MARANDA – Marine application of a new fuel cell powertrain validated in demanding arctic conditions
Grant agreement no: 735717

D7.1 Design and layout of fuel cell system into 10ft container for durability testing in Äetsä

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Summary

This report represents the design and layout of the fuel cell system that will be used for durability testing in MARANDA project. The site for durability testing will be Kemira Chemicals plant in Äetsä, Sastamala, Finland.

The durability test system will be installed into two 10-ft freight containers and consists of three sub-systems: fuel cell power module (FCPM), power electronics (PE) and higher-level control system (HLCS). The FCPM is manufactured by Swiss Hydrogen, the power electronics by ABB and the integration of these two systems, together with safety features and higher-level control system, is implemented by VTT. The higher-level control system is based on industrial automation and will allow data logging and remote monitoring of the test system.

A system overview, the sub-system specifications and interfacing of these sub-systems mechanically and electronically are represented, and the system layout as well as necessary drawings for full system installation with preliminary component list are given in the Annexes.

Confidentiality	Public

Contents

1. Glossary

Aranda	The naval research vessel Aranda
AUTO SD	Automatic shutdown
BoP	Balance of Plant
CAN	Controller Area Network, communication bus standard
ECU	Engine control unit
EMSD	Emergency shutdown
FC	Fuel cell
FCPM	Fuel cell power module
H2	Hydrogen (gas)
HLCS	Higher-level control system
HEX	Heat exchanger
HMI	Human-machine interface
LFL	Lower flammability level
MARANDA	The European H2020 research and development action/project
PEMFC	Proton exchange membrane fuel cell
PE	Power Electronics
PLC	Programmable logic controller
SCADA	Supervisory control and data acquisition

2. Durability test system overview

In the MARANDA project, a 165 kW(AC) PEMFC (proton exchange membrane fuel cell) system, consisting of two 82.5 kW FCPMs (fuel cell power modules) is installed on board the research vessel Aranda. To guarantee reliable operation of the MARANDA system, its first generation, consisting of one FCPM will be tested on shore in a durability test bench.

The durability test bench will be built by VTT. The test bench is divided into two containers: the FC (fuel cell) system container and the PE (power electronics) container illustrated in Figure 1.

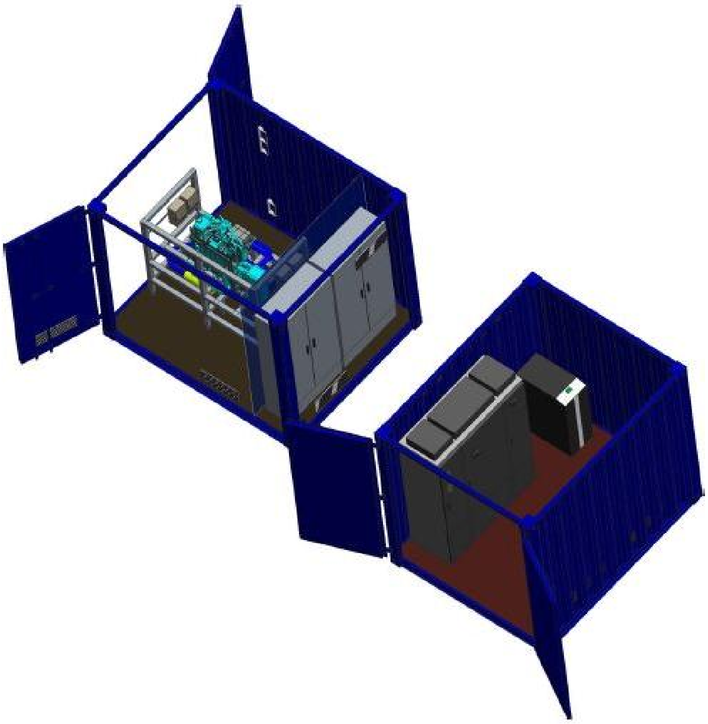


Figure 1. Layout of containers. FC system container on the left side and PE container on the right side.

The FCPM and test bench controls will be initially tested in VTT laboratory in Finland, Espoo. After successful tests, necessary development of the control system and FCPM characterisation it will be transported to Kemira Chemicals plant site in Äetsä, Finland, for long-term durability testing. The FCPM will be run for more than 4380 hours (six months).

The involved partners and their main responsibilities in this work are listed in Table 1.

Table 1 - Partners and their roles in system durability testing

VTT Technical Research Centre of Finland Ltd.	FI	Test bench design & assembly, HLCS (higher level control system) development, commissioning tests, plant site installation and durability testing
Swiss Hydrogen SA	CH	Provider of PEMFC power module (FCPM) to VTT and support in system integration
ABB Oy	FI	Support in system integration and testing regarding power electronics

Additionally, Kemira Chemicals from Finland will provide the long-term test site at their plant in Äetsä. Kemira is not a partner in the MARANDA project but has agreed to support the long-term testing operations as well as test bench installation.

2.1 Higher-level control system

The higher-level control system is based on Schneider Modicon Premium Automation platform and PLC (programmable logic controller), **Error! Reference source not found.**. Modicon Premium PLCs are used for example in manufacturing processes, plant infrastructure or complex machine applications. It has a high performance processor and a multitasking operating system. Programming of the PLC is carried out through the Schneider Unity Pro environment where any of the IEC 61311-3 standard programming formats can be used, such as structured text or function block programming.

Figure 2. Schneider Modicon Premium Automation platform and PLC

Cromi, by THT Control Oy, software (based on the Inductive Automation Ignition platform) is used for the human-machine-interface (HMI) and supervisory control and data acquisition (SCADA). Cromi provides tools for communicating with the Schneider PLC through a gateway, for the user to see the measurement values, control the outputs and delivers the data into a MySQL database. This arrangement is illustrated in Figure 3.

