Design and testing of 50 kW PEM electrolyser in FinH2-project

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beyond the obvious

Report's title

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Project name

FinH2

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Keywords

PEM electrolyser, containerized, turnkey solution, combined heat and hydrogen

Summary

A PEM electrolyser system was designed, built, and tested by VTT in the FinH2-project. The system has the following main characteristics:

- turnkey solution installed in 30-ft container
- only electricity supply and tap water required
- 50 kW nominal electrolysis power
- multi-stack (8 stacks) assembly
- hydrogen output 40 bar(g) and dried
- safety aspects highly prioritised in design
- capability of operating the stacks electrically in parallel (500 A / 100 VDC)
- capability of operating the stacks electrically in series (62 A / 800 VDC)
- integrated heat pump for combined heat and hydrogen production
- fully automated operation
- distant monitoring
- well instrumented with database

The design of the system and initial test results are presented.

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1. Introduction

In FinH2 project a 50 kW multi-stack turnkey PEM electrolyser system with integrated heat pump was designed, built, and characterized at VTT. The system was built in an insulated 30-ft sea container for easier transport. The idea was to build autonomous system containing all necessary equipment starting from water purification to produce ultrapure water suitable for electrolysis and ending at gas dryer for the product gases. The only inputs needed are electric supply and tap water.

Figure 1 shows a CAD picture of the components fitted into the container. The container is divided into two spaces separated with a wall – a “system space” on the right and an “auxiliary space” on the left. The system space contains everything related to hydrogen, i.e. the electrolyser stacks and hydrogen post-treatment components. Rest of the components are in the auxiliary space, i.e. water purification, cooling piping, heat pump, two sets of power electronics, automation, and electrical cabinets.

This document gives an overview of the design including main components and also presents the initial test results of the system.

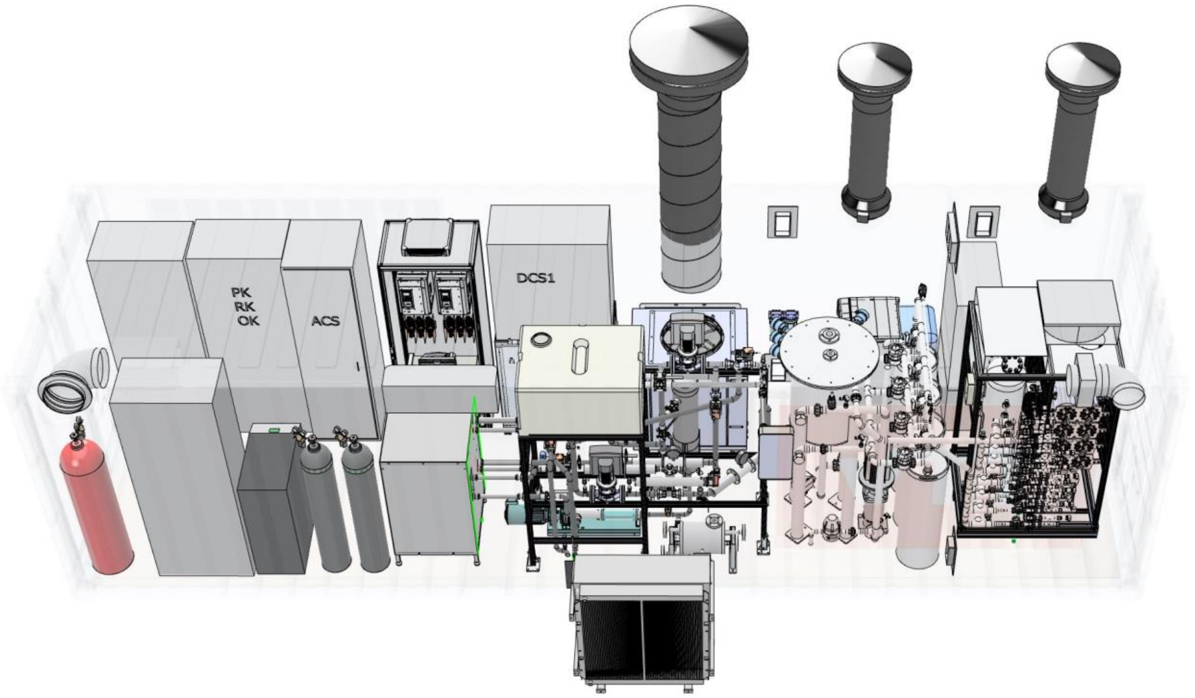

Figure 1. CAD picture of the system installed in a 30-ft sea container.

