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PEM electrolysis system performance and system safety integration

***Abstract**. In this paper, the performance and design of hydrogen production system using two commercial 4.2 kW proton exchange membrane (PEM) water electrolysis stacks embedded in a custom-designed electrolyser is described. The PEM electrolyser system has multiple levels of construction which include, stack section, cooling unit, Balance of Plant (BOP), power electronics and system safety, all integrated with aid of PLC controller. Particular system alarms and fault conditions trigger the emergency mode, which safely shuts down the system. A crucial aspect of design and operation protocols around hydrogen safety application in the whole integration process is applied. The system integrated with in-house built metal hydride compressor supplies high pressure hydrogen (up to 200 bar, 5 Nm^3/h) to SAIAMC testing facilities.*

***Streszczenie.** Artykuł omawia konstrukcję oraz badanie osiągów systemu przeznaczonego do produkcji wodoru, który został zbudowany na bazie dwóch stosów elektrolizy wody typu PEM (4.2 kW każdy).System elektrolizera składa się z szeregu podzespołów, do których zaliczają się sekcja stosów, układ chłodzenia, zespół urządzeń wspomagających proces elektrolizy (BoP), układy zasilania elektrycznego, układ zabezpieczeń oraz kontroler typu PLC. Z uwagi na istotny aspekt bezpiecznej produkcji wodoru, kontroler wyłącza system w razie wystąpienia stanów alarmowych. System zintegrowano z kompresorem działającym w oparciu o wodorki metali, dostarczającego wodór przy wysokim ciśnieniu (200 bar, 5 Nm^3/h) do laboratoriów badawczych (SAIAMC) na użytek własny.(**Efektywność pracy elektrolizera typu PEM na tle bezpiecznej konstrukcji systemu produkcji wodoru**).*

Keywords: renewable hydrogen; hydrogen safety; PEM water electrolysis performance; metal hydride compressor
Słowa kluczowe: odnawialny wodór; bezpieczeństwo użytkowania wodoru; elektrolizer wody typu PEM; kompresor na wodorkach metali

1. Introduction

The widespread use of fossil fuels within the current energy infrastructure is the largest source of anthropogenic emissions of carbon dioxide, which contribute to global warming and climate change [1]. Fossil fuels are non-renewable energy source that currently account for about 90 percent of world energy consumption (including manufacturing, heating, cooking, electricity and fuels for cars). Petroleum leads with a share of about 40% of total world energy consumption, followed by coal (24%) and natural gas (22%) [2].

The problem with humanity's heavy reliance on these sources of energy is that reserves are finite, and are rapidly running out. There are also health and environmental concerns surrounding the use of fossil fuels e.g. greenhouse gas emissions leading to global warming and climate changes. An estimated 4.6 million people die each year due to air pollution [2] and global warming is widely regarded as one of the most critical issues facing the planet. Additionally, given the market volatility of the oil price and the tenuous political climate surrounding oil production and delivery, researching cleaner, renewable energy alternatives to fossil fuels will contribute to a sustainable, stable energy [3].

The energy crisis has given birth to the Hydrogen Economy [4]. Hydrogen is an alternative energy source to the current energy crisis. A wide range of technologies can generate hydrogen such as reforming of natural gas, liquefied petroleum gas, gasoline and electrolysis of water using nuclear, fossil or renewable energy sources [5].

Hydrogen is a promising fuel, produced from water. This is a renewable and sustainable source, which can obtain a high hydrogen purity via electrolysis. Among the processes for obtaining hydrogen from the water, the electrolytic conversion is the best known, in which two electrodes are responsible for conducting electricity and production of this gas. However, to promote this segregation, there are some technological challenges such as the efficiency of electrolysers, efficiency and durability of the main fuel cells and the integration of the electrolysis systems for supply and energy, aiming to reduce production costs [6].

The production of H_2 through electrolysis is an environmentally attractive process. There is a necessity of searching for sustainable methods whose implementation will lead to the reduction of global warming [7]. Renewable energy sources reduce the dependence on fossil fuels and minimize environmentally harmful emissions. With near-zero or zero end-use emissions and continually replenished resources, hydrogen can be an ideal sustainable energy carrier.

Literature suggests scenarios with regard to hydrogen applied as a renewable energy carrier. For instance, Miland and Ulleberg [8] were testing a small-scale stand-alone power system based on solar energy and hydrogen stored in metal hydrides. The system consisted of 1.5 kW electrolyser and 0.5 kW fuel cell, and programmable power supply to simulate renewable energy source (PV, MPPT). A strategy evaluated in the paper was a direct connection of particular system components without DC/DC converters for system design simplification. The authors have found that depending on the control strategy the overall system efficiency can be as high as 52.3%. Kosonen et al [9] have examined optimization strategies of PEM electrolyser as part of solar PV system. Laboratory measurements have been carried out with the 5.5 kW PEM electrolyser and the 5 kW solar PV system. The main idea was to study, how the electrolyser can follow the solar PV production at a single plant. The authors concluded that the solar PV output power could be synchronised in order to follow the power reference with the commercial PEM electrolyser; however, limitations and degradation in the electrolyser's performance should be considered. In another paper, Ghribi et al [10] designed and studied a PEM electrolyser powered by a low power PV system. The system had a 60 W PV connected to a 50 W PEM electrolyser and the results showed that production of hydrogen varies greatly throughout the different months and sites. Hydrogen production was dependent directly on availability of solar radiation.

In the paper [11], authors proposed a review and evaluation of hydrogen production methods for better sustainability using renewable and non-renewable sources. Nineteen selected hydrogen production methods were evaluated and they concluded that hybrid (PV and grid power) hydrogen production method have the highest rankings based on assessing environmental, financial, social and technical performance. Dincer and Acar in their paper [12] described comparative assessment of hydrogen production methods from renewable and non-renewable sources indicate that hydrogen production by electrolysis was the least attractive when production costs are considered.

