STUDY ON PERFORMANCE OF A GREEN HYDROGEN PRODUCTION SYSTEM INTEGRATED WITH THE THERMALLY ACTIVATED COOLING

Laince Pierre Moulebe[*]
Department of Electrical Engineering
Laboratory of Complex Cyber-Physical Systems (LCCPS) of ENSAM Hassan II University
150 Bd du Nil, Casablanca 20670, Morocco, mpierrelaince12@gmail.com
https://orcid.org/0000-0001-7149-5694

Abdelwahed Touati
Department of Electrical Engineering
Laboratory of Complex Cyber-Physical Systems (LCCPS) of ENSAM Hassan II University
150 Bd du Nil, Casablanca 20670, Morocco, touati2010@hotmail.com
https://orcid.org/0000-0001-9589-0090

Eric Obar Akpoviroro
Department of Electrical Engineering
Laboratory of Complex Cyber-Physical Systems (LCCPS) of ENSAM Hassan II University
150 Bd du Nil, Casablanca 20670, Morocco, akposobar@yahoo.com
https://orcid.org/0000-0002-4776-4708

Nabila Rabbah
Department of Electrical Engineering
Laboratory of Complex Cyber-Physical Systems (LCCPS) of ENSAM Hassan II University
150 Bd du Nil, Casablanca 20670, Morocco, nabila_rabbah@yahoo.fr
https://orcid.org/0000-0002-2221-4830

Highlight
Process for the cost reducing of green hydrogen through the production of cold using the recovered heat from the hydrogen production process.

Abstract
The energy transition is at the centre of research and development activities with the aim to fight against the effects of global warming. Today, renewable energies play a significant role in the electricity supply to the World and their use increases day after day. Because of the intermittency of a large-scale production system generates the need to develop clean energy storage systems. Hence, energy storage systems play is one of key elements in the energy transition. In this perspective, a green hydrogen is defined as an energy carrier thanks to its high energy density in relation to its negligible mass, not to mention its abundance in our environment, and its extraction, which does not contribute to any greenhouse gases. However, the production cost is not negligible. Hence, this work shows a numerical modelling of the heat balance from a green hydrogen production system using a thermal storage in a Metal Hydride (MH) tank for an electrification by Proton Exchange Membrane (PEM) fuel cell integrated into the production of heating, cooling and sanitary hot water (SHW) through the recovery of the heat released by the whole system combined with the technology of thermally activated cooling of an adsorber. This allows demonstrating that the green hydrogen can be an interesting solution according in the hydrogen production chain and in the tertiary sectors.
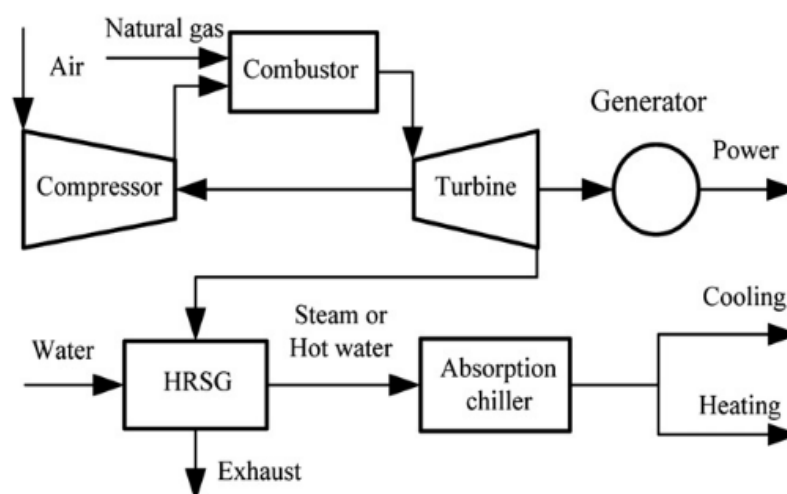
Introduction
A reduction of the world's energy consumption is one of the biggest challenges in the fight against the global warming. However, it is especially difficult with a continues grow of population [1] as it results in an increasing demand for energy. Hence, the research on the production and storage of clean energy is developing considerably

to meet these demands. Therefore, to face these issues, the production of clean energy is growing on a large scale, especially through solar and wind system, leading to need for a development of clean storage systems. In the same strategy of sustainable development, reducing energy losses becomes essential. Therefore, the energy efficient techniques for the energy storage have been developed. Among them are the recovery of waste thermal energy in power plants to cover certain demands in heating and cooling.

Air conditioning is responsible for almost 15% of the energy consumption today [2] and this percentage is expected to increase considerably by 2050 due to the advance of global warming [3]. Knowing that the most used technology is still the mechanical steam compression cycle, which contributes to greenhouse gases, it is important to develop novel solutions of a cold production using more sustainable systems. In this perspective, techniques of cogeneration and trigeneration were born and they found to be the most frequently used in hospitals, hotels and large public spaces. The combined cooling and heating and power systems (trigeneration) is a technique dating from the 80's, resulting from cogeneration, which itself has more than 110 years of maturity [4]. As can be seen in Figure 1 (a), trigeneration allows the recovery of waste heat from electricity production to produce heat and cooling. As presented by Baudry et al. [5], the building sector is the second largest consumer of energy in the World, far ahead of industry. Furthermore, the need for heating and cooling is relatively important and represents the most energy consuming part in the tertiary sector [6]. Therefore, a trigeneration using thermally activated cooling has been developed over time in several sectors [7].