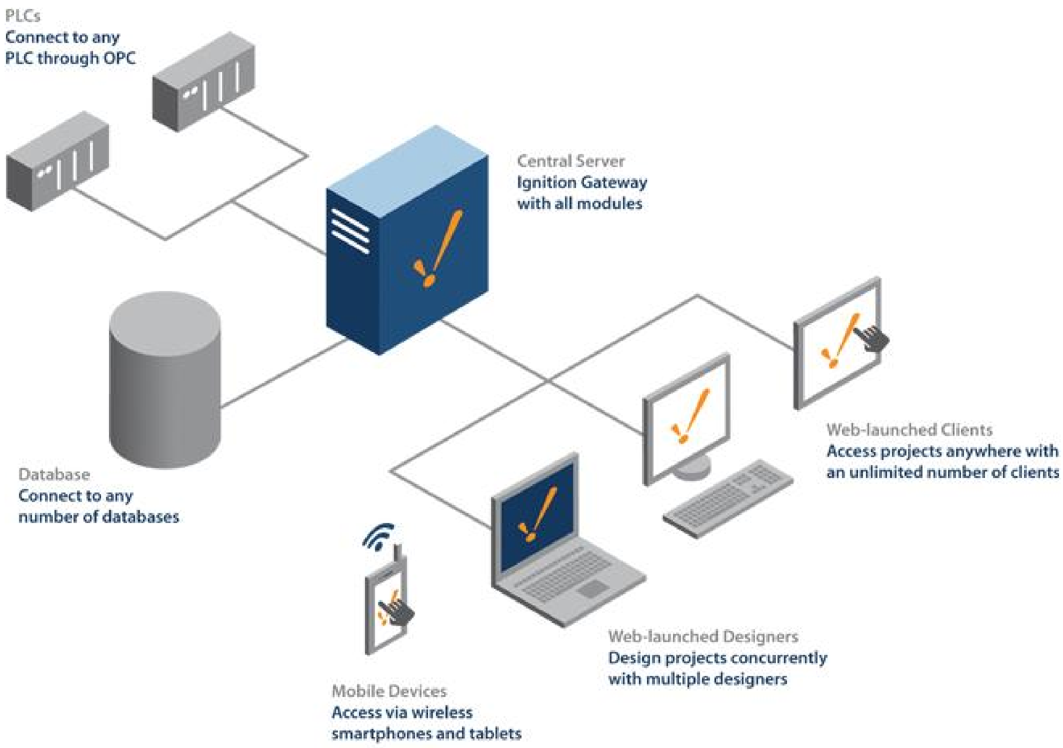


Figure 3. Cromi SCADA/HMI standard architechture

2.2 Fuel cell power module

Swiss Hydrogen will provide the FCPM to VTT for integrating into the durability test bench. The FCPM is based on the Swiss Hydrogen model SHA-100-E module, which is further developed for marine applications within the MARANDA project (WP4). The SHA-100-E system general specifications are given in Table 2.

Table 2. SHA-100-E general specifications

Nominal power	96,9 kW
Nominal current	300 A
Peak current	450 A
Nominal voltage	323 V
Voltage range	250…500 V
Number of cells	455
Waste heat	82 kW
Dimensions (H x W x D)*	708 x 403 x 528 mm
Weight	98 kg
***Not included: air filter, air mass flow meter, brackets, wiring harness, covers, heat shields, coolant reservoir, compressor inverter**	

FCPM includes following components and subsystems:

- Fuel cell stack
- Cathode subsystem: air compressor, charge air cooler, cathode drain valves
- Anode subsystem: proportional valves to control flow rates and pressures, purge valve, hydrogen cyclone, heat exchanger for pre-heating fed hydrogen
- Primary cooling loop: plate heat exchanger, coolant pump, by-pass valves, coolant reservoir, ion exchanger
- Programmable automotive engine control unit (ECU)

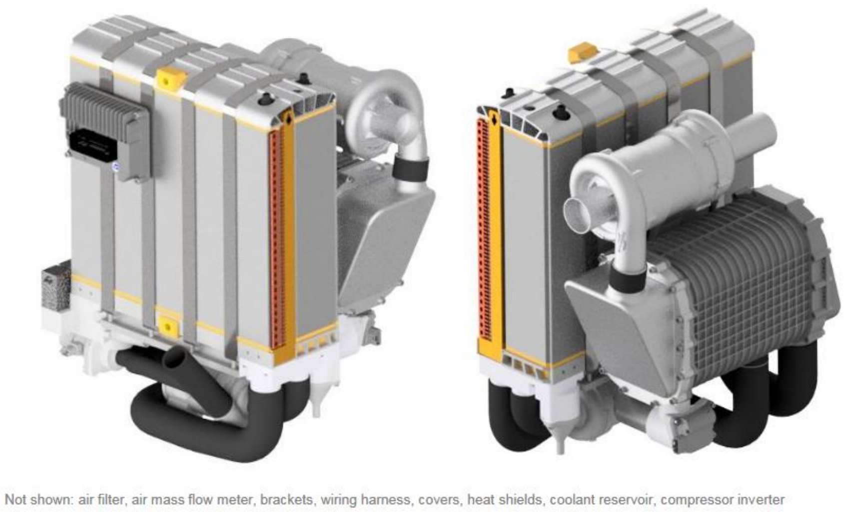


Figure 4. Illustrative 3d-model of SHA-100-E

2.3 Power electronics

A commercial ACS-880 converter/inverter by ABB functions as the main interface between the test bench and the power grid. The power electronics setup includes the air cooled inverter, LCL-filter and galvanic isolation transformer from grid. The schematic is illustrated in Figure 5.

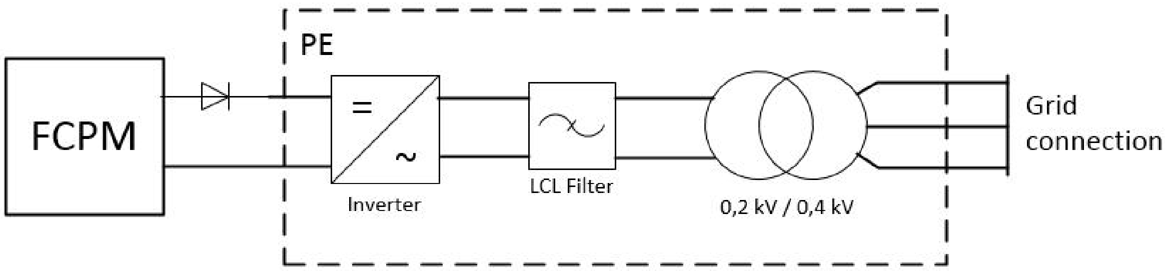


Figure 5. Power electronics (PE) schematic

The DC/AC inverter implements the load control of the fuel cell test bench. In practice, the load current setpoint given at the HLCS is relayed to the inverter as an operating setpoint.

Communication between the inverter and the HLCS is based on Profibus digital communication protocol.

2.4 Operating principles

PEMFCs are electrochemical devices which produce electrical energy when fed with reactant gases, usually hydrogen and air. The chemical energy from the reactants is converted into electricity and heat through an electrochemical reaction occurring inside the fuel cell. This allows for continuous power if the reactant gases are fed constantly.