The focus of this work is the performance of PEM water electrolyser and system safety integration. The proposed design of the system represents modern approach to the development of hydrogen applications in terms of combination of both digital technologies and renewable power generation and storage. Such a combination allows on uninterrupted operation, constant remote upgrading of operational and safety standards and promoting of the idea of decentralized energy production using hydrogen as a fuel.

2. Hydrogen as a fuel

Hydrogen can successfully replace conventional fossil fuels [12-14]. Some of the advantages of this fuel are as follows [15].

- High energy conversion efficiencies;
- Production from water with no harmful emissions;
- Abundance;
- Different forms of storage (e.g. gaseous, liquid or absorbed in metal hydrides);
- Long distance transportation;
- Ease of conversion to other forms of energy;
- Better HHV and LHV values than most of the conventional fossil fuels as seen in table 1 below.

Table 1: Higher (HHV) and lower (LHV) heating values of hydrogen and other common fuels at 25 ˚C and 1 atm

Fuel	HHV (kJ/g)	LHV (kJ/g)
Hydrogen	141.9	119.9
Methane	55.5	50.0
Gasoline	47.5	44.5
Diesel	44.8	42.5
Methanol	20	18.1

Hydrogen can be directly utilized to produce electrical energy and useful thermal energy in an electrochemical process with high efficiency. The devices that allow on such a conversion are called fuel cells. There are many types of fuel cells, however the most popular are Proton Exchange Membrane Fuel Cells (PEMFC) [16-18].

The main disadvantages of hydrogen as a fuel are that hydrogen production technology is still expensive compared to conventional fossil fuels. There are also complications associated with hydrogen storage.

2.1. Water electrolysis

Electrolysis of water is its decomposition to give hydrogen and oxygen gases due to the passage of an electric current [19]. The most widespread electrolysis system are alkaline and PEM electrolysers. The alkaline electrolysis is one of the most developed technologies and is considered a simple method where the electrolytes have basic form – typically a diaphragm made from composite material of zirconia and polysulfone immerse in the aqueous alkaline solution [6,20] The electrolysis with a so-called polymer electrolyte membrane (PEM), one of the most promising technologies for decomposing of water, provides greater efficiency and purity of the gas. However, the technology is still under development [21].

Electrolysis of water in Polymer Electrolyte Membrane Water Electrolyser (PEMWE) is the decomposition of water into oxygen and hydrogen gas due to an electric current passing through the water as shown in fig 1. The (liquid) water is supplied to the anode of the electrolyser and is decomposed into hydrogen ions (protons: H^+) and molecular oxygen (O_2), this reaction is called Oxygen Evolution Reaction (OER). The protons transported through the membrane from the anode to the cathode under the influence of an applied potential. At the cathode, the protons and electrons react to form molecular hydrogen; this reaction called the Hydrogen Evolution Reaction (HER) [22]. Hydrogen obtained is of very high purity, 99.999%.

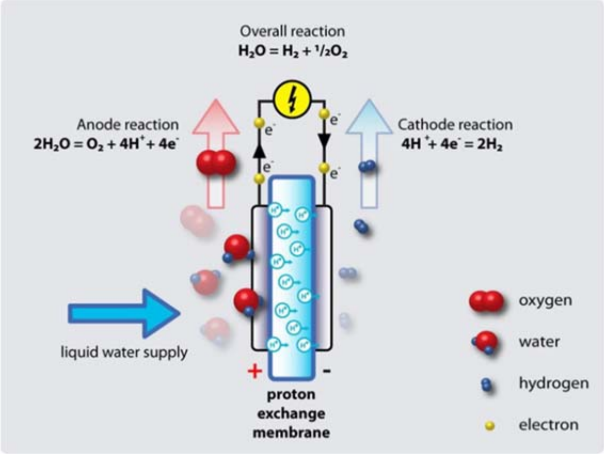

Fig. 1. PEM water Electrolysis Reactions

The PEM electrolyser has the following advantages compared to alkaline electrolysers [11]:

- provides high proton conductivity,
- it has a compact construction and may operate under high pressure,
- the electrolyte is thinner than the alkaline (lower Ohmic losses),
- operating costs of electrolysis are smaller because the PEM can operate with high energy density, the gases have a high purity,
- effective at high voltages.

Additionally, there are some disadvantages in alkaline electrolyser application compared to PEM electrolysers [11]:

- the electrolyte used is corrosive,
- operating pressures are low,
- high cost of components,
- lower efficiency due to diffusion of oxygen to the cathode chamber and the diffusion of hydrogen into the chamber of oxygen.

The characteristics of Alkaline and PEM electrolysers are summarized in table 2.

The electrolysis process is associated to two laws formulated by Faraday [23]. Equation (1) presents Faraday's first law of electrolysis. According to this law, the mass of ions generated at the electrode is proportional to the total charge that flows through the electrolyte.

(1) $$J = \frac{i}{n * F}$$

where: F – Faraday constant value, F= *96485.3365 C/mol;* n – amount of electrons involved in the reaction, I – current in Ampere *(A).*

Equation (2) represents Faraday's second law of electrolysis, which determines the charge *q* needed to separate the mass of substance m.

(2) $$m_{H2} = M * J * k$$

where: J - Amount of hydrogen flow kg/h; M – Molar mass of hydrogen = 1.008; n - amount of ions involved in the reaction; k - number of cells in a stack; m_{H2} – amount of hydrogen produced (kg/h).

Substituting equation (1) into equation (2) results in the following equation:

(3) $$m_{H2} = \frac{i * n}{F}$$

Table 2: Alkaline and PEM Electrolysers main characteristics [11]

Character	Alkaline Electrolyser	PEM Electrolyser
Temperature (^oC)	40 - 90	20 - 100
Pressure (bar)	< 30	< 30
Voltage (V)	1.8 – 2.4	1.8 – 2.2
Efficiency (%)	62 -82	67 - 82
H_2 production Nm^3/h	< 760	< 450
Decay rate (mV/h)	< 3	< 4
Power consumption (kWh/Nm^3)	4.5 - 7	4.5 – 7.5

The above relationship based on Faraday's laws shows that the mass of hydrogen produced by electrolysis of water is directly proportional to the current passing through the electrolyser and the duration of the electrochemical reaction. The number of ions involved in the reaction is two.