Considering that the use of green hydrogen is one of the pillars of the energy transition nowadays [8] this article is focus on a trigeneration in the production of green hydrogen to obtain electricity. With the aim of enhancing green hydrogen in the second energy consumer sector through innovative solutions [9], this study takes into consideration all thermal losses of the production system (PEM electrolyser), storage MH and electrification (fuel cell) to cover the needs of SHW production, cooling and heating (Figure 1 (b)), by using the zig-zag configuration exchanger [10] with a better performance. A trigeneration demonstrates several advantages in hydrogen storage because the temperatures released in alkaline electrolysers can reach up to 160°C and in Proton Exchange Membrane (PEM) electrolysis, temperatures are between 60 and 80°C [11,12]. On the other hand, the High Temperature Electrolysis (HTE) allows achieving temperature as high as 200°C. The power-to-hydrogen-to-power cogeneration [13–15] integrated to the novel elements presented herein, the hydrogen as an energy vector in the energy transition can be considered for heating and cooling with a benefits for the energy sector and the environment [16].

The study conducted in this article shows the technological potential of systems based on green hydrogen. Notwithstanding, given the intermittency of renewable energy plants, a proper storage system is the "must". Hence, several studies concerning the use of green hydrogen as a means of storage have emerged [17,18]. However, the major drawback in the use of green hydrogen is its cost of production. This work contributes to this challenge and shows that enough cooling and heating energy can be produced from the heat that normally would be lost from the power-to-hydrogen-to-power process.
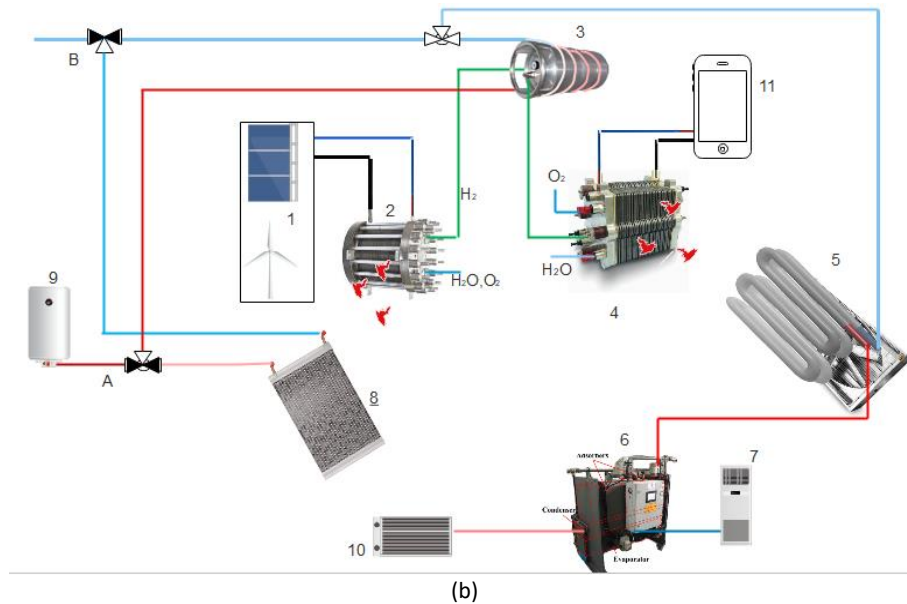

(a)

(b)

Figure 1 (a) Trigeneration according to [16]. (b) green hydrogen production with integrated cooling and heating.

Methods

This work was made using the numerical modelling performed in Matlab R2013a software. MATLAB® is a programming platform designed for engineers and scientists to analyse and design systems and products. The heart of MATLAB is the MATLAB language, a matrix-based language allowing the most natural expression of computational mathematics.

Results and discussion

SWH-Cooling-Heating by green hydrogen heat wasted.

    a.   Interest of thermally activated cooling in green hydrogen

Green hydrogen technology is well known today and there is a variety of research on this topic [18–21]. The technologies in competition today are Alkaline and PEM [11]. In this study the PEM technology for the storage of green hydrogen is discussed. This technology is relatively easily adaptable to the intermittency of the voltage applied to its terminals; therefore, this solution can be used in case of renewable energies (solar and wind). As shown in Figure 1 (a), one of the important elements in the combined cooling heating and power or thermally activated cooling technology is the process of absorption and adsorption chiller or dehumidifier [22]. Absorption technology is widely used; however, adsorption has the advantage of operating at low temperatures, which is relatively suitable for this study as the temperature lost in a hydrogen production system with PEM technology are rather low. Hence, there is a considerable interest in the thermally activated cooling performed in the adsorption mode. Several works show that adsorption is a thermodynamic phenomenon suitable for low quantities of waste heat .[23,24]

    b.   Description of the system.

The proposed system, unlike to the previous one [13–15] is equipped with a thermal storage (metal hydride), which presents very interesting aspects in terms of thermal power [25], and an adsorber for a heating and cooling production. The main components, given in Figure 1 (b), used herein are: (5) the tubular heat exchanger to recover heat coming from the fuel cell through forced convection to stimulate cooling on the fuel cell side, (6) the adsorber containing the thermodynamic system, which produces cold, heat, SHW using the hot water coming from (5) or (3) and the cold water coming from the chiller. The proposed adsorber was selected according to the literature [26], and as shown in [23,24,27], the silica gel is an refrigerant fluid efficient in the adsorption of low temperature for trigeneration systems. The system contains the cooling module (7), which diffuse frigid air from the evaporator. The recovery of hot water from the condenser is given as (10). In the tube exchanger (8), the cold water circulates allowing the recovery of the heat coming from the electrolyser, which is modelled according to the characteristics given in the literature [28]. Such produced water can be directly used to cover the needs of domestic applications. In addition, an additional supply of hot water can be obtained from the MH/fuel cell. It is relevant to note that the storage of hydrogen in the MH tank generates a heat, which is

released during the storage (exothermic reaction). This heat can be used to boil water. The hydrogen storage allows to heat up water to about 65°C from (5), which is later superheated by an external heater to about 150°C and circulates around the MH tank and is used for a desorption (endothermic reaction). Furthermore, the system contains the supply of the electrolyser constituted by a hybrid system (PV solar – wind) (1), the electrolyser (2), the fuel cell (4), and the electrical consumption system (11).

Thermal study.
  a. Fuel cell/electrolysis recovery.