The durability test bench will be built for the FCPM developed and built in MARANDA WP4. This FCPM is based on the Swiss Hydrogen SHA-100-E module and has readily integrated most of the balance of plant (BoP) components integrated necessary to ensure continuous operation of the FCPM. Basic functionality, such as air feed, thermal and water management of the fuel cell stack, primary cooling loop etc. are provided as part of the FCPM.

The HLCS (higher-level control system), developed by VTT, has the responsibility over the anode gas feed, secondary coolant circuit, exhaust gas treatment and safe venting. The electrical power produced by the FCPM will be fed into electric grid through ABB's PE cabinet, which includes filtering, DC/DC and DC/AC converters. The HLCS will be responsible of test bench control, container safety and operating state changes of each system.

2.4.1 Operational states of HLCS

The HLCS will have five operational states given in Table 3 and Simplified system flow chart from stand-by state to normal operation state is presented in Figure 6.

Table 3. HLCS Operation states and corresponding actions

Operation state	Overview of actions
Stand-by	HLCS confirms communication between systems, confirm systems healthiness, waits for user command
Start-up	Open gas feed valves, start coolant pump, initialize start-up routines of FCPM, pre-load inverter from grid, wait for FCPM to be ready for loading, connect FCPM to grid
Normal	User gives command of stack current, FCPM limits current when necessary
Auto shutdown (AUTO SD)	Normal system shutdown routines are done in safe manner, afterwards system returns to Stand-by -state
Emergency shutdown (EM SD)	Container ventilation fan to maximum output, power off FC system container, nitrogen purge of hydrogen lines

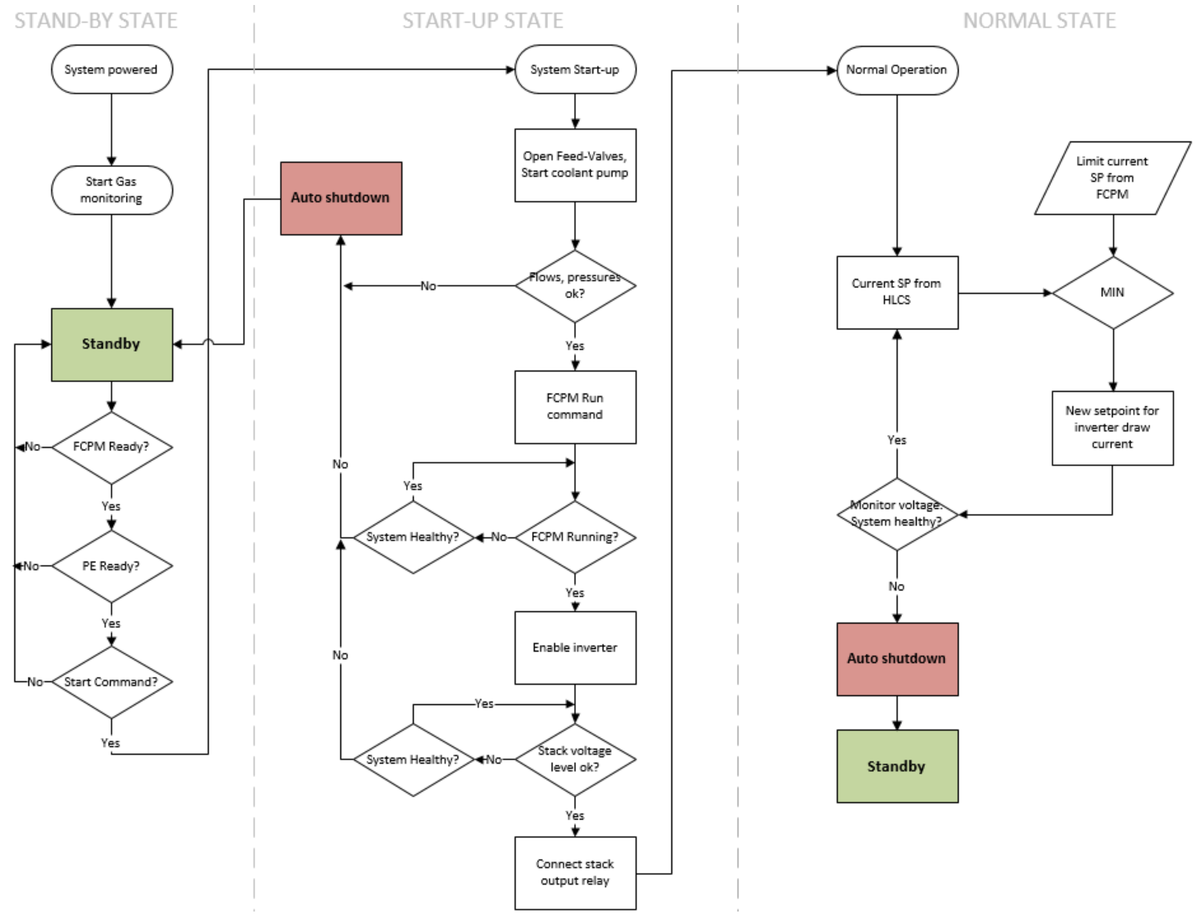


Figure 6. Simplified system flow chart

After powering the system, it will remain in Standby-mode until each subsystem is ready, communication and self-tests are successfully made, and user gives a star-up command.

When system start-up command is initialized, it will run through series of routines (valve controls, flow, pressure and cell voltage monitoring etc.) until state for normal operation is reached. At this point, the FCPM will be connected to the grid, through power electronics, to enable feeding its output power into the factory grid.

In the normal operation state, the desired FCPM current setpoint is given through the HLCS either directly by a human user or as a load cycle (e.g. based on load cycle or a load cycle generated by an algorithm). The given current setpoint is compared to the current limiting information, which is available all the time from the FCPM. Finally, the minimum of these two values is realized through the power electronics, which will load the system accordingly. The current limitation by the FCPM is mostly relevant during transients and is due to the inertia of the system, especially related to the air compressor. This limits the current ramp rate. The given current setpoint from HLCS is, however, normally reached in a matter of seconds.

Two modes of shutdown are used to ensure safety of personnel and materials around the system: auto shutdown (AUTO SD) and emergency shutdown (EM SD). AUTO SD corresponds to a “normal” controlled shutdown routine, and can be triggered by either the operator or the system safety automation. In particular, the safety automation will trigger an automatic shutdown if a level of > 20 % of the hydrogen lower flammability limit (LFL, 4 vol-% in air) is reached at the hydrogen leak detector. The AUTO SD routine will bring the system to a safe, inert mode in a manner which has no significant influence on the system lifetime or performance.