2. Main components

2.1 Electrolyser stacks

A total of 8 stacks from HIAT (Hydrogen Innovation GmbH) were installed. Data sheet of a single stack is shown in Figure 2. We can see that the nominal production rate of hydrogen is 9.4 m3/h which at 0 °C and normal atmospheric pressure is 0.84 kg/h. The hydrogen is produced at up to 40 bar pressure. The stacks should be operated at 80 °C maximum and temperature difference between water inlet and outlet needs to be kept under 5 °C.

Purifier (HYP40/19.5k/45/60)	
General Information	
Number of Cells	45
Active Electrode Area (Single cell)	28.3 cm²
Active Electrode Area (Total)	1,272.3 cm²
Maximum Current Density	2.2 A $\cdot$cm^{-2}
Hydrogen Production Rate	19,512 ml $\cdot$min^{-1} | 1.17 m^3 $\cdot$h^{-1}
Oxygen Production Rate	9,756 ml $\cdot$min^{-1} | 0.59 m^3 $\cdot$h^{-1}
Length x Width x Height @ Weight	approx. 485 x 122 x 120 mm @ 13 kg
Water Quality	DIN ISO 3696 type 1
Control	Current controlled and voltage limited
General Operating Parameters	
Maximum Operating Temperature	80 °C
Maximum Temperature Difference (H_2O_{IN} & H_2O_{OUT})	5 K
Minimum Flow Rate	approx. 4.5 l $\cdot$min^{-1}
Maximum H_2 - Outlet Pressure	40 Bar
Maximum O_2 - Outlet Pressure	Ambient
Maximum H_2O - Inlet Pressure	1.5 Bar
Electrical Operating Parameters @ 40 bar @ 70 °C	
Stack Voltage	approx. 73.5 - 100.2 V
Current (DC)	2.8 - 62.2 A
Connected Load	approx. 0.21 - 6.23 kW

Figure 2. Data sheet of a stack. The final assembly has eight stacks.

Multiplying the electrical parameters gives us a nominal power of 50 kW. Depending on if the stacks are connected in parallel or in series, we get a maximum voltage of 800 V at 62 A or 100 V at 500 A. The product gases are H2O saturated and require drying before use or storage.

2.2 Rectifier

The stacks use DC power, which is fed to them from a three phase 230 VAC 200 A supply through power electronics that convert the AC to DC. One of the goals of the project was to test the operation of the stacks when connected electrically in parallel or in series. Only parallel connection is officially supported but connecting multiple stacks in parallel leads to high currents.

Two power electronics systems were installed. Both supplied by ABB

2.2.1 Parallel connection

For high current operation, running parallel connected stacks, two 12-pulse thyristor based DCS880-S01-0405-04/05 (H3) DC drives were installed in parallel. One as the master and the other as the slave. They are fed through a AQ Trafotek 400 VAC-120 VAC / 115 kVA -transformer for potential free installation, and can output 810 A (2x405 A) at the calculated UDC max.

Figure 3. ABB DCS880 H3 (left) and ABB ACS880-204 IGBT (right).

The DC output from the DCS880 units is filtered with a 1.0 mH choke (L-filter) to reduce ripple. The max. voltage output is 465 VDC. It is not enough to run the stacks in series, but it would be enough to run 2x4 configuration – four stack pairs in two series. In theory, 4x2 configuration – two stack pairs in four series, is also possible at nominal point.

2.2.2 Series connection

For high voltage operation, running series connected stacks, an insulated-gate bipolar transistor (IGBT) based ACS880-204-0150A-7 (R6i) drive was chosen. It can output DC power at maximum 1100 VDC. This is enough to run all stacks in series.

2.3 Cooling

The cooling setup comprises an ultrapure-water loop (electrolyser stack circuit) that is separated from an intermediate circuit that is connected to a heat pump (Figure 4). The separation of theses circuits is necessary because the electrolyser stacks use the same water circulation for cooling as well as the reactant, thus, require very pure water (see section 2.4).