This part aims evaluating the water heating temperature at the adsorber inlet. A heat transfer by forced convection, to implicitly cool the fuel cell or the electrolyser, is proposed. The following assumptions, which are in agreement with those proposed in the literature [27,28], were made in this work:

(1)
$$R_e = (\rho \times v \times D_h)/\mu$$

(2)
$$Pr = (C_p \times \mu)/\lambda$$

(3)
$$N_U^{vap} = C.R_e^{vap\,n} \times P_r^{vap\,1/3}$$

(4)
$$N_U^{vap}(tur) = 0.023 \times Re^{0.8} \times Pr^n$$

(5)
$$N_U^{hw} = 1.86 \times (R_e^{hw} \times P_r^{hw})^{\frac{1}{3}} \times (\frac{D}{L})^{\frac{1}{3}} \times (\frac{\mu}{\mu_t})^{0.14}$$

where:
N_u - the Nusselt number;
Pr - the Number of Prandtl;
D - the hydraulic diameter;
S and P - the section and the exchange perimeter, respectively;
μ - dynamic viscosity (kg/(m·s));
R_e - Reynolds number;
C_p - the specific heat capacity (J/(kg·K)).

Tables 1-3 summarise values used for the simulation.

Table1. Specifications Adopted for The Simulation. *Source: Author.*

Components	Rating values
L_e(PCM)	1.8 m
λ_{PCM}	1.32 W/(m·K)
v_{air}	0.1 m/s
v_{water}	0.15 m/s
μ	0.000891 kg/(m·s)
μ_t	0.000404 kg/(m·s)
L(coil)	2 m
ρ_w	997.63 kg/m³
λ_{MH}	2 W/(m·K)
λ_{H2}	0.1815 W/(m·K)
λ_{CU}	386 W/(m·K)
λ_{WATER}	0.6 W/(m·K)
μ	0.000891 kg/(m·s)
μ_t	0.000404 kg/(m·s)

The coefficients C and n in Figure 2 are determined according to equation (6), and γ is a coefficient as given in the literature [29].

(6) $$\gamma = S_p/D$$
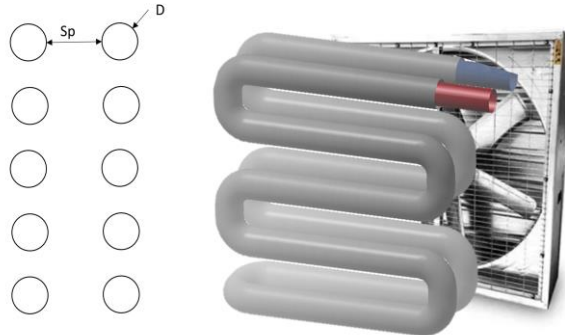

Figure 2. Forced convection heat exchanger (C = 0.386; n = 0.592). *Source: Author.*

Figure 2 represents the heat recovery mode on the electrolyser and fuel cell sides. The air extractor is used behind a coil. The coil and extractor assembly are fitted into a box to promote a heat transfer around the coil. The thermal power φ (W) can be calculated according to the following equations:

(7) $$\varphi = h \times S \times (T_{fuel_{cell}} - T_{serpentine})$$

(8) $$h = \frac{\lambda \, Nu}{D_h}$$

(9) $$D_h = \frac{4\,S}{P}$$

(10) $$\Delta T = \frac{(T_{fuel_{cell}} - T_{serpentine})}{\ln\left[(T_w - T_{serpentine}) - (T_{serpentine} - T_{fuel_{cell}})\right]}$$

where:
D_h - the hydraulic diameter (mm);
N_u - the Nusselt number;
Pr - is the Prandtl number;
S - the section exchange (mm²); P the perimeter exchanger (m).

The calculation of the outlet temperature can be expressed by the following equation:

(11) $$T_{out} = \frac{T_{in}}{e^{\frac{K.A}{\dot{m} \times C_w}}}$$

where:
C_p and C_w - the specific heat capacities (J/K);
$\dot{m}$ - the mass flow rate and k the thermal conductivity (W/(m·K)).
The same principle of heat recover can be used on the electrolysis side.

b. Heat recovery in the metal hydride (MH) tank
As presented in Figure 1(b), the cold water recovers heat from the MH storage system presented in Figure 3. According to equation (12), during storage, a significant amount of heat is released by the adsorption (hydrogen storage). It is important to note that for a desorption, the amount of thermal energy supplied is equivalent because it is an endothermic reaction [20]. The proposed numerical mathematical model is based on the calculation models of heat exchanger and heat transfer as given in the literature [29,30]. For this model, a transfer by conduction through MH - PCM wall - coil – water can be considered. The surface contact

between the coil and the MH can be estimated at 1/8 of the lateral surface of the coil, as presented in Figure 3.
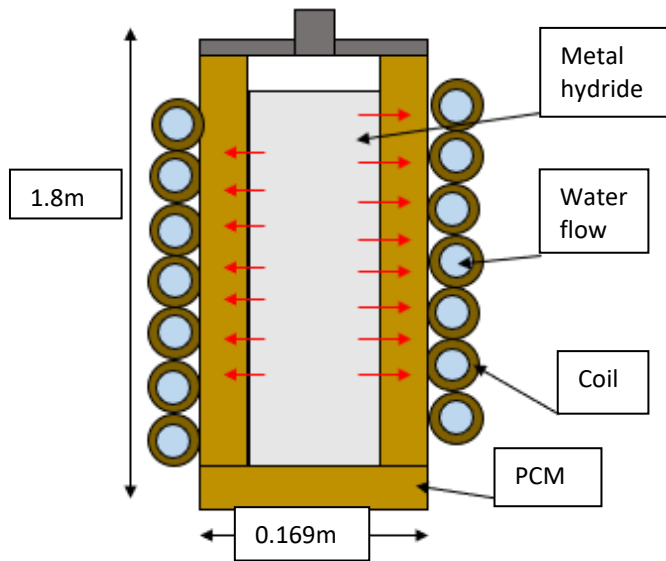

Figure 3. The internal shape and size of the MH tank surrounded by a coil recovering heat. *Source: Author.*

The numerical modelling of the heat production in the MH storage tank by thermal compression is based on different works presented in the literature [18,31,32] The expression of heat released is as follows:

(12)
$$Q_{MH} = \int_{c_d}^{c_a} \Delta H_d(C)dC$$

where:
C_a and C_d - are determined by PCT diagram.
For this study, the values used were C_d = 6 NL/kg; C_a = 143 NL/kg; Ta = 20°C; Td = 150 °C and ΔH_d is a standard enthalpy of hydride formation expressed in J/mol$_{H2}$.