Hydrogen is produced by water electrolysis due to the reaction occurring at the cathode and anode of the electrolysers. Electricity is used in this case to break the water into two basic elements - hydrogen and oxygen [24]. The oxidation process occurs at the anode and the reduction process at the cathode. Electrolyser stack has cells connected in series responsible for the water electrolysis process. One electrolyser does not necessarily have to consist of only one stack of cells.

2.2. Electrolyser safety

Hydrogen is a colourless, odourless and flammable substance. It is highly combustible in the presence of oxygen and burns with a colourless flame [25]. The explosion range (in air) is 4 - 77% and the gas auto-ignites at 560˚C. Leaking gas may be hot and pose a burn danger. Furthermore, hydrogen is subjected to spontaneous ignition if it flows out at high speed [26].

The most important consideration with electrolysers is to prevent mixing of hydrogen and oxygen, the development of a flammable atmosphere, flammability and detonability limits of hydrogen and oxygen mixtures. Hydrogen and oxygen are generally separated by the membrane thus a key consideration when it comes to electrolyser safety is ensuring the membrane is intact and having a strategy in place in the event that either the membrane or a seal/gasket ruptures [4].

Considering the membrane, several factors may contribute to its degradation or rupture like hotspots. This may be caused by poor water management across the membrane as insufficient water will result in parts of the membrane not being sufficiently hydrated, leading to decay [4].

Mitigation methods to detect degradation of the membrane include the usage of a hydrogen or oxygen sensor that allows on examination of hydrogen crossover to the anode of the electrolyser. In addition to hydrogen sensors, voltage and current measurement can monitor or detect any short circuits. A further safety issue arises with high-pressure electrolysers. Whilst they may have advantages there are safety disadvantages in that the inventory of hydrogen in the system is increased, this becomes significant in the case of a leak [4].

There are many risks associated to hydrogen technologies implementation [27].

- Fire i.e. hydrogen is extremely flammable (4 – 77 vol% in the air, ambient pressure and temperature).
- Inhalation - can cause asphyxia in high concentrations.
- Specific risk - exposure to fire may cause containers to rupture/explode. Low flammable energy, from 0.02 mJ.
- Incompatible materials - can form explosive mixture with air. May react violently with oxidizing agents.
- Leak - molecule small size leaks easily.
- Embrittlement - degradation of mechanical properties of metals, can lead to component failure.
- Leak - creates flammable clouds.
- Pressure - enlarges flammable clouds.

Additionally, during the electrolysis process the oxygen is released and if not managed, it can pose several risks as given below [28].

- The excess of oxygen may cause or intensify the fire.
- Continuous inhalation of concentrations higher than 75% may cause nausea, dizziness, breathing difficulties and convulsions.

Specific risk is an exposure to fire that may cause containers to rupture or explode.