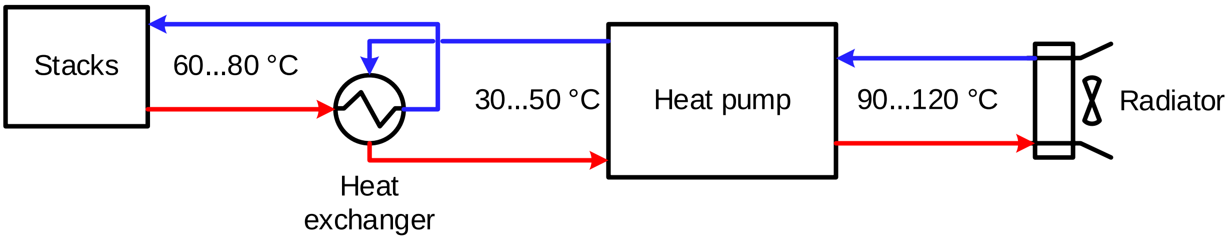

Figure 4. Cooling setup of the 50 kW PEM electrolyser system.

The operating temperature of PEM electrolyser stacks is 80 °C at most. This is not quite enough for example for district heating applications in wintertime in Finland. To overcome this, a heat pump (Oilon P30, Figure 5) was installed in the current setup. It is capable of boosting the waste heat up to 120 °C using the refrigerant R1233zd(E).

Figure 5. Oilon P30 industrial heat pump (left) and Milli-Q CLX 7040 water purification system (right).

2.4 Water purification

The electrolysis stacks require minimum of 10 MΩ·cm water. Resistance is a measure of water purity as impurities tend to increase conductivity / lower resistance. Water to the electrolyser system is supplied from the municipal water network. Before it is usable for electrolysis at the stacks, it must be purified.

The purification begins by a series of mechanical filters from coarse to fine to remove solids. Further purification is handled by Milli-Q CLX 7040 water purification system (Figure 5). It uses ion exchange resins and other complementary purification techniques to produce 18 MΩ·cm water. The purification level is monitored and reported by the device itself.

The pure water is fed from the Milli-Q CLX 7040 to the ultrapure water circuit whenever the level drops below a threshold. The ultrapure water level monitoring and feeding of fresh water is handled by the automation system.

2.5 Gas drying

The electrolyser outputs products gases (hydrogen and oxygen) saturated with water. Many end-use applications require dry gases. This is why gases in the current setup are dried before vented out.

The produced hydrogen is dried in two steps. The first step is a condenser that removes most of the moisture and the final step is an absorption dryer which removes any leftover moisture.

The produced oxygen is dried in one step - a condenser that removes most of the moisture.

The condensers are Vahterus model PSHE 2HA-32/1/1 plate & shell -type heat exchanger with adequate pressure vessel rating. It is cooled by “condensation loop” in which Lauda Ultracool UC 14 (L002946) chiller circulates a water-glycol -mixture. Target temperature for the condensation loop is above, but close to 0 °C.

The absorption dryer is a customized ø324 mm vessel by Lautrette Industries. The vessel is filled with single use absorbent pellets that must be replaced periodically. The vessel is pressure vessel rated adequately. Because the dryer uses pellets, a particle filter with 1 µm sieve is installed after it.

2.6 Automation

B&R X20 system, supplied by ABB, was chosen as the process automation control system. In addition, the electrolysis container is equipped with a separate safety automation logic system. It is running on a safety variant of the B&R X20 system. Control logic for the automation was planned in house. The process automation has been designed for remote operation by a secure access through Tosibox Platform and a firewall. For local access, the container is equipped with a control PC with a local programming environment - B&R Automation Engineering station. It also has ABB Ability System 800xA – a distributed control system, Ability Optimax – a smart energy manager, and Ability History – a time series database.

3. Safety

3.1 Risk assessment

Risk assessment for the 50 kW PEM electrolysis system was conducted by means of Layers of protection analysis (LOPA). It uses orders of magnitude for assessing probability and severity of risks (1/year, 1/10 years etc.). Risk reduction methods are then thought of as independent protection layers and graded with probability or severity reducing points. The layers typically consist of mechanical protection, process automation and other measures. If these don’t provide sufficient risk reduction, a separate safety automation should be considered.

Most risks were mitigated sufficiently by mechanical protection or process automation or a combination of them. The most severe risks are related to hydrogen explosion. Mitigation of those risks often required implementation of a separate safety automation on top of mechanical protection and process automation.

3.2 Safety automation

The safety automation was designed using standard series SFS-EN 61508 - Functional safety of electrical/electronic/programmable electronic safety-related systems[1] and SFS-EN 61511 - Safety instrumented systems for the process industry sector[2]. The first one is the generic standard and the latter one a process industry specific standard.

Most safety instrumented functions (SIF) carried out by the safety automation were designed to meet SIL 2 (Safety integrity level) requirement. For some, SIL 1 was enough. The components were chosen with the requirement in mind and the achieved SIL level was verified through probability of dangerous failure (PFD) calculations.