EM SD means in practice an abrupt shutdown, de-energization and purge of the whole system. This shutdown mode is triggered if > 40 % of hydrogen LFL is reached at the hydrogen detector.

In conjunction to both shutdown modes, the (ATEX rated) ventilation blowers are set to maximize the container ventilation air flow rate. A flow chart of gas-monitoring and shut down routines are illustrated in Figure 7.

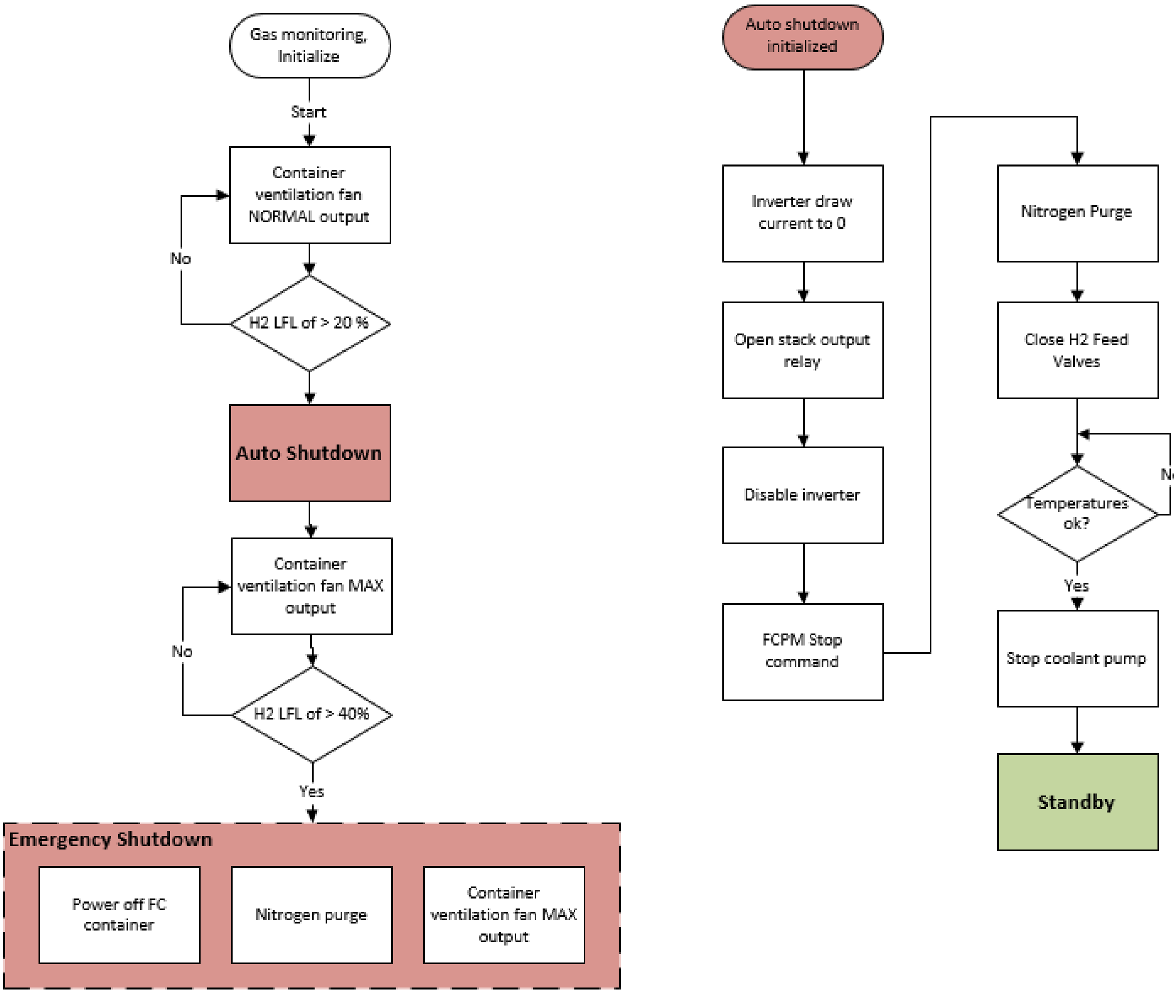


Figure 7. Flow charts of gas monitoring, EM SD initialization and AUTO SD

3. Interfacing

The interface specification of the durability test bench is given in the following section. This information forms the basis for the test bench design work.

3.1 Durability test site properties

The durability test site will be located within the Kemira Chemicals Oy chemical plant site in Äetsä, Sastamala, Finland. The test site has previously been used in VTT's DuraDemo-project, where a 50 kW PEMFC system was studied and run at the site for more than 4000 hours. Because of this, some of necessary infrastructure for durability test bench is ready-made and properties of the site are given in

Table 4.

Table 4. Durability test site properties

By-product hydrogen supply from factory processes	< 6 barg, Vmax ? (DN 20)
Tap water for cooling	T > 5 degC, Vmax ?
Drain pipe for water	
Exhaust pipe lines	Anode exhaust (Ø 100 mm) Cathode exhaust (Ø 150 mm) Container ventilation (Ø 300 mm)
ATEX rated fan for container ventilation	Systemair DKEX 225-4 centrifugal blower
Ambient temperature	10…40 degC (factory hall)
Electrical connection to grid	3-phase 100 kVA

The durability test bench is fed with purified by-product hydrogen from the industrial sodium chlorate process. The quality of the hydrogen will be continuously monitored to assure its quality. Hydrogen supply is available in max 5.3 barg pressure, but is expected fluctuate from previous experience.

3.2 FCPM interfaces

Mechanical connecting ports or necessary pipe/hose dimensions, flow medium properties and pipe specifications of the FCPM system are given in Table 5.

Table 5. FCPM mechanical connections and fluid specifications

Line name	Medium	Pipe Specifications			Flow rate [nlpm]			Pressure [bar(a)]			Temperature [°C]		
		Material	Diameter [mm]	Connection	min	nom	max	min	nom	max	min	nom	max
H2 Feed	Hydrogen	SS	12	Swagelok	0	1015	1355	8	9	10	0	20	90
N2 Feed	Nitrogen	SS	12	Swagelok	0	300	600	6	9	10	0	20	90
H2 Purge	Hydrogen, Water (few)	SS	10	-	0	150	200	1	2,2	2,4	0	80	90
H2 Drain	Water, Hydrogen (few)	SS	10	-	0	0,3	0,6	1	2,2	2,4	0	80	90
Air Feed	Air, pre-filtered	-	-	G 2" inner	0	4400	6000	0,8	1	1,05	-40	20	45
Coolant in	DI-water, Glycol mix	Silicon	61/51		0	150	300	0	2	16	-40	30	45
Coolant out	DI-water, Glycol mix	Silicon	61/51		0	150	300	0	2	16	-40	37	52

The durability test bench need to have enough capacity to provide sufficient flow rates of given mediums and stay within specified limits regarding pressure and temperatures. Some

connecting ports are preinstalled and are provided with FCPM, others will be added on the pipelines during integration of FCPM into the test bench.