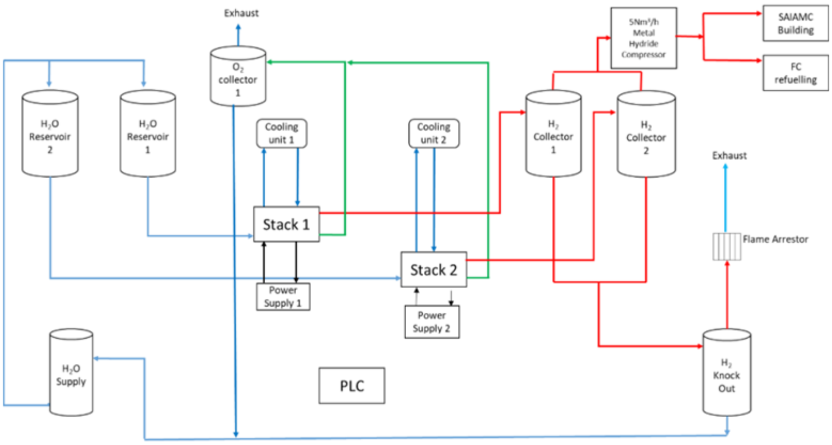

Fig. 2. PEMWE System Block Diagram

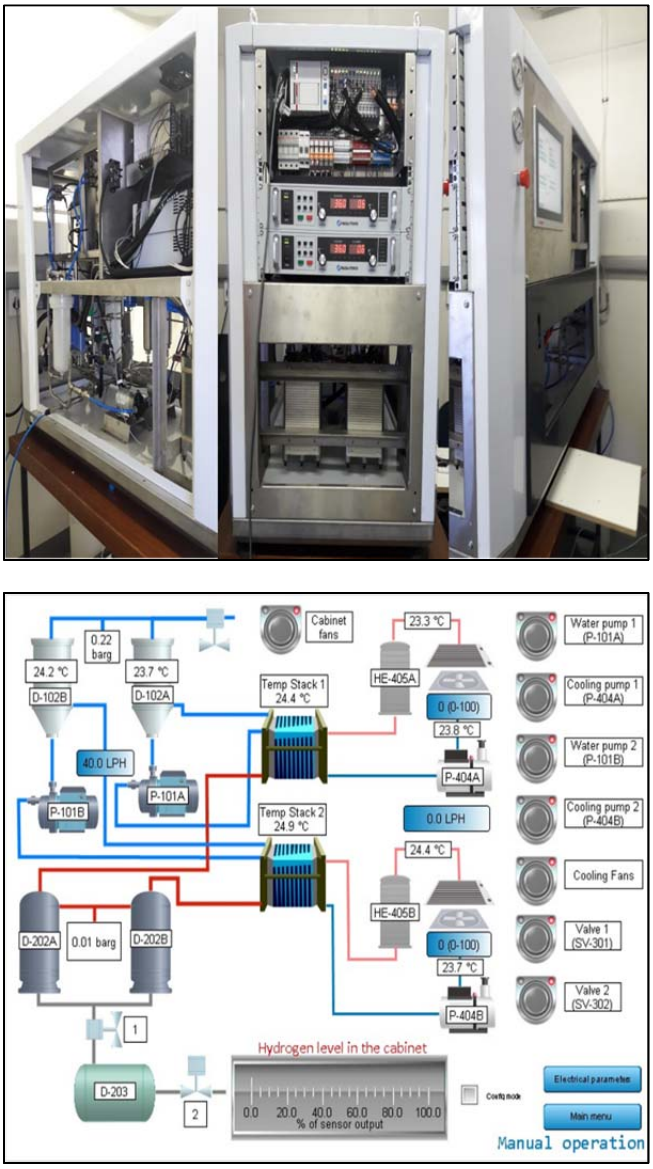

Fig. 3. Prototype PEMWE System Overview: the real view and HMI panel with a simplified P&ID design

3. System integration and overview

The prototype system has evolved following the concept depicted in Fig. 2 with two commercial PEM stacks that can produce hydrogen with rate of 1 Nm^3/h each manufactured by Hydron Energy B.V (commercial supplier). The Balance of Plant was designed and integrated in conjunction with the application of hydrogen safety in order to produce an intrinsically safe electrolyser system. The produced hydrogen is supplied to a Metal Hydride (MH) compressor [29] locally produced in South Africa. The compressed hydrogen is dispensed to either South African Institute of Advanced Materials Chemistry (SAIAMC) gas supply system or refuels various Fuel Cell Vehicle (FCV) prototypes produced by Hydrogen South Africa (HySA) Systems. The system integration was subdivided into three main subtasks, namely the stack and system characterization, balance-of-plant development and hydrogen compression unit.

3.1. Process water supply

The anode loop is supplied with Ultra-Pure Water (UPW) of 18 MΩcm quality (according to ISO 3696). The water supply of higher conductivity than 1.5 μS/cm can damage the electrolysis cells. The operation of prototype electrolyser stack with process water above this conductivity will lead to rapid degradation of the internal parts and will irreversibly decrease lifetime of the electrolyser stack. Water conductivity sensor continuously monitor the process water quality and trip at the threshold value of 1.5 μS/cm in the PLC algorithm in order to protect the stack degradation.

3.2. System integration

The PEM electrolyser stacks were integrated with the BoP components following the system block diagram (Fig 2). The real view of the system and the HMI window of the controller in Fig. 3 provides the system overview.

3.3. System safety

The system has been equipped with a hydrogen sensor and cathode exhaust line connected to a flame arrestor. The oxygen from the anode loop is connected to an exhaust line that takes produced oxygen outside the building into the environment in order to avoid high concentration of oxygen inside the location of the electrolyser. Safety procedures were implemented to protect the stacks. BoP, cooling system and power supply units are integrated with the PLC to protect the entire prototype system.

3.4. PLC controller with dedicated algorithm

The electrolysis system bases on implemented Programmable Logic Controller (PLC). It includes embedded personal Windows-based computer, signal input and output terminals (digital and analog for connections of measurement sensors and controlling of BoP devices), digital extension modules (including energy meter and data acquisition unit) and communication modules that base on internal communication protocol and external Ethernet-capable communication processor for remote management. Additionally, dedicated terminal couplers and 24 VDC power supplies are coupled according to the PLC architecture requirements. The basic control panel display (HMI) is integrated for an on-site management and maintenance.

PLC control algorithm has been written according to IEC 61131-3 standard and Structured Text (ST) (TwinCAT environment). The general description of the algorithm structure is depicted as a flowchart in Fig. 4. The controller operates in a closed infinite loop. Once the electrolyser is switched on, the inspection of critical parameters takes place. This includes but is not limited to hydrogen leaking detection, maximum allowable output pressures of gases and temperature of the stacks, feed water pressure and temperature, cooling water presence, and PEM electrolysis cells voltage measured independently (every three cells combined).

If the failure is detected, the system reconnects to the safe operational mode and the electrolysis process is suspended. Each cycle of the infinite loop triggers reading and writing of PLC terminals that includes temperature and pressure readings and setting of analog and digital voltage signals (e.g. water pumps, electric relays). Control algorithm includes both manual and automatic operation modes. The manual mode is used in case of testing and maintenance while automatic mode is fully autonomous enabling the uninterrupted long-term operation. The system allows on sensitive data acquisition, writing CSV files as well as displaying data based on virtual or embedded HMI. Self-testing and remote upgrade of the control algorithm is also implemented.