3.3 Gas and fire safety

Both spaces of the container are continuously ventilated and monitored for gas (hydrogen and oxygen) leakages and for fire. Gas and fire monitoring is done with a dedicated system (based on Crowcon Vortex monitoring system) that is connected to the safety automation. The safety automation also monitors ventilation.

ATEX classification was performed for “system space” (comprising everything that is in contact with hydrogen) as per standard SFS-EN IEC 60079-10-1:2021. The system space is non-hazardous space on the grounds of strong dilution ventilation. The ventilation is designed to prevent the possibility of explosive mixture from forming even in case of a major hydrogen leak. The ventilation is monitored, as required by TUKES[3] if ventilation is used as the reason for non-hazardous classification. However, for extra safety in case something breaks, everything that remains powered on in case of hydrogen alarm are treated like they are installed in Zone 2.

3.4 Pressure equipment

The hydrogen side of the electrolyser operates at up to 40 bar(g) pressure. PED directive, or Directive 2014/68/EU, applies to the design, manufacture and conformity assessment of stationary pressure equipment and assemblies with a maximum allowable pressure greater than 0,5 bar.[4] Therefore, the hydrogen side assembly is designed to conform with the directive and the local legislation[5] and decrees[6], [7] that are based on the directive.

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[1] SFS-EN 61508 Functional safety of electrical/electronic/programmable electronic safety-related systems.
[2] SFS-EN 61511:2017 Functional safety - Safety instrumented systems for the process industry sector.
[3] Finnish Safety and Chemicals Agency
[4] Directive 2014/68/EU - pressure equipment. https://osha.europa.eu/fi/legislation/directive/directive-201468eu-pressure-equipment [accessed 8.5.2024]
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4. Test results

4.1 Stack characterization

Before connecting all electrolyser stacks to the rectifier, all stacks were characterized pair-wise (series connected) with a smaller power supply unit (EA-ELR 10500-90 3U, 500V, 90A, 15kW). The measurements were done at 70 °C stack coolant, ca 5 barg H_2 pressure and ramping up the current as follows: I_{sp} = 3 A, 10 A, 20 A, 30 A, 40 A, 50 A, 60 A, 62.3 A