(13)
$$C_a = C_a(p_L, T_L)$$

(14)
$$C_d = C_d(p_H, T_H)$$

Where:
C - is the hydrogen concentration in MH (mol$_{H2}$/kg);
C_a - the hydrogen concentration during absorption (NL/kg);
C_d - the hydrogen concentration during desorption (NL/kg);
p_h, p_L - the hydrogen pressure during the desorption and absorption, respectively (atm).

The characteristic of the Pressure-Composition-Temperature (PCT) curve determining the reversibility of the storage capacity using the MH LaNi5 alloy is given in Figure 4.
The desorption equilibrium pressure can be determined according to the PCT diagram given in Figure 4 and is expressed by the following function:

(15)
$$P = P_d(C, T)$$

Compression productivity can be expressed as:

(16)
$$V = \frac{m \, \Delta C}{\Delta t}$$

where: *m* is the mass of MH, *Δt* the time of the absorption-desorption cycle and *ΔC* is the productivity cycle.

The van't Hoff relation allowing to express the partial molar enthalpy is expressed by the following relation:

(17)
$$d \ln (P) = \frac{\Delta H_d}{RT} - \frac{\Delta S}{R}$$

where:
T - is the temperature (K);
R - is the universal gas constant (8.314 J/(mol·K))
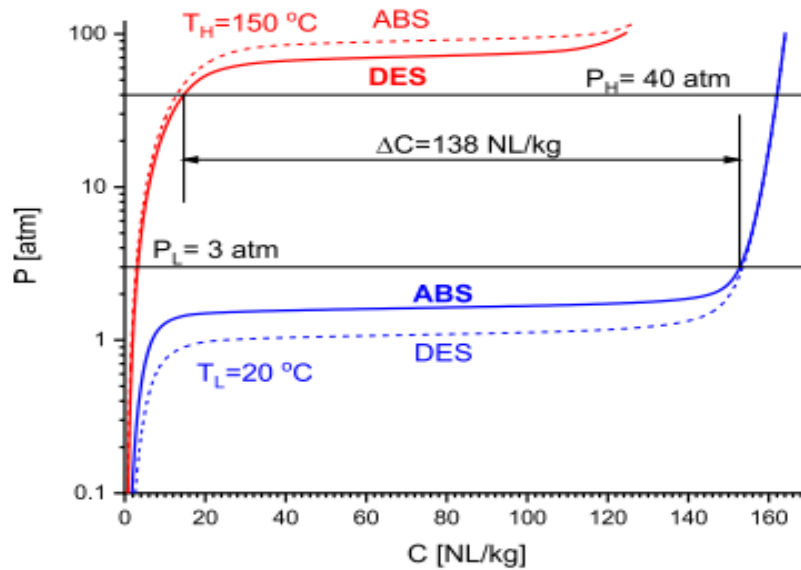ΔS - is the standard entropy of hydride formation (kJ/(kg$_{H2}$·K).

Figure 4. Curve Phase Change Material (PCM) of MH LaNi5. *Source [33].*

Expression of the total heat consumed is equal to the total heat produced during adsorption with the total hydride mass (m) and can be calculated according to the following equations:

(18)
$$Q_{MH} = \delta C \times m \times \left(\frac{\Delta H_1 + \Delta H_N}{2} + \sum_{k=2}^{N-1} \Delta H_k\right)$$

(19)
$$\delta C = \frac{C_a - C_d}{N-1}$$

This heat can be also expressed by the equation (20) and can serve to determine the resulting temperature. It is relevant to observe that the temperature released by the MH tank is estimated in the vicinity of the desorption temperature, i.e., close to 150°C. Figure 5 shows the curves of thermal heat release in MH tank, obtained by simulation.

(20)
$$Q_{MH} = m \times C_H \times (T_{MH}^d - T_H^{in})$$

The heat transfer on 1/8 of the coil given in (Figure 5) can be calculated from:

(21)
$$Q_{MH} = \frac{T_{MH}^d - T_p}{\frac{Di}{\lambda_{H2} \times (\frac{D_i^2 \times \pi}{4} \times L_{PCM})}} = \frac{T_p - T_s}{\frac{ln\left(\frac{re}{r_i}\right)}{2\pi \times l \times k_{PCM}}} = \frac{T_s - T_{water}}{\frac{ln\left(\frac{re}{r_i}\right)}{2\pi \times l \times k_{serpe}}}$$

where
$T_{MH}^d, T_p, T_s, T_{water}$ - are the temperatures of MH, external face of MH tank, the coil internal surface and water

circulating in the coil, respectively;
k_{serpe} and k_{PCM} - are the heat transfer coefficient of the serpentine and PCM; D_i
r - are the internal diameter and radius and λ_{H2} the thermal conductivity.