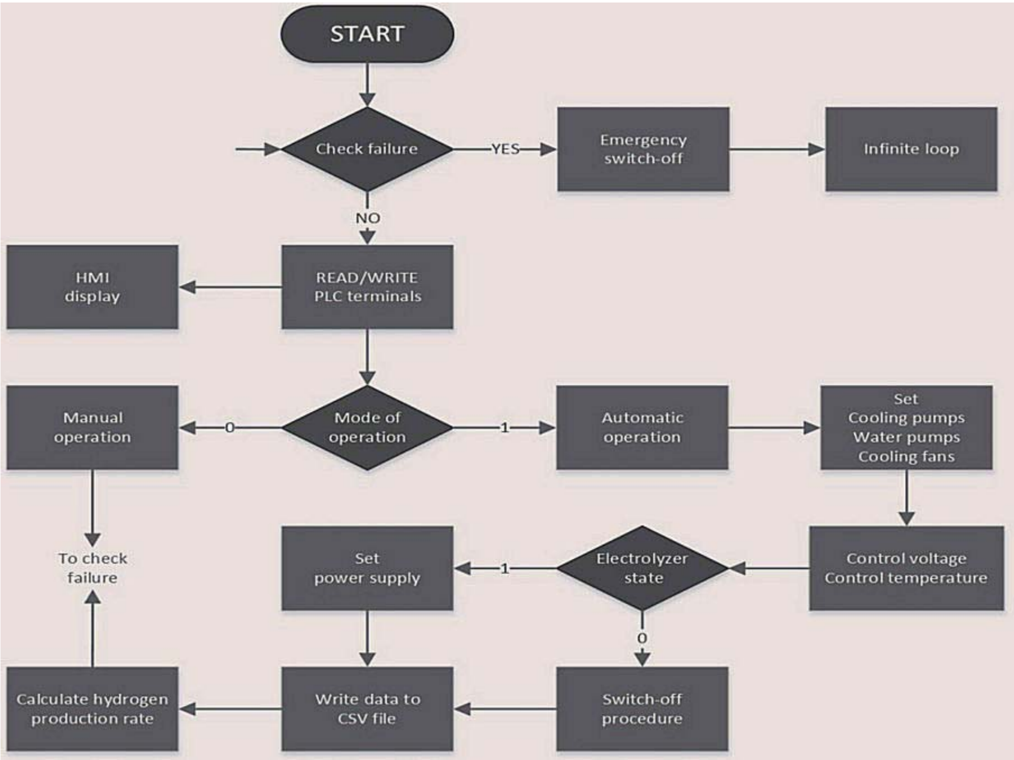

Fig. 4. Flowchart of control algorithm, PLC managed, manual or automatic operation

4. Electrolysis system evaluation

Water electrolysis system consists of two low-temperature PEM electrolysis stacks that work in parallel. Table 4 compares various parameters that describe both particular stack and the whole system. To illustrate the hydrogen production process in terms of its efficiency and performance, various technical parameters were calculated at three different voltage points i.e. 1.4, 1.6 and 1.8 V.
Electrolysis process starts at approx. 1.4 V per cell at which low hydrogen production rate occurs. At this voltage, the efficiency of the stack is high due to slow rate of electrochemical reactions as well as low current density. System efficiency is low as most of the power is consumed internally by balance-of-plant (BoP) components.

Once the voltage is scaled up by 200 mV, the rate of hydrogen production increases significantly to 41 and 82 g/h for single stack and the system, respectively. It is an optimal point in terms of system efficiency (77%) as activation losses of the stack are predominant. At maximum power point (11kW), the highest throughput is obtained (99 and 197.8 g/h of hydrogen production) whereas the efficiency for both the stack and the system is decreased - ohmic and mass transport losses become significant.
The system efficiency is decreased by electrical losses occurring at power supplies that generate high amount of thermal energy. The heat is removed from the system by forced circulation of air through the radiators as well as increased flow rate of cooling water. This also generates additional parasitic energy consumed by BoP components. For long lifespan of the system, it is advisable to operate at either low or nominal power point (4.2 or 9.9 kW). The operation of the system at maximum performance will quickly lead to creation of additional losses due to ageing process of the electrolysis stack. The power required for nominal hydrogen production at BoL (Beginning of Life) and EoL (End of life) for the stack is 4.2 and 5.8 kW, respectively.

The characterization of electrolysis stack is crucial from the system design point of view. Stack power and efficiency is depicted as a function of electrical current in Fig. 5. The nominal power point (at BoL) for the stack is at the voltage of 42 V and current of 100 A. At this point the efficiency calculated for the lower heating value of hydrogen (LHV, 33.4 kWh/kg) is around 86%. This allows on the generation of low amount of thermal energy in the consequence of small electrochemical losses and changes of the entropy for given reactants and products of hydrogen and oxygen evolution reactions. The maximum power point is achieved at the point of 44 V, 120 A (5.3 kW). Lifetime of the PEM electrolyser was taken into consideration during development process of the system, as at EoL the power requirement of the stack might exceed the available resources.

Table. 4. The comparison of parameters obtained and calculated at different cell's voltage for one electrolysis stack and electrolysis system consisting of 2 stacks

Parameter		Average cell voltage [V]		
		1.4	1.6	1.8
Stack	Power [kW]	0.049	1.75	4.73
	Efficiency, LHV [%]	89.0	78.4	70.0
	H_2 production [g/h]	1.3	41.1	99.0
System	Power [kW]	0.37	4.23	11.01
	Efficiency, HHV [%]	28.7	76.7	70.9
	H_2 production [g/h]	2.7	82.2	197.8

Total energy consumption of the electrolysis system is an aggregation of the utilization by two stacks and BoP components. The latter includes high power supplies, water and cooling pumps, cabinet and cooling fans and PLC controller with its dedicated hardware (programmable voltage sources, input/output terminals, etc.). Calculation of the total energy utilization includes all internal consumption in order to obtain reliable dependency of system efficiency.

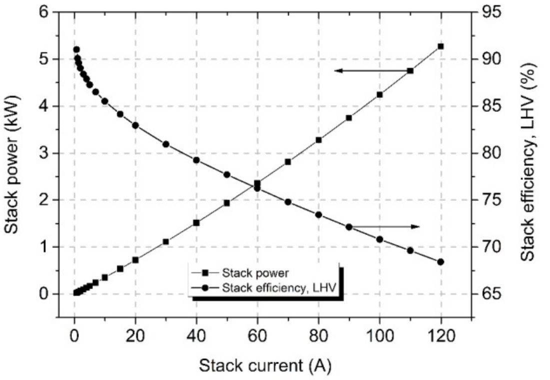

Fig. 5. Electrical characterization of the 1.0 Nm^3/hr PEMWE stack and lower heating value of hydrogen taken for calculation of efficiency

Fig. 6 describes the system performance as a function of total power. At low hydrogen production rate (less than 12 g/h), the system efficiency is low due to BoP requirements. Increasing the production rate increases also the efficiency maximally up to 77% (3.7 kW). It is an optimal point of operation for the system, at which the ratio of hydrogen energy produced to the total energy consumed has the highest value. Above this point, the efficiency is still high (around 70%). However, it is linearly decreasing.