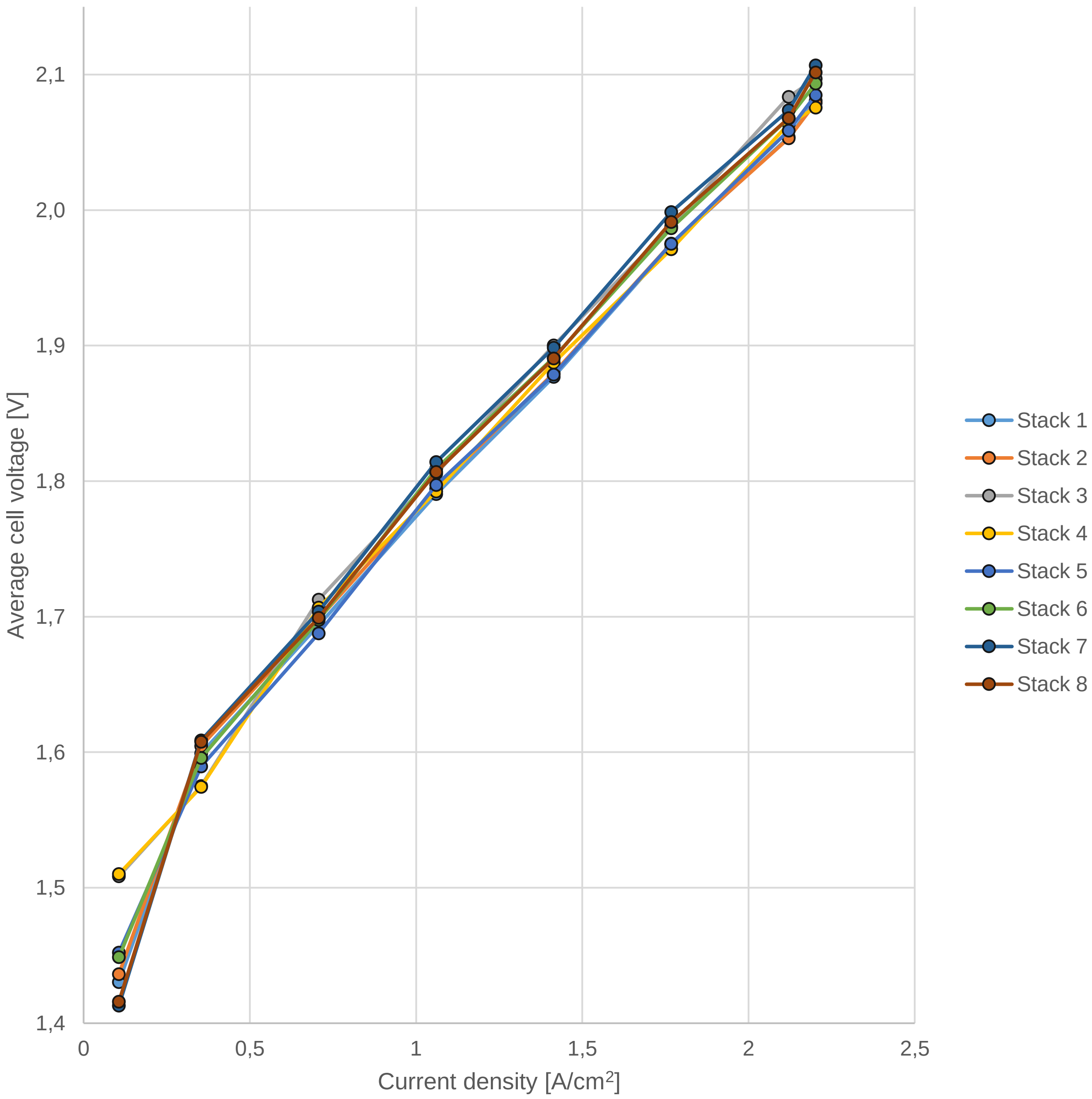

Figure 6. Average cell voltage measured during stack characterization tests.

4.2 Complete system tests

After performing the pair-wise stack characterization tests, all stacks were connected in parallel. The measurements were done at 70 °C stack coolant, 0-1.5 barg H_2 pressure and ramping up the current as follows: $I_{sp,tot}$ = 25, 80, 120, 160, 200, 240, 280, 320, 360, 400, 440, 480, 500 A

The measured power consumptions are plotted in Figure 7.