Table2. Specifications Adopted for The Simulation. *Source: Author.*

Components	Rating values
r_i(coil)	0.077 m
r_e(coil)	0.08 m
$D_i(MH)$	0.149 m
L_e(MH)	1.65 m
r_e(PCM)	0.169 m
r_i(PCM)	0.149 m
L_e(PCM)	1.8 m
λ_{PCM}	1.32 W/(m·K)

Using the equation given in the literature [31], the mass conservation can be calculated:

(22)
$$\left(\varepsilon \times V_r \frac{d\rho_{H2}}{dt}\right) = (\dot{m}_{H2} \times V_r) - \overline{m_{el-MH}}$$
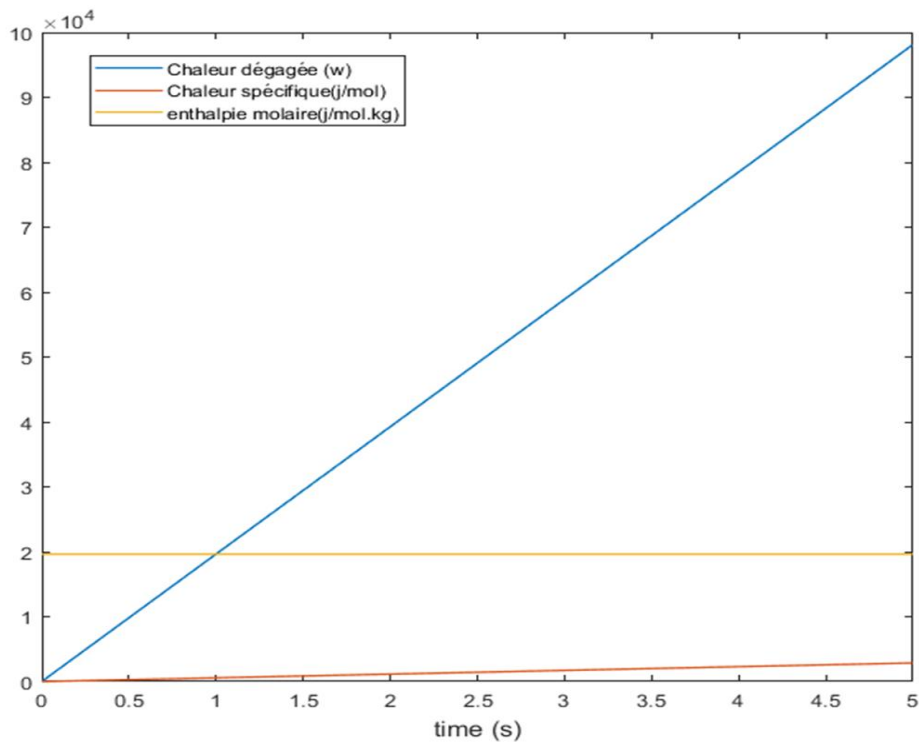

Figure 5. Characteristics of the thermal power in the MH tank(line blue is the heat output (W), line red represents the specific heat (J/mol) and line yellow is the molar enthalpy (J/(mol·kg)). *Source: Author.*

Mass flow of hydrogen circulating between storage tank and fuel cell can be expressed as given here:

(23)
$$\dot{m}_{H2} = \frac{1}{2} N_o \frac{\partial x}{\partial t} M_{H2} R_P$$

where:
$\dot{m}_{H2}$ - the mass flow rate of hydrogen during MH desorption;
$M_{H2}(\frac{kg}{kmol})$ - the molar mass of hydrogen;

x - atomic ratio of the reaction;
Rp - the particle density (H_2 particle/m^3);
N_o - molar mass
ε - the MH porosity.

c. Evaluation of the cooling-heating-SHW capacity by adsorption silica gel

The performance of the adsorber is defined according to the coefficients of performance for cooling and heating, as well as the different affiliated powers. The heat transfer calculations used above with adaptation of the coefficients according to the temperatures can be used to calculate the outlet temperature of the chiller. All the characteristics and data were established according to [24,27,34,35].

$$ (24) \qquad Q_{cool} = \sum_{j=1}^{n} \frac{\left[V_{ch}\rho_{ch}C_{ch}(T_{chi}^j - T_{cho}^j)\right]}{n} $$

$$ (25) \qquad Q_{heat} = \sum_{j=1}^{n} \frac{\left[V_w\rho_w C_w(T_{wi}^j - T_{wo}^j)\right]}{n} $$

$$ (26) \qquad SCP = \frac{Q_C}{M_a} $$

$$ (27) \qquad COP = \frac{Q_C}{Q_h} $$

where:
V_{ch} and V_w - volume flow rate in chilled water and hot water, respectively,
ρ_{ch} and ρ_w – densities;
C_{ch} and C_w - specific heats;
T_{chi}^j and T_{wi}^j - inlet temperatures;
T_{cho}^j and T_{wo}^j - outlet temperatures of the chilled water and hot water, respectively;
J - data number;
n - number of complete cycles;
Ma - the mass as in the literature [10] used for the calculation of the temperature at the outlet of the chiller.
All the characteristics and data were established according to [23,26,34,36].

Table 3. Specifications Adopted for the Simulation. *Source: Author.*

Components	Rating values
V_{H2}^{el}	10000
ρ_{H2}	0.09 kg/m^3
$K.A$(evopo+bed adsorption)	2557 W/(m·K) ×1.37 m²+10300
$K.A$(cond+bed desorption)	4115 W/(m·K)×03.71 m²+9850
C_w	4180 J/(kg·K)
ΔS	108.3 J/(mol·K)
R	8.314 kJ/K
v_{air}	0.1 m/s
v_{water}	0.15 m/s