FCPM needs to be supplied with electrical power with given specifications in Table 6.

Table 6. FCPM supply power requirements

Supply voltage	400 V, 50 Hz, 3 phase
Nominal Power	10, 6 kW
Peak Power	15 kW

3.3 Power Electronics interfaces

Electronic train concept: PEMFC + inverter + line transformer.

- ABB ACS-880 drive, LCL-filter and 230/400 Vac 3-phase transformer
- PEMFC produces 300 – 600 Vdc, 0 – 200 A which is fed to the inverter DC-bus
- Isolation transformer has 230/400 Vac windings, providing voltage matching
- Inverter is operated at half the voltage it was designed
- System built according to relevant standards
    - IEC 62282-3-x, ISO/TR 15916, EN 50438, IEC 60664-1, IEEE 1547 etc.
- Can be used for reactive power compensation as well

3.4 Communication interfaces

Connectivity and communication layers between systems connected to HLCS are illustrated in Figure 8. Main purposes of the higher-level control system is to control between different operational modes, manage power output into the grid and ensure safe operation of the system. This control is done through different physical layers (copper wire, twisted pair, Ethernet) and several communication standards are used.

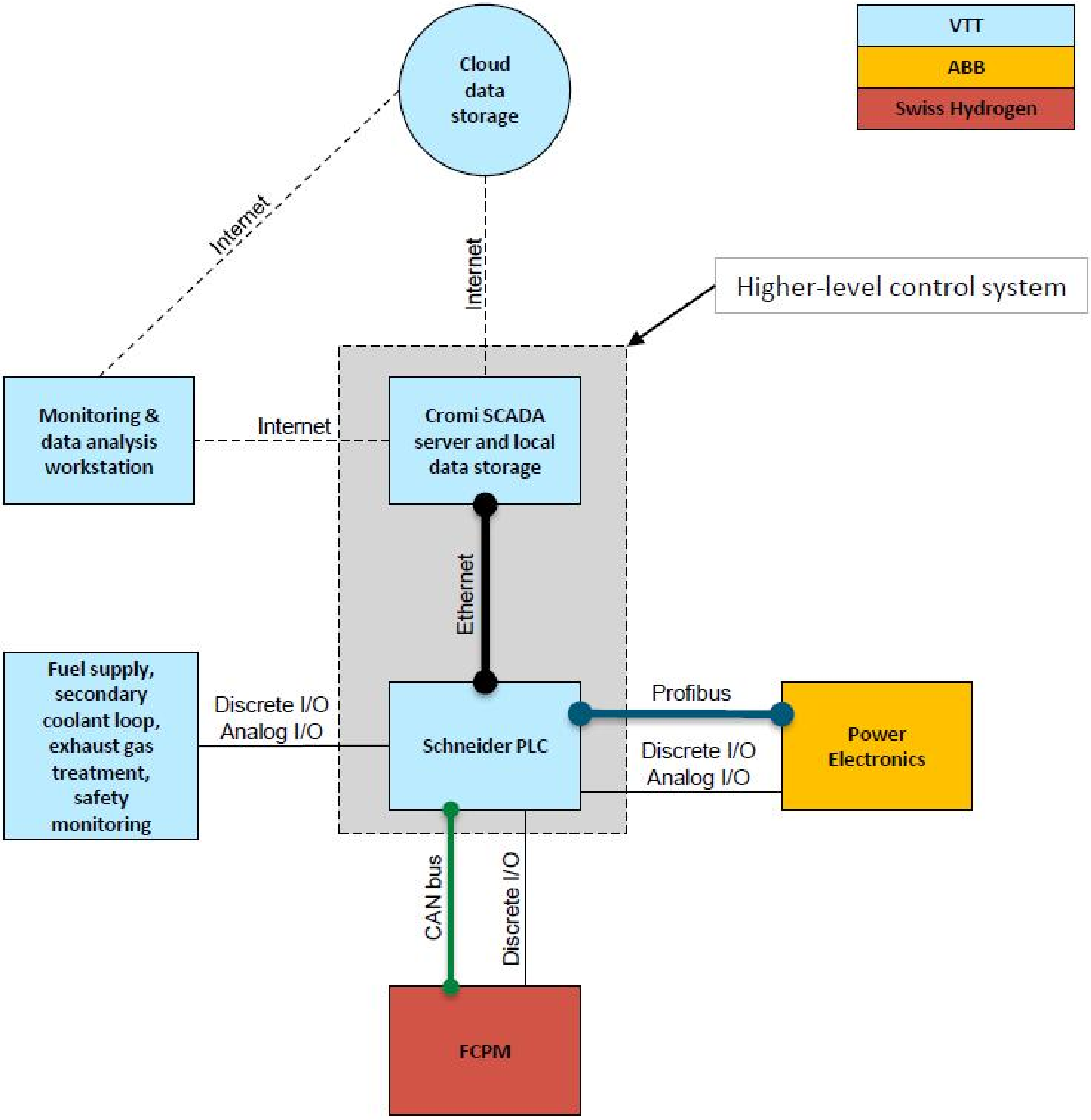


Figure 8. Connectivity between subsystems

Communication between HLCS and FCPM will be implemented with CAN communication standard and additional discrete signals. These discrete signals can be used during CAN communication failure to initiate the FCPM automatic shutdown (AUTO SD) and emergency shutdown (EM SD). Communication with the power electronics will be implemented with Profibus communication standard and with additional discrete I/O signals from HLCS.
Simplified list of I/O and bus messages are represented in ANNEX I: Piping and instrumentation diagram (PID).

4. Requirements for the durability test bench

The physical interfacing and equipment as well as the data communications devices documented in the previous Sections form the basic framework for the durability test bench. In the end, the capacities of said parts must be fit with the requirements set to the durability test bench regarding its test performance capacity.

An initial requirements list for the test bench was formulated based on the FCPM and PE specifications, the test site properties and the chosen control principles. The requirements list will guide the design work for the test bench and is used as a communication tool between system suppliers. The final design needs to fulfil all the requirements specified in the requirements list. The test bench preliminary requirements list is given in Annex I.