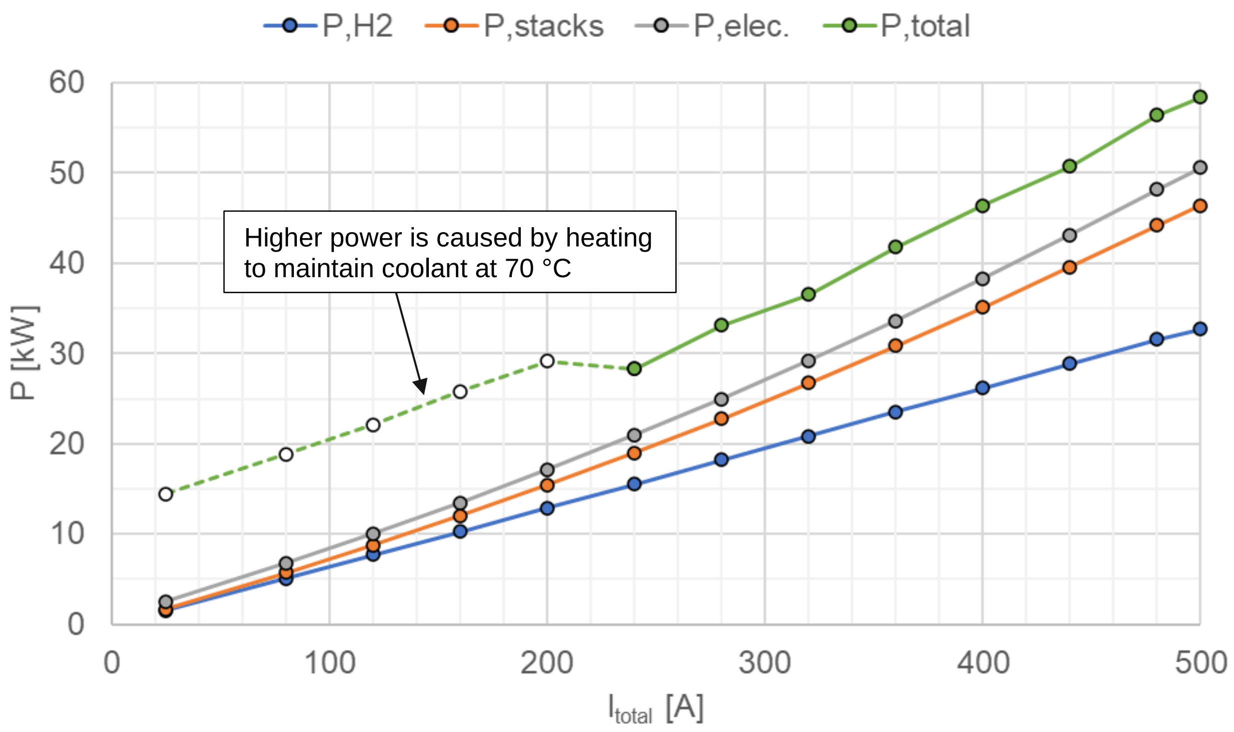

Figure 7. "Hydrogen production power" (P_{H2}, see definition below), stack power (P_{stacks}), electrolysis total power consumption ($P_{elec.}$), and total system power consumption excluding heat pump power (P_{total}) as function of total stack current ($I_{tot} = \Sigma(I_{stack,i})$).

Definitions of symbols in Figure 7:

$P_{H2} = \dot{m}_{H2} \cdot HHV_{H2}$

where	$\dot{m}_{H2}$	Hydrogen production rate [kg/s]
	HHV_{H2}	Higher heating value of hydrogen (=141800 kJ/kg H_2)

$P_{stacks} = \Sigma(U_{stack,i} \cdot I_{stack,i})/1000$

where	$U_{stack,i}$	Stack i voltage [V]
	$I_{stack,i}$	Stack i current [A]

$P_{elec.}$ = the power that the electrolysis powertrain takes from the AC-grid (excluding electrolysis system auxiliary devices)

$P_{total} = P_{elec.} + P_{aux.}$

where	P_{aux}	the power that the auxiliary devices takes from the AC-grid excluding the heat pump electrical power

The total system power consumption excluding heat pump power (P_{total}) is very high below 240 A total stack current, as seen in Figure 7. This is because the stack coolant requires heating (at 6 kW) at low power to remain at 70 °C. In practical applications, the heating would be omitted and, consequently, the power consumption would be lower.

It should be stressed that the total system power plotted here really comprises everything that the containerized system consumes excluding the heat pump power. In small systems like this, the power consumption easily becomes unproportionally large because exactly the same power consuming devices could be used in a much larger system.

The heat pump power is omitted in this analysis because it runs intermittently. Because of this, the system should be run longer times at constant power to get reliable figures for its effect. However, it's safe to say that accounting for the heat pump would improve the total efficiency of the system since it operates with COP (coefficient of performance) more than 1 and hence, adds more power output to the system (in the form of heat) than it consumes electrical power.

The calculated efficiencies are plotted in Figure 8.