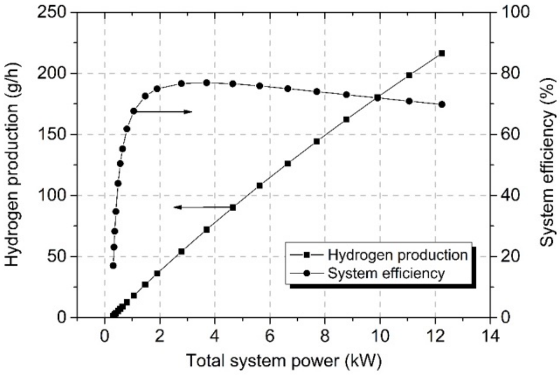

Fig. 6. Electrolysis system performance, including Balance-of-Plant and two stacks under operation

Taking into account the higher heating value of hydrogen (39.49 kWh/kg) and measuring the energy utilization for electrolysis system, the energy input/output dependency obtained is high.

In Fig 7, chemical energy of produced hydrogen is shown as a function of total energy consumption. The amount of hydrogen generated in electrolysis process is calculated based on Faraday's law assuming there were no electrochemical losses nor internal currents. Hydrogen mass (m_{H2}) is calculated from the following equation:

$$m_{H_2} = \frac{M_{H_2} \cdot I \cdot N_o}{nF} \tag{4}$$

where M_{H2} is molecular mass of H_2, I – electrical current, N_0 – number of cells in the stack, n – number of electrons per hydrogen molecule, F – Faraday's constant. Hydrogen production method via the electrolysis is an energy-consuming process. For the designed system, at least 30% of the energy has to be lost. The system operates the most effectively at the efficiency of 77%, which means a constant utilization of 3.7 kWh of electrical energy that corresponds to 2.85 kWh of hydrogen produced (HHV). However, it is relatively slow production rate. At the nominal point of operation, this relation is 9.9 vs. 7.1 kWh, while at maximum power point 12.2 vs. 8.5 kWh.

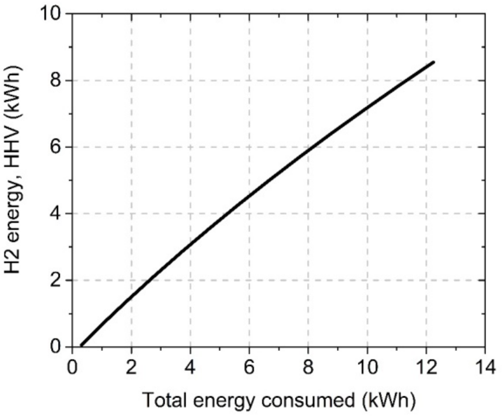

Fig. 7. The performance of the system in terms of ability to produce chemical energy in the form of hydrogen, calculated based on the higher heating value of this fuel (39.49 kWh/kg)

5. Hydrogen compression

Hydrogen produced in the prototype PEMWE is supplied to a metal hydride compressor. The H_2 compression (3–200 bar, up to 5 Nm^3/h) is driven by the periodic heating (steam) and cooling (circulating water) of metal hydride materials disposed in metal hydride containers for hydrogen compression. The compression is carried out in three stages using AB_5 material ($LaNi_{4.9}Sn_{0.1}$) for stage 1, AB_5 material ($La_{0.8}Ce_{0.2}Ni_5$) for stage 2 and AB_2-type material (C14-$Ti_{0.65}Zr_{0.35}(Mn,Cr,Fe,Ni)_{2+x}$) for stage 3 [29].

Hydrogen from the electrolyser (see Fig. 8) is supplied to the input (suction) pipeline of the compressor (H2IN) via shut-off valves (V1, V2), buffer cylinders (B1..4), reducer (R1) equipped with low- (LP) and high-pressure (HP) manometers, and mass low meter (MFM). The compressed H_2 from the output (discharge) pipeline of the compressor (H2OUT) equipped with a pressure sensor (PS), via shut-off valve (V3), check valve (CV1) and shut-off valve (V4), is supplied to hydrogen cylinder pack (CP) and, further, via shut-off valve (V5), to high-pressure hydrogen manifold of SAIAMC gas supply system. The cooling is provided by a cooling tower (CT) connected to water supply and drain lines of the compressor via shut-off valves V6 and V7, respectively. The heating steam, from steam generator (SG) equipped with manometer (SP) and safety relief valve (RV1) is connected, via shut-off valve (V8), to steam supply line of the compressor. Switching of the steam and water flows is carried out automatically by solenoid valves in the compressor (MHC) while switching gas flows is provided by a check valve arrangement in the compressor.

A typical cyclogram of the compressor operation is presented in Fig. 9. Periodic heating and cooling of two compression modules in the opposite phase (T1, T2) results in the increase of H_2 pressure from 3–5 bar in the suction line (P(in)) to 20–30 bar between stages 1 and 2 (P1–2), 40–80 bar between stages 2 and 3 (P2–3) and higher, up to 200 bar at the output of the compressor (P(out)). In doing so, the H_2 flow rate at the input of the compressor periodically changes between 0 and 3–4 Nm^3/h. The values of H_2 flow rate (up to 6 Nm^3/h) and the average compressor productivity (1–4 Nm^3/h) depend on the duration of the heating / cooling cycle (20–35 minutres), steam temperature (120–150 °C) and, in the lesser extent, the suction (above 3 bar) and discharge (up to 200 bar) H_2 pressures.