4.1 Test bench basic process and mechanical design

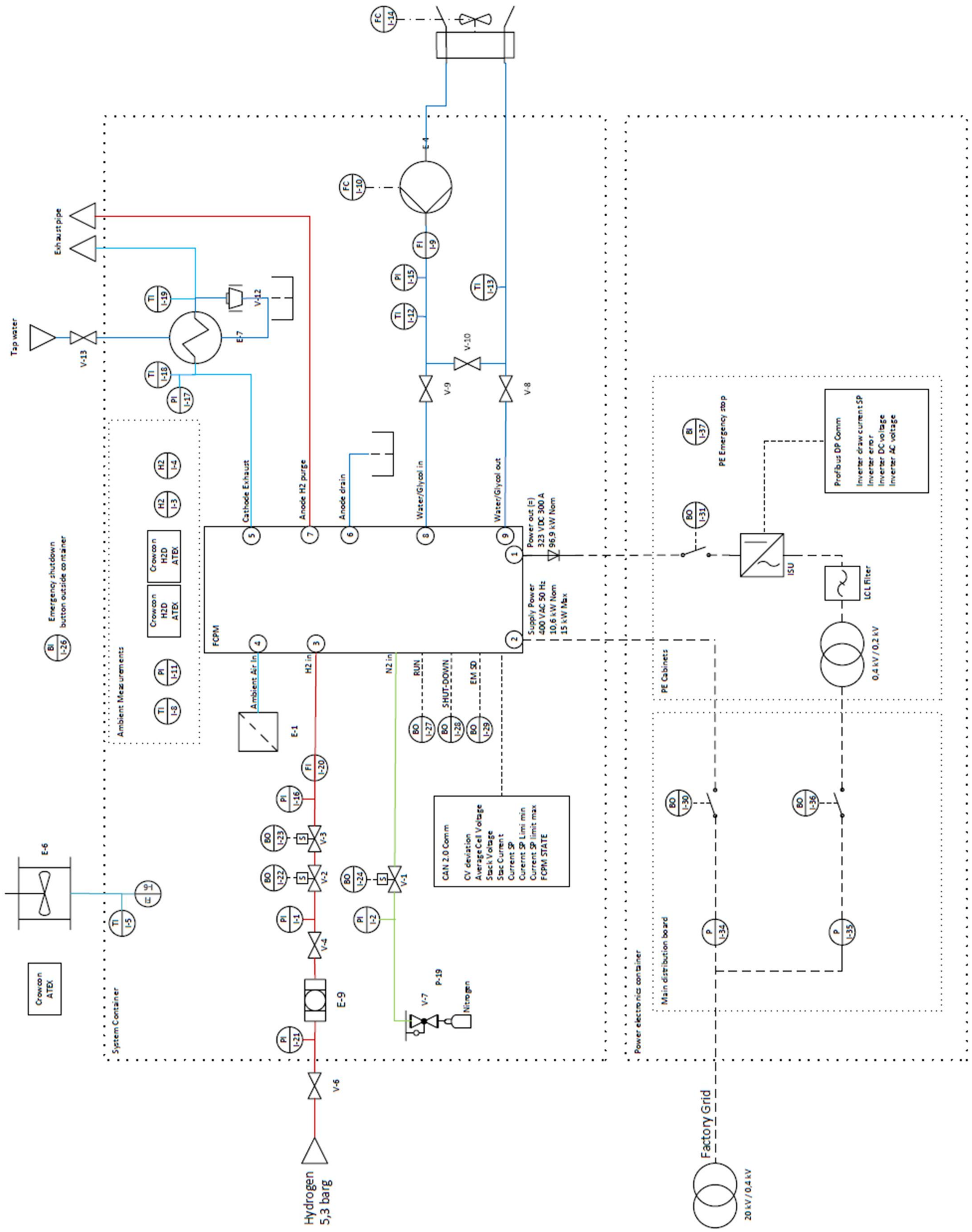
Based on the technical subsystem information and the requirements list, a piping and instrumentation diagram was drawn including necessary test bench system components (Annex II). Mechanical design of the test bench frame was started together with component selection. The mechanical design of the system together with layout of the full test bench system in two containers is represented in Annex III. These documents, along with the technical subsystem data and system operating principles, constitute the basic design documentation of the durability test bench.

ANNEX I: Preliminary requirements list of durability test bench

20.10.2017		Requirements list (D = Demand, W = Wish), Valtteri Pulkkinen
#		Durability test bench for 100 kW fuel cell power module
		1. General info
1.1	D	The durability test bench allows comprehensive, long term testing of Fuel Cell Power Module (SHA-100-E) produced by Swiss Hydrogen.
1.2	D	Test bench consists of two 10 ft containers: System container and power electronics container. In system container, the FCPM and Higher-Level control system will be installed. The power electronics container includes the power electronics module, a server and system control computer.
1.3	D	Test bench will be installed in Kemira Chemical Factory site.
		2. Dimensions and installation
2.1	D	All components need to fit into two 10 ft containers.
		Outer dimensions of 10 ft container: 3,1 x 2,5 x 2,6 m (W x L x H)
		Inner dimensions of 10 ft container: 2,8 x 2,3 x 2,3 m (W x L x H)
		3. Gas feed lines
3.1	D	Hydrogen gas feed line from test bench to FCPM
	D	Flow Rate 0 - 1400 nlpm
	W	Pressure 8-10 bar(a), initial demand can not be met at factory site where only maximum of 6,3 bar(a) is available
	D	Temperature: 0 - 90 ˚C
	D	Humidity: 0-100 % RH
	D	Connection: Swagelok SS12M0-1-4RS
3.2	D	Nitrogen gas feed to FCPM
	D	Flow Rate < 600 nlpm
	D	Pressure 8-10 bar(a)
	D	Temperature: 0 - 90 ˚C
	D	Humidity: 0-100 % RH
	D	Connection: Swagelok SS12M0-1-4RS
3.3	D	Ambient air inside the container to the FCPM
	D	Flow Rate < 6000 nlpm
	D	Pressure: 0,8 - 1,2 bara
	D	Temperature: -40 - 90 ˚C
	D	Humidity: 0-100 % RH
	D	Connection: Swagelok SS12M0-1-4RS
3.4	D	Hydrogen supply line from factory site to test bench
		Pressure: 1 - 6,4 bara
		Temperature: 0 - 40 ˚C
		4. Exhaust gas, exhaust water and venting lines
4.1	D	Hydrogen purge line from FCPM to H2 Exhaust
	D	Flow rate: < 200 nlpm
	D	Pressure: 1 - 2,4 bara
	D	Temperature: 0 - 90 ˚C
	D	Humidity: 0 - 100 %RH
	D	Pipe diameter from FCPM: 10 mm OD
4.2	D	Hydrogen drain line from FCPM to H2 Exhaust
	D	Flow rate: < 0,6 nlpm
	D	Pressure: 1 - 2,4 bara
	D	Temperature: 0 - 90 ˚C
	D	Pipe diameter from FCPM: 10 mm OD