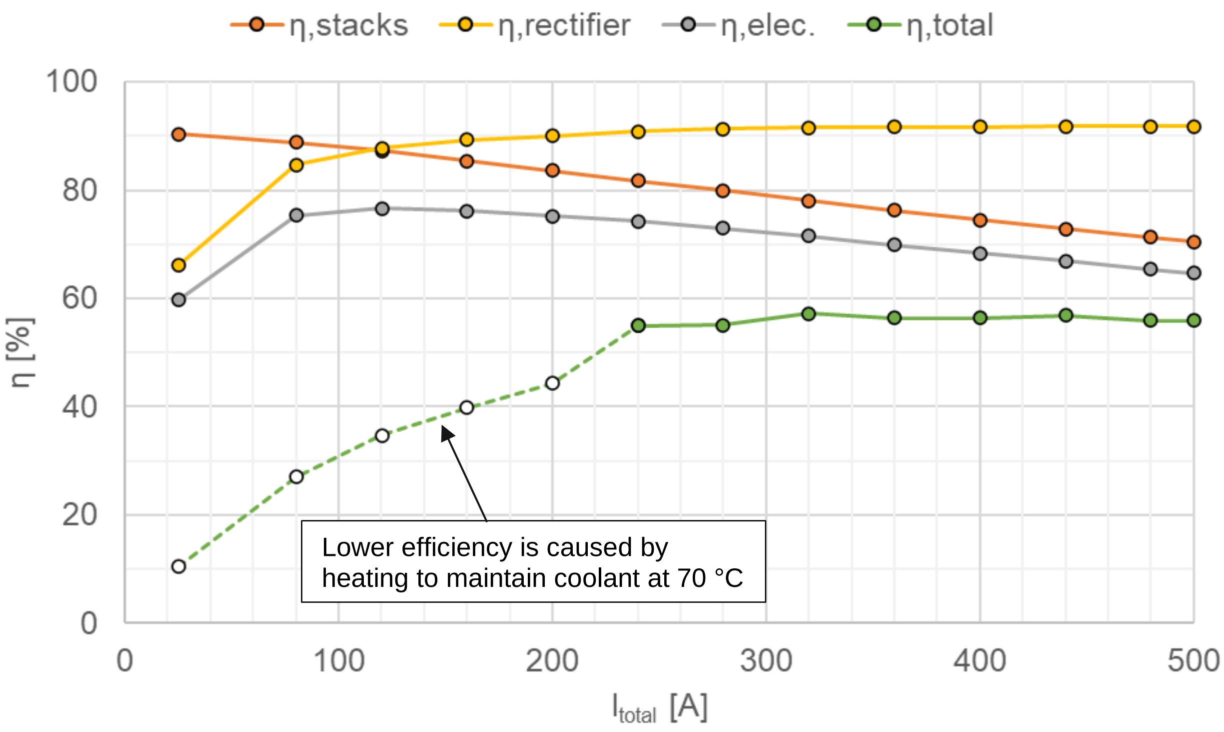

Figure 8. Stack efficiency (η_{stacks}), rectifier (including transformer) efficiency ($\eta_{rectifier}$), electrolysis efficiency ($\eta_{elec.}$), and total system power consumption (η_{total}) as function of total stack current ($I_{total} = \Sigma(I_{stack,i})$). Effect of heat pump not included.

Definitions for symbols in Figure 8:

$\eta_{stacks} = P_{H2} / P_{stacks}$	(efficiency of stacks converting electricity into hydrogen)
$\eta_{rectifier} = P_{stacks} / P_{elec.}$	(efficiency of rectifier and transformer converting AC-power from grid into DC-power seen by the stacks)

$\eta_{elec.} = \eta_{stacks} \cdot \eta_{rectifier} = P_{H2} / P_{elec.}$ (total efficiency of electrolysis – from AC-power into hydrogen, not accounting for auxiliary devices)

$\eta_{total} = P_{H2} / (P_{elec.} + P_{aux.})$ (total efficiency of system – from AC-power into hydrogen, also accounting for auxiliary devices except the heat pump)

The efficiency of the stacks (η_{stacks}) decrease with increasing total current and vary between 90 % (at minimum power) and 70 % (at nominal power). The power train efficiency ($\eta_{rectifier}$) behaves the opposite reaching it's lowest efficiency 66 % at minimum power and highest 92 % at nominal power. Hence, the electrolysis efficiency ($\eta_{elec.}$) accounting for both these reach a maximum 77 % at 120 A total current and being 65 % at nominal power. The total efficiency is relatively poor, around 55 % between 240 A and 500 A total current and decreases further at lower total currents because of the beforementioned reasons.