Experiences and analysis

The performed simulation takes into account the parameters from several research papers, namely [27,29,37]. Figure 6 shows the system considered for modelling and according to the numerical modelling the input current in the electrolyser was 52 A and was obtained from renewable source.
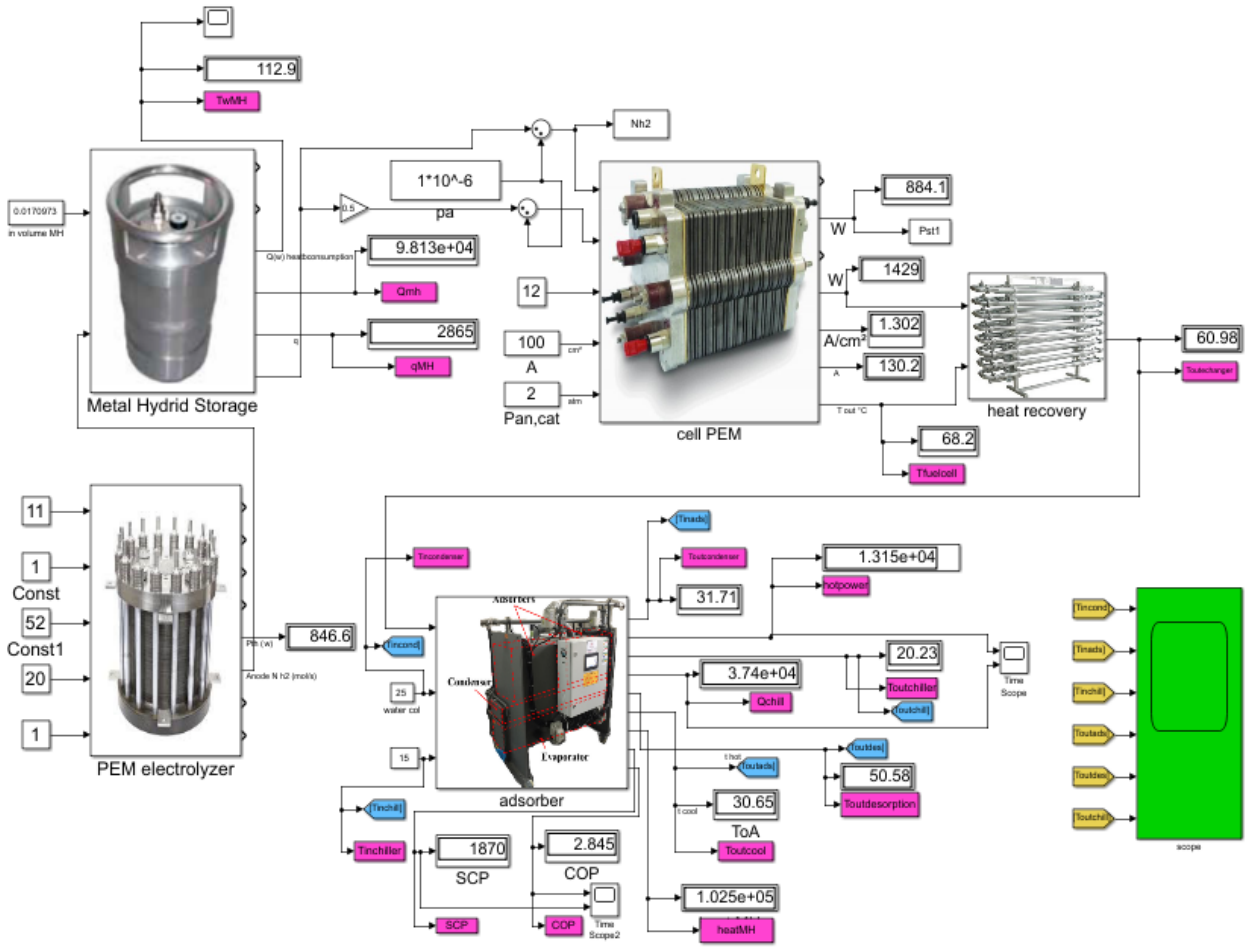
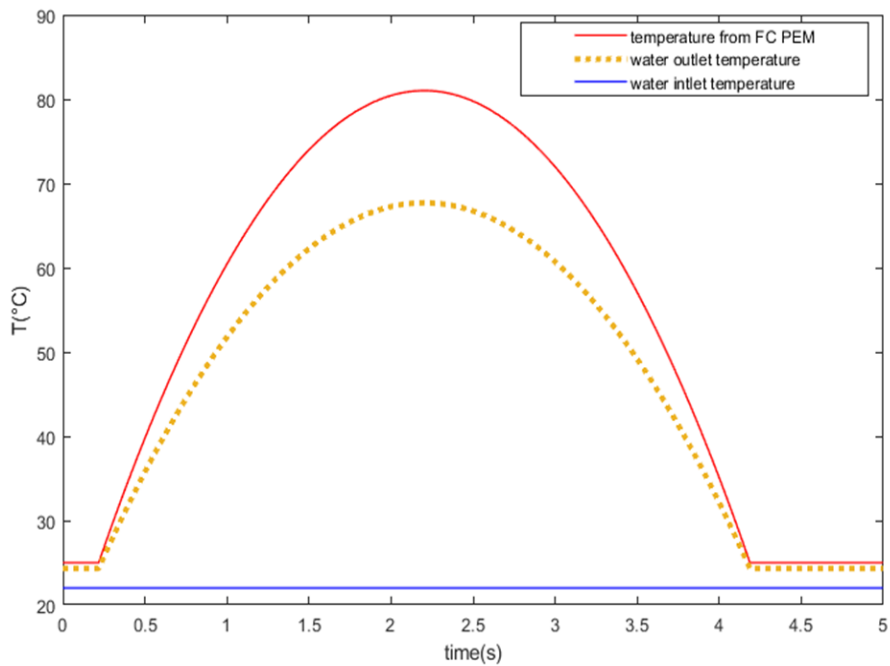Figure 6. System modelling. *Source: Author.*

Figure 7. Value of the temperature within the fuel cell resulting from the experimental system. *Source: Author.*