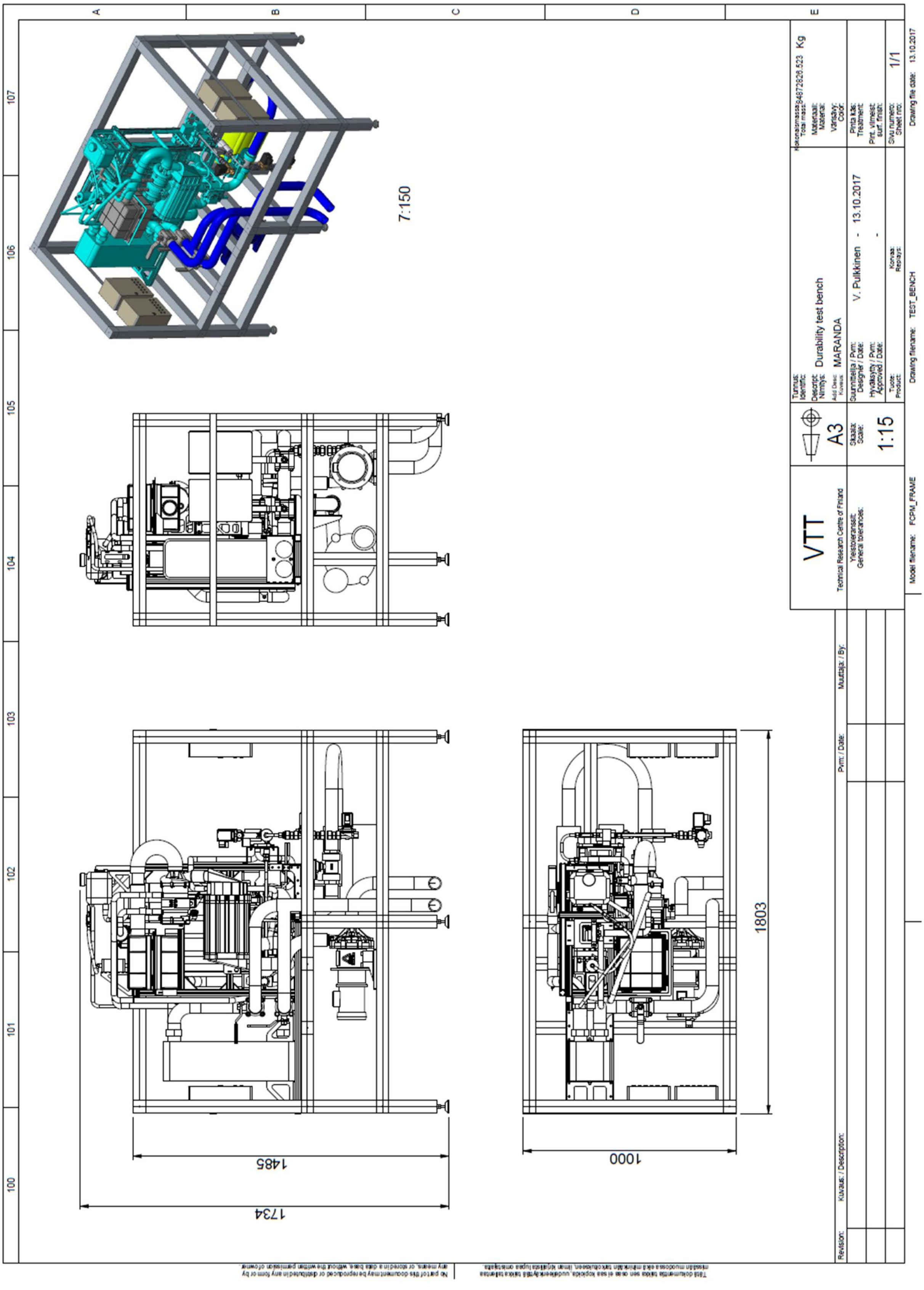
4.3	D	Tap water from factory site to test bench exhaust air condenser
		Flow rate: < 5 nlpm
		Temperature: 5 -15 ˚C
4.4	D	Drain pipe for exhaust water and tap water at factory site
		Flow rate: < 10 nlpm
		5. Secondary coolant loop to FCPM
5.1	D	Coolant line from test bench to FCPM
		Adjustable flow rate: 0 - 300 nlpm
		Pressure: 0 - 16 bara (2 bar nominal)
		Temperature: -40 - 45 ˚C
		Connection to FCPM: ID 51 silicon rubber hose
5.2	D	Coolant line from FCPM to test bench
		Adjustable flow rate: 0 - 300 nlpm
		Pressure: 0 - 16 bara (2 bar nominal)
		Temperature: -40 - 52 ˚C
		Connection to FCPM: ID 51 silicon rubber hose
		6. Electrical Connections
6.1	D	Power supply connection to FCPM from test bench
		400 V, 50 Hz, 3-phase
		Nominal power: 10,6 kW
		Peak power: 15 kW
6.2	D	DC connection from FCPM to PE
	D	250-500 V 0 - 300 A, 50 kVA
	W	250-500 V 0 - 300 A, 100 kVA
6.3	D	AC connection from PE to factory grid
	D	400 V 50 kVA
	W	400 V 100 kVA
		7. Communication readiness with systems
7.1	D	Communication with FCPM
		Standard: CAN
		Protocol: CAN 2.0
		Physical media: Twisted pair
7.2	D	Communication with PE
		Standard: Profibus
		Protocol: Profibus DPV0/DPV1
		Physical media: Twisted pair
		8. Environment (factory site)
8.1	D	Temperature: 10 - 40 ˚C
		9. Safety
9.1	D	Gas detection unit monitors hydrogen content inside the FC container
		LEL 0 - 40 %
	D	Auto-shutdown of the system is initiated if LEL > 20 % is detected.
	D	Emergency shutdown (power cut-off in FC container) is initiated if LEL > 40 % is detected.