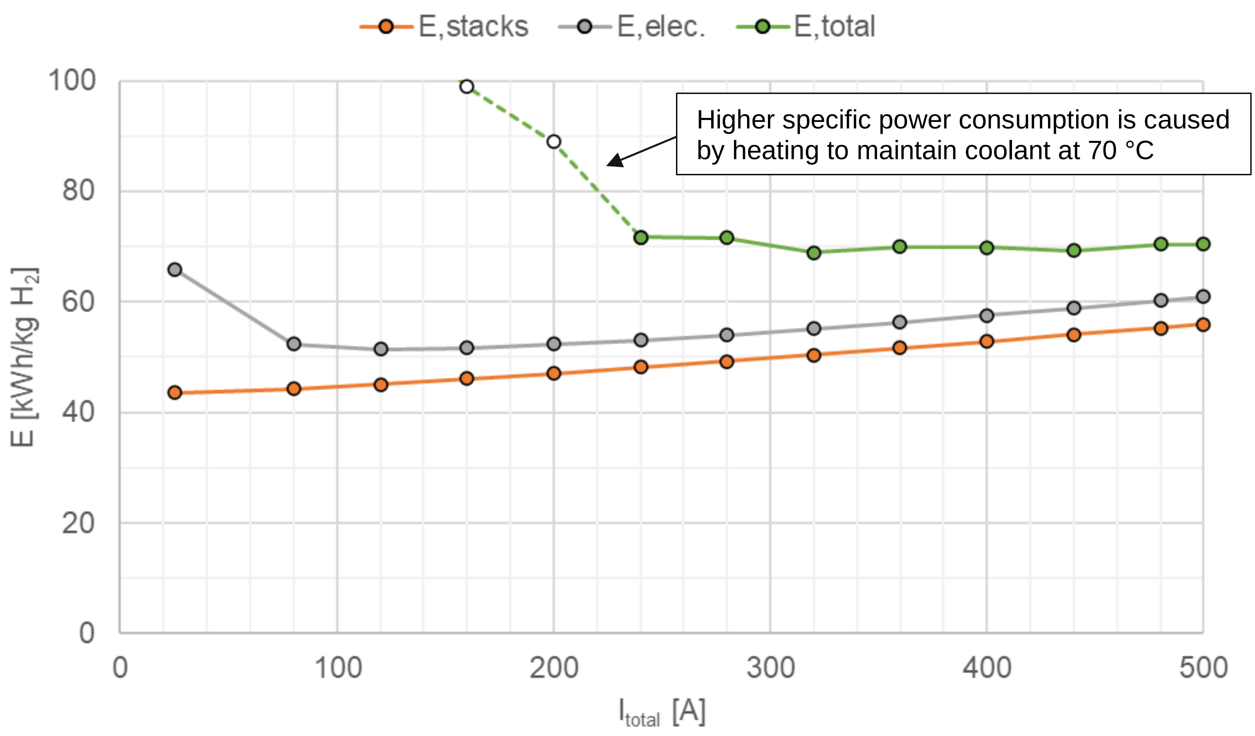

Figure 9. Stack energy consumption (E_{stacks}), electrolysis energy consumption ($E_{elec.}$), and total system energy consumption (E_{total}) per kg of hydrogen as function of total stack current ($I_{total} = \Sigma(I_{stack,i})$). Effect of heat pump not included.

Definitions of symbols in Figure 9:

$E_{stacks} = P_{stack} / \dot{m}_{H2} \cdot (1h / 3600s)$ (the energy used by the stacks to produce 1 kg of hydrogen, DC-to-H_2)

$E_{elec.} = P_{elec.} / \dot{m}_{H2} \cdot (1h / 3600s)$ (the energy used by the stacks and electrolysis power train to produce 1 kg of hydrogen, AC-to-H_2)

$E_{total} = P_{total} / \dot{m}_{H2} \cdot (1h / 3600s)$ (the energy used by the entire container (excluding heat pump) to produce 1 kg of hydrogen)

The specific energy consumption of stacks (E_{stacks}) varies between 44 kWh/kg H_2 at minimum power and 56 kWh/kg H_2 at nominal power. The specific energy consumption of eletrolysis ($E_{elec.}$) varies between 66 kWh/kg H_2 at minimum power and 51 kWh/kg H_2 at 120 A total current and being 61 kWh/kg H_2 at nominal power.

5. Summary

In FinH2 project, VTT designed and built a standalone containerized 50 kW PEM electrolyzer system producing hydrogen. Balance of plant components from Finnish companies was favored according to the research plan, e.g. automation by ABB, industrial heat pump by Oilon, and heat exchangers by Vahterus. The electrolyzer stacks were purchased from a European manufacturer (Hydrogen Innovation GmbH, Germany).

The plan was to employ a multi-stack design in the PEM electrolyzer system. This was also realized but instead of using two bigger stacks, eight smaller stacks were installed. In addition, the total electrolysis power (50 kW) was a bit higher than planned (20-40 kW). The use of eight stacks instead of two enabled to increase the operating voltage when connecting the stacks in series. On the other hand, connecting the stacks in parallel is also possible. Because of this, both series and parallel connection options were implemented by having two sets of power electronics.

One of the targets in the project was to demonstrate co-production of heat and hydrogen. For this purpose, an industrial heat pump was integrated into the electrolyzer system, and it was successfully operated as part of the electrolyzer cooling system.

The project targeted extensive testing of the PEM electrolyzer system. Unfortunately, the system was finished later than anticipated and only basic characterization was conducted during the project. Nonetheless, the system was proven to function as planned.

Table 1 summarizes the achievements in the project compared to the project plan.

Table 1. Comparison of research plan and project realization.

	Research plan	Realization
Design and build standalone PEM electrolyzer system	Yes	Done
Electrolyzer stack manufacturer	European	German
Favor BoP components from participating companies	Yes	Done
Integrate an industrial heat pump	Yes	Done
Electrolysis power	20-40 kW	50 kW
Number of stacks	2	8
Possibility for both parallel (low voltage) and series (high voltage) stack connection	No	Done
Extensive testing of PEM electrolyzer system	Yes	Only basic

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