Figure 7 shows that the temperature variation in the exchanger on the fuel cell side as well as the variation of the temperature in the fuel cell for 50 minutes. As it can be seen, in the fuel cell temperature can reach up to 82°C and at this temperature water leaving a double tubular heat exchanger can reach 68°C.
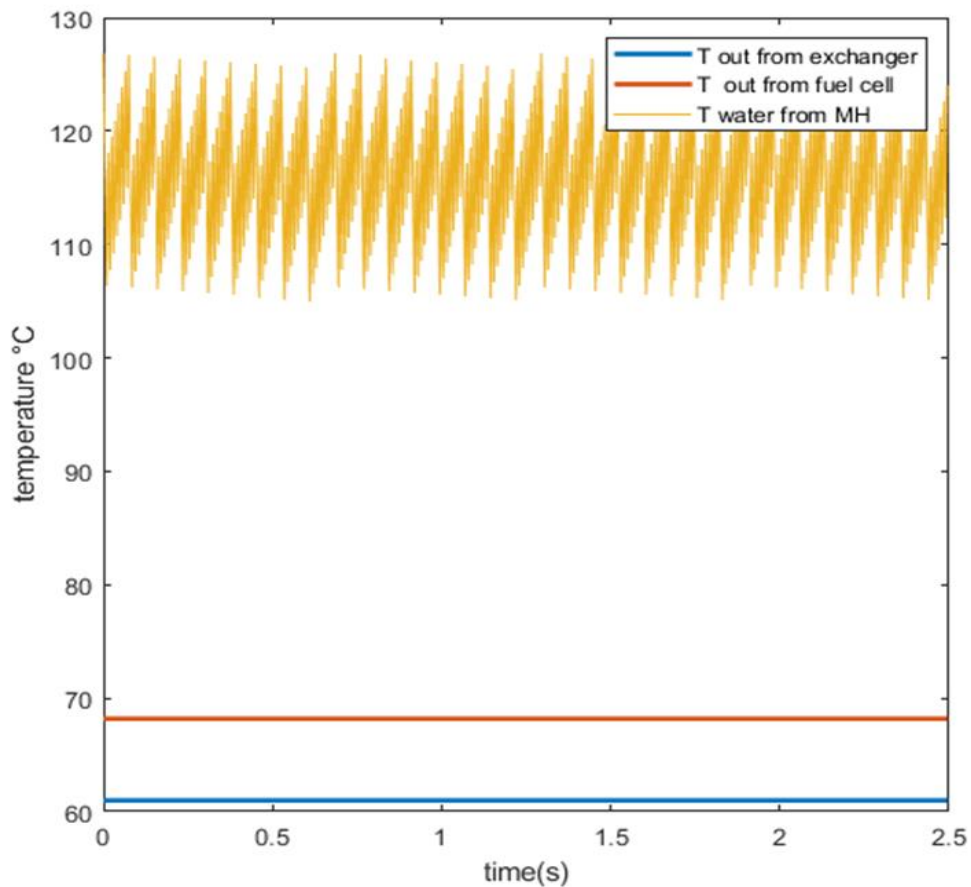

Figure 8. Hot water circuit temperature. *Source: Author.*

Assuming that during the exothermic cycle according to Figure 4, the temperature in the MH tank is as high as 150°C, the water temperature resulting from the exchanger varies between 100 and 120°C. Figure 8 also shows that the use of the MH as a storage medium has a major advantage in terms of thermal power released with temperatures of 110 °C around the tank. It can be noticed that the temperature released by the PEM fuel cell allows to feed the adsorber for the desorption of the silica gel. After the hot water passes through the desorption chamber, a hot water with temperature 50 and 95°C depending on the source can be used.

From Figure 9 the cooling and heating capacities vary proportionally to their efficiency with average values of Q_c = 18.691 kW and Q_h = 12.273 kW, respectively. Certainly, these powers fit into the energy consumption of heating and cooling systems. Therefore, they can cover the Heating Ventilation and Air Conditioning (HVAC) needs in the building and some industries. Thus, they can play a key role in the achieving the economic feasibility of the hydrogen sector.

Figure 10 presents the efficiency of heating and cooling. The values vary between 0-2 and 0-2000 for heating and cooling, respectively and on average the COP = 1.52 and SCP = 934.5735 (W/kg) can be obtained.
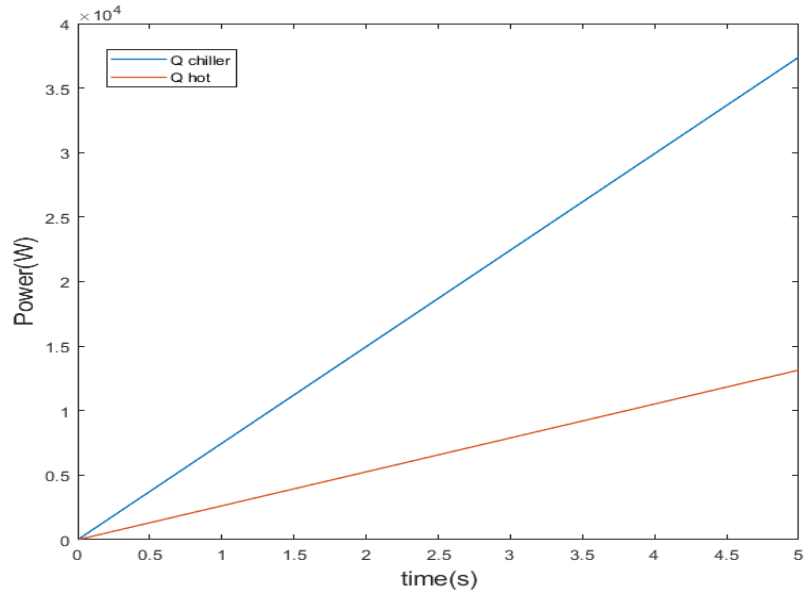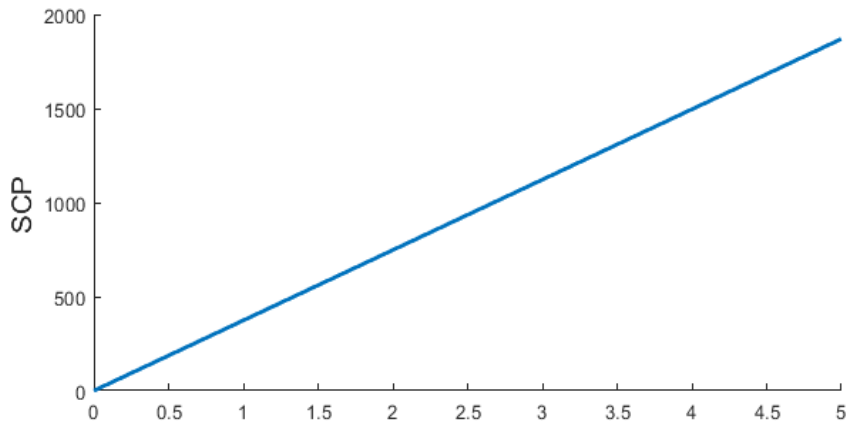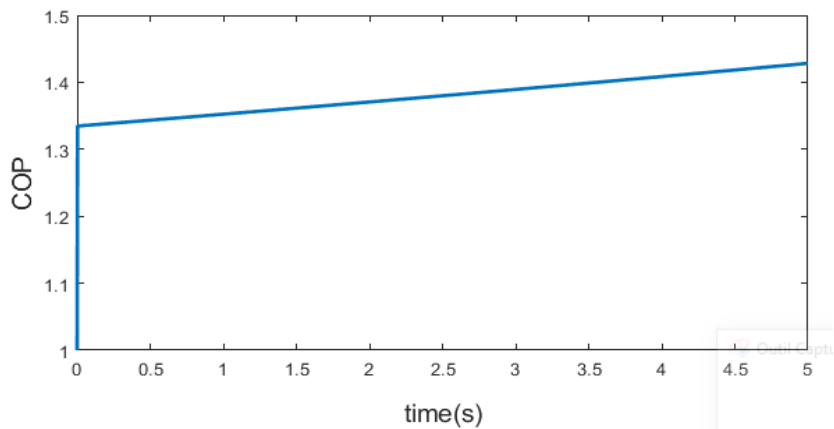
Figure 9. Heating and cooling power. *Source: Author.*