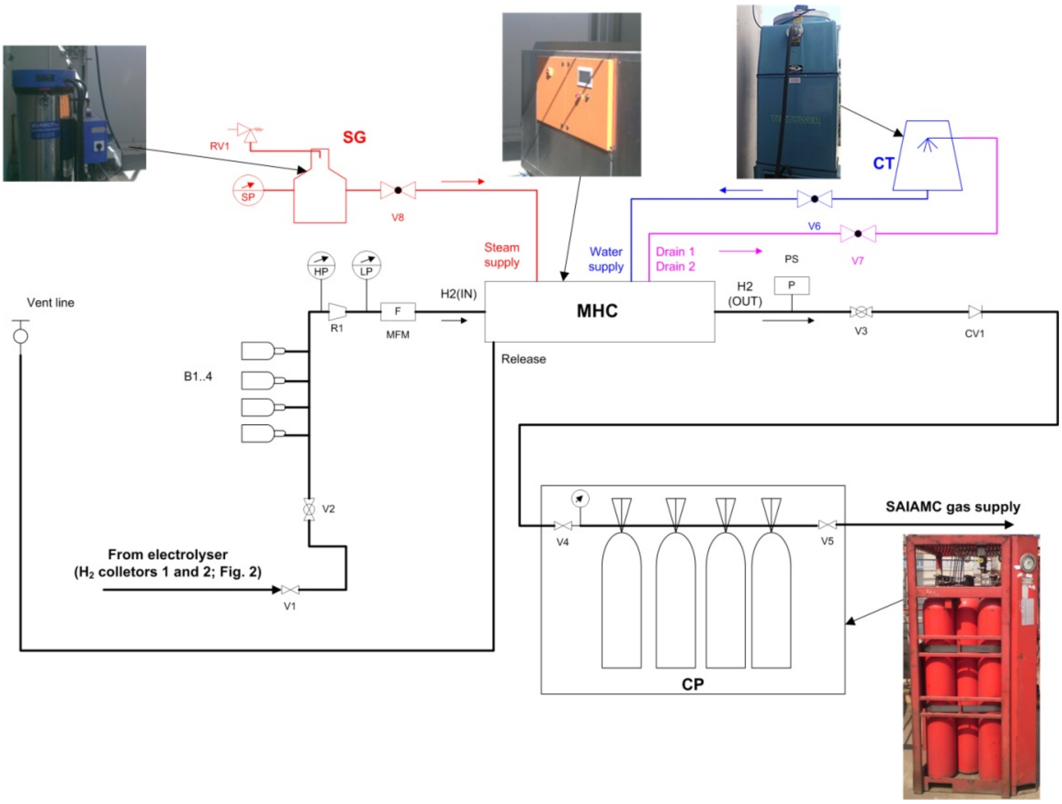

Fig. 8. MH compressor (MHC) installed at SAIAMC hydrogen supply facilities; the insets show main system components. SG – steam generator; CT – cooling tower; CP – cylinder pack

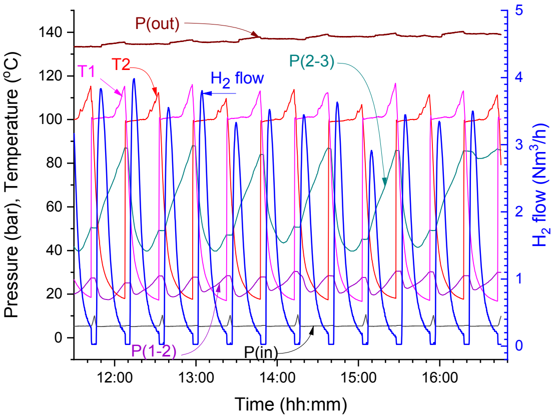

Fig 9: Typical operation of MH compressor at SAIAMC; heating / cooling time 25 minutes, average productivity 1.2 Nm^3/h. Left Y-axis: T1, T2 – temperatures in the first and the second compression modules, respectively; P(in) – H_2 suction pressure; P(out) – H_2 discharge pressure; P(1-2) – H_2 pressure between stages 1 and 2; P(2-3) – H_2 pressure between stages 2 and 3. Right Y-axis: H_2 flow in the suction line of the compressor.

The compressed hydrogen is supplied to either SAIAMC Research facility for consumption, or for refuelling fuel cell vehicle prototypes.

Conclusions

Hydrogen economy becomes a necessary action for our civilization due to environmental issues such as global warming effect and air pollution, and depletion of fossil fuels. In this paper, the hydrogen production autonomous system was described including its engineering, testing and analysis. Hydrogen safety is taken into consideration as one of the most important issue arising when it comes to development of practical hydrogen production applications.

Electrolysis system operates based on two 4.2 kW PEM stacks managed by PLC controller. The system is capable of working with the efficiency of up 77% at optimal conditions. Its efficiency depends on selected power point therefore this value can vary significantly. Hydrogen production method via the electrolysis is an energy-consuming process. For the designed system, at least 23% of electrical energy is converted into the heat and consumed internally. Thermal energy generated due to stack electrochemical losses and BoP electrical losses accounts for app. 33% increase of energy consumed. The PLC controller operates in a closed infinite loop, this enables system safety that protects the whole system and ensures reliable operation.

The electrolysis system has been integrated with thermally-driven metal hydride hydrogen compressor to supply high pressure hydrogen (up to 200 bar, 2 Nm^3/h) to SAIAMC testing facilities. The economic usage of hydrogen as an efficient energy carrier has been justified assuming the production of so-called green hydrogen based on the excess of renewable energy sources.

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REFERENCES

[1] S. A. Zanganeh KE, “A novel process integration, optimization and design approach for large-scale implementation of oxy-fired coal power plants with CO2 capture,” International Journal of Greenhouse Gas Cont, vol. 1, p. 47, 2007.

[2] The Environmental Literacy Council, “http://www.enviroliteracy.org/subcategory.php/21.html,” The Environmental Literacy Council, 28 January 2015. [Online]. http://www.enviroliteracy.org/subcategory.php/21.html. [Accessed 15 June 2018].

[3] M. Balat, “Potential importance of hydrogen as a future solution to environmental and transportation problems,” International Journal of Hydrogen energy, vol. 33, pp. 4013-4029, 2008.

[4] V. Molkov, Fundamentals of hydrogen safety enegeering 1, Belfast: Ventus Publishing ApS, 2012.

[5] M. Conte, A. Lacobazzi, M. Ronchetti and R. Vellone, “Hydrogen economy for a sustainable development: State of the art and technological perspectives,” J Power sources, pp. 171-187, 2001.

