Evaporation of methanol leading to improper mixture of methanol / water	The system will not be able to operate at full capacity	• Fuel quality sensor • Leakage detector • Spill tray for fuel tank • Fuel tank level transmitter Correct selection of fuel tank, piping etc. compatible with methanol / water mixture
Fuel processor system (APR and main reformer)	To supply methanol reformate gas to the FC system at specified flow and estimated quality of 0.86% CO, 22.2% CO_2, 68.32% H_2, 0.37% MeOH, 8.25% H_2O.	The fuel processor is unable to deliver methanol reformate gas to the FC system in the correct amount, flow, and quality. Potential reformer stressors: 1) Thermal stress on catalyst 2) Catalyst degradation 3) Incorrect fuel mix for reformer 4) Incorrect fuel for burner 5) Physical stress form shocks and vibrations	a) Thermal stress / sintering of catalyst reduces the amount of active catalyst, whereby conversion ratio is reduced potentially increasing methanol slip and CO levels damaging the FC system. Complete system degrades quickly b) Incorrect fuel mixture to the reformer burner causes the temperature in the burner and reformer to increase, which causes poor combustion and potential structural damage to the reformer c) Physical damage and ruptures in heat exchanger, fuel line, reformer mechanical structure can lead to leakages of reformate gas creating hazardous environment	• Careful control of fuel mix inlet and burner power. Calibrated fuel supply system • Controlled operation of the reformer according to specified reformer manual • Measures to minimize shock and vibrations must be implemented. Use of vibration dampeners is recommendable • Sensors to measure leakage

FC System	To convert methanol reformate gas into electricity delivered at 48V DC and heat.	The HT-PEMFC is unable to operate correctly causing the HT-PEMFC stack the complete system to shut down. Major stressors affecting the HT-PEMFC: 1. Fuel starvation 2. Air starvation 3. Fuel contaminates 4. Air contaminates 5. Acid reduction 6. Freeze start-up Physical damage to the HT-PEMFC stack can cause leakage from the anode triggering an emergency shutdown of the system	a) Ongoing exposure to stressors increases degradation rate and directly effect performance of the FC system. Air contaminants and fuel starvation negatively affects the catalyst layer lowering HT-PEMFC performance. b) Fuel contaminates (CO, MeOH and other hydrocarbons) causes membrane thinning and potential release of harmful emissions such as formaldehyde. c) Leakage form the anode creates an explosive environment with potential harm and injury to personnel	• A feed forward current control loop to always ensure a higher fuel lambda during current ramp-up situations. • Ensure correct fuel quality and flow from the Fuel processor system • Use filters on cathode air inlets in very heavily contaminated areas • Ensure fuel cell operation only on a heated stack and system • All piping and tubing will be tested and over dimensioned for a higher fuel pressure Measure fluctuations in stack output voltage to detect any abnormalities
Heat management system	*During start-up phase*: to continuously circulate the coolant fluid at required pressure and flow conditions; to absorb heat from the catalytic start-up burner and heating the fuel stack to the required temperature	The cooling fluid is not getting circulated because of missing cooling liquid or cooling pump failure The initial and final temperature of the cooling fluid is too low, or the circulating flow rate is too low. Potential failures can arise from cooling pump failure, coolant leakage,	a) The complete system comes to a halt as the HT-PEMFC stack temperature is not rising at all b) Complete system start-up time is prolonged as HT-PEMFC stack temperature is rising slowly	• Coolant circulation pump is tested to ensure compliance with specification • Sensor measuring pressure and flow to detect changes in coolant volume / level

		heat-exchanger failure, start-up burner failure.		• Test(s) during commissioning to eliminate faulty installation and connections of piping/tubing/hoses.
	During operational phase: to continuously circulate the coolant fluid at required pressure and flow conditions. a) To release the heat to (methanol + water) mixture and air b) To extract the heat from fuel stack and transfer to (external cooling loop).	The coolant fluid is not getting circulated and the HT-PEMFC stack temperature is no maintained within 160°C and 180°C. Potential failures can arise from cooling pump failure, coolant leakage, heat-exchanger failure, faulty temperature readings from sensor and heavy leakage of cooling fluid.	The complete system stops producing power because of overheating of the HT-PEMFC causing severe damage and the fuel processors are not able function correctly.	• Coolant circulation pump is tested to ensure compliance with specification • Sensor measuring pressure and flow to detect changes in coolant volume / level • Test(s) during commissioning to eliminate faulty installation and connections of piping/tubing/hoses.