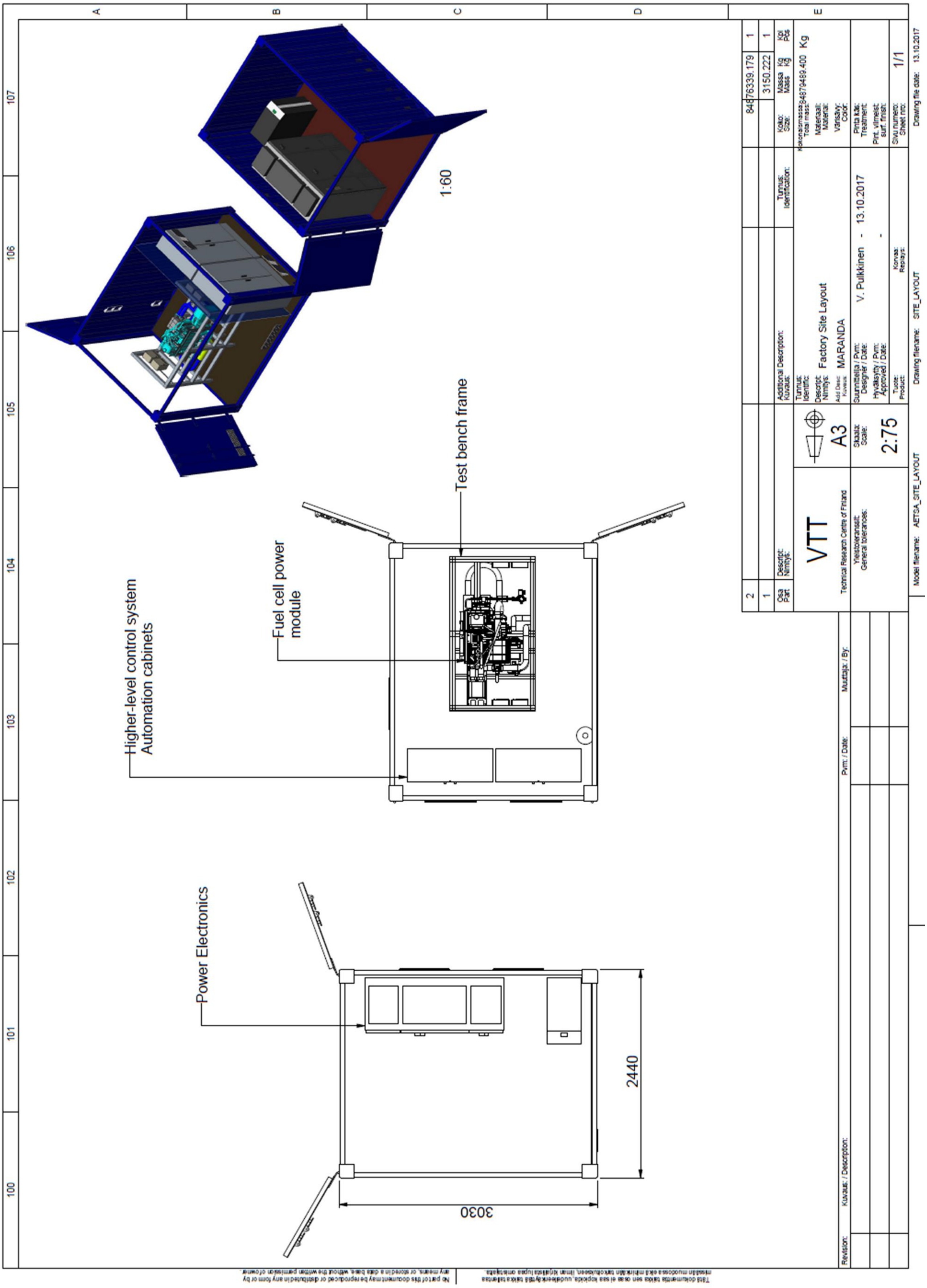
ANNEX II: Piping and instrumentation diagram (P&ID)



Position	Comment	Data type
FC I-10	Water pump control	AO
FC I-14	Radiator fan control	AO
BO I-22	Hydrogen feed valve 1	BO
BO I-23	Hydrogen feed valve 2	BO
BO I-24	Nitrogen feed valve	BO
BO I-27	HLCS to FCPM Command RUN	BO
BO I-28	HLCS to FCPM Command SHUT-DOWN	BO
BO I-29	HLCS to FCPM Command EM SD	BO
BO I-30	FCPM Power Supply Contactor	BO
BO I-31	Inverter contactor	BO
BO I-33	Inverter pre-charging circuit	BO
BO I-36	Grid contactor	BO
BO I-37	Power electronics emergency stop	BO
TI I-5	Container vent pipe temperature	TI
TI I-8	Container temperature	TI
TI I-12	2nd coolant temp from FCPM	TI
TI I-13	2nd coolant temp to FCPM	TI
TI I-18	Cathode exhaust temp to HEX	TI
TI I-19	Cathode exhaust temp from HEX	TI
H2 I-3	Hydrogen concentration sensor 1	AI
H2 I-4	Hydrogen concentration sensor 2	AI
FI I-6	Container ventilation flow meter	AI
FI I-7	Air to FCPM flow meter	AI
FI I-9	Coolant flow meter	AI
FI I-20	Hydrogen flow meter	AI
PI I-1	Hydrogen feed line pressure after filter	AI
PI I-2	Nitrogen feed line pressure before solenoid valve	AI
PI I-11	Container pressure	AI
PI I-15	Coolant line pressure	AI
PI I-16	Hydrogen feed line pressure to FCPM	AI
PI I-17	Cathode exhaust pressure to HEX	AI
PI I-21	Hydrogen feed line pressure	AI
BI I-26	Emergency shutdown button	BI
P I-34	Electrical power from grid	MODBUS RTU
P I-35	Electrical power produced to grid	MODBUS RTU
	Inverter draw current	PROFIBUS
	Inverter error	PROFIBUS
	Inverter DC voltage	PROFIBUS
	Inverter AC voltage	PROFIBUS
	CV deviation	CAN
	Cell Voltages Average	CAN
	Stack_voltage	CAN
	Stack_current	CAN
	Current_SP	CAN
	Current_SP_limit_min	CAN
	Current_SP_limit_max	CAN
	FCPM STATE Stand-by	CAN
	FCPM STATE Startup	CAN
	FCPM STATE Running	CAN
	FCPM STATE Shut-down	CAN

ANNEX III: Layout and engineering drawings

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Test bench frame
Fuel cell power module
Higher-level control system
Automation cabinets
Power Electronics
2440
3030
VTT
Factory Site Layout
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