[6] K. G. d. Santosa, C. T. Eckerta and E. D. Rossia, “Hydrogen production in the electolysis of water in Brazil, a review,” Renewable and Sustainable Energy Reviews, vol. 68, pp. 563-571, 2017.

[7] S. Kasai, “Hydrogen electrical energy storage by high-temperature steam electrolysis,” International Journal of Hydrogen energy, vol. 39, pp. 358-370, 2014.

[8] H. Miland and U. Ollerberg, “Testing of a small-scale stand-alone power system based on solar energy and hydrogen,” Solar Energy, vol. 86, no. 1, pp. 666-680, 2012.

[9] E. Kosonen, “Optimization strategies of PEM Electrolysers as part of solar PV system,” in 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe), Karlsruhe 2016, 2016.

[10] D. Ghribi, A. Khelifa, S. Diaf and M. Belhamel, “Study of hydrogen production system by using PV solar energy and PEM electrolyser in Algeria,” International Journal of Hydrogen Energy, vol. 38, pp. 8480-8490, 2013.

[11] I. Dincer. and C. Acar, “Review and evaluation of hydrogen production methods for better sustainability,” International Journal for Hydrogen energy, vol. 34, pp. 11094-11111, 2015.

[12] P. Moldrik, Z. Hradilek, “Research of the hydrogen storage system with photovoltaic panels”, Przeglad Elektrotechniczny (Electrical Review), vol. 87(9a), pp. 210-213, 2011.

[13] D. Gluchy, D. Kurz, G. Trzmiel, “The use of fuel cells to store energy from renewable sources”, Przeglad Elektrotechniczny (Electrical Review), vol. 90(4), pp. 81-84, 2014.

[14] Z. Belgroun, M. Hatti, S. Hanini, “Power interface efficiency evaluation for photovoltaic system used in hydrogen production”, Przeglad Elektrotechniczny (Electrical Review), vol. 95(6), pp. 81-85, 2019.

[15] C. Acar and C Dincer, “Comparative assessment of hydrogen production methods from renewable and non-renewable sources,” International Journal of Hydrogen Energy, vol. 39, pp. 1-12, 2014.

[16] A. Razniak, M. Dudek et al, “Determination of Electrical and Efficiency Parameters of Air Cooling of Low-Temperature PEM Fuel Cell Stack with Power of 5kW”, Przeglad Elektrotechniczny (Electrical Review), vol. 94(4), pp. 140-147, 2018.

[17] N. A. Zambri, A. Mohamed, “Hybrid Proton Exchange Membrane Fuel Cell with Battery Energy Storage for Stand-Alone Distributed Generation Applications”, Przeglad Elektrotechniczny (Electrical Review), vol. 89(5), pp. 161-166, 2013.

[18] M. Malinowski, J. Chmielowiec, G. Pasciak, T. Swieboda, “Usability evaluation of PEM fuel cell and supercapacitors application in the Emergency Power Backup System”, Przeglad Elektrotechniczny (Electrical Review), vol. 89(8), pp. 201-204, 2013.

[19] M. Chaplin, “http://www1.lsbu.ac.uk/water/electrolysis.html,” Water Structure and Science, 17 May 2017. [Online]. Available: http://www1.lsbu.ac.uk/water/electrolysis.html. [Accessed 26 June 2017].

[20] M. Schalenbach, A.R. Zeradjanin, O. Kasian, S. Cherevko and K.J.J Mayrhofer, “A Prospective on Low-Temperature Water Electrolysis - Challenges in Alkaline and Acidic Technology,” International Journal of Electrochemical Science, vol. 13, p. 1173, 2018.

[21] M. Carmo, D. L Fritz, J. Mergel and D. Stolten, “A comprehensive review on PEM water electrolysis,” International Journal of Hydrogen Energy, vol. 38, pp. 4901-4934, 2013.

[22] N. A. Kelly, “Hydrogen production by water electrolysis,” Advanced Hydrogen production, storage distribution, vol. 6, pp. 159-185, 2014.

[23] S. Grigoriev. P. Millet, “Water electrolysis technologies,” in Renewable Hydrogen Technologies: Production, Purification, storage Application and safety, Amsterdam, Luis M. Gandia; Gurutze Arzamendi; Pedro M. Dieguez, 2013, pp. 19-42.

[24] D. S. Agata Godula-jopek, Hydrogen Production, Chicago: John Wiley & Sons Inc, 2015.

[25] J. O. M. Bockris, “The hydrogen economy: it’s History,” International Journal of Hydrogen Energy, vol. 38, pp. 2579-2588, 2013.

[26] S. Grigoriev, P. Millet, S. Korobtsev, V. Porembskiy, C. E. M. Pepic, C. Puyenchet and V. Fateev, “Hyrogen safety aspects related to high -pressure polymer electrolyte membrane water electrolysis,” International Journal of Hydrogen Energy, vol. 34, pp. 5986-5991, 2009.

[27] European Industrial Gases Association AISBL, “Gaseous hydrogen stations.,” European Industrial Gases Association AISBL, IGC Doc 15/06/E;, Chicago, 2006.

[28] J. Duboisb, G. Hûa, P. Poggia, F. Montignacb, P. Serre-Combeb, M. Musellia, J.C. Hoguetc, B. Vesyc, F. Verbeckec “Safety cost of a large scale hydrogen system for photovoltaic energy regulation,” in 4th Symp. (Int.) on hydrogen safety. September 12-14 2011, San Francisco, CA;, 2011.

[29] M. Lototskyy, Y. Klochko, M. W. Davids, L. Pickering, D. Swanepoel, G. Louw, B. v. d. Westhueizen, S. Chidziva, C. Sita, B. Bladergroen and V. Linkov, “Industrial-scale metal hydride hydrogen compressors developed at the South African Institute for Advanced Material Chemistry,” Materials today, vol. 5, pp. 10514-10523, 2018.