(a)

(b)

Figure 10. Variation of the SCP (a) and COP(b) coefficients for hot form of MH. *Source: Author.*

where:
SCP - is the specific cooling power (W/kg);
COP - is the coefficient of performance.

Impact

This article discusses the integration of a thermally activated cooling system into the green hydrogen production process. Several studies concerning approaches to reduce the cost of acquiring green hydrogen was given in the literature. Among them are cogeneration techniques showing that the heat recovery from the hydrogen production process can be used for, e.g., drying food, or for the water heating. This in turn, generates a financial revenue by reducing the expenses related to acquisition of energy from diverse sources.

Considering the challenges to combat the global warming, one of aspects to be addressed is to use renewable energies to meet the supply needs especially in heating and cooling system. This is especially relevant as both represent the vast part of the energy consumption in the tertiary sector. This work highlights the ability to produce cold from the same heat losses as the one used to meet the need for heating. Considering that the cost of acquisition and use of green hydrogen is high, this study shows that this cost can be reduced by using a heat loss management system adapted to the equipment used. In this study, the use of electrolyser and a fuel cell proton exchange membrane (PEM) for the production of hydrogen and for its combustion is demonstrated. These two elements emit heat, which is potentially lost during the process. In addition, for storage, MH balloons can be considered, and they also contribute to the heat losses. The recovery of all these heats and its conversion into cooling and heating is a key factor from the environmental and economic point of view. It is especially relevant when taken into consideration that the energy consumption related to cold, and heating is not negligible and will increase by 2050. This study shows that it is possible to generate a cooling capacity of up to 18.691 kW in 50 minutes. All the results analysed showed the potential in the combined cold production systems with the process of energy storage by the green hydrogen production. Likewise, this work shows the feasibility of simultaneous production of electrical, thermal and cooling energies from the use of as a source of clean energy. The implementation of this study could allow a rapid insertion of green hydrogen in the tertiary system at a competitive cost with a considerable reduction of greenhouse gases in this sector.

Conclusion

In this article the thermally activated cooling technology applied to a green hydrogen production system using a set of components have been studied
The applied system showed that different potential heat losses of the system allow to produce considerable heating and cooling powers. The thermal power released during the adsorption in the MH tank is the highest along the time of the thermodynamic reactions and it reaches as much as 98 kW with water at 112 °C. On the fuel cell and electrolyser sides a thermal power of 1.4 kW and 0.8 kW, respectively can be obtained. The temperature around the fuel cell is 68°C for 0.884 kW of electricity produced and 0.83 kW of electricity consumed during electrolysis. At the leaving side of the system in the adsorber, the resulting air conditioning and heating temperatures are around 20 °C and 50 °C, respectively.

For a simulation estimated on 1000 s, average powers of 12 kW and 18 kW for heating and cooling, respectively, were obtained. At the same time good coefficients of performance, namely 1.52 and 935 for COP and SCP were achieved, respectively. In addition, the fuel cell can deliver an electrical power of 0.88 kW, which is within the range of the electrical needs of a household of 5 peoples. This allowed to consider that the design of a kit for the tertiary sector or certain industries with the different components used can easily cover the electricity, heating and air conditioning needs contributing to the cost reduction of acquired hydrogen for this sector.

Conflict of interest

There are no conflicts to declare.

Acknowledgments

References

[1]   World Population Prospects, World Popul. Prospect. (2016). https://doi.org/10.18356/cd7acf62-en.
[2]   A. Cascini, M. Gamberi, C. Mora, M. Rosano, M. Bortolini, Comparative Carbon Footprint Assessment of commercial walk-in refrigeration systems under different use configurations, J. Clean. Prod. 112 (2016)

3998–4011. https://doi.org/10.1016/j.jclepro.2015.08.075.

[3]   The Future of Cooling – AnalysisIEA, https://www.iea.org/reports/the-future-of-cooling., (2020).

[4]   D.W. Wu, R.Z. Wang, Combined cooling, heating and power: A review, Prog. Energy Combust. Sci. 32 (2006) 459–495. https://doi.org/10.1016/j.pecs.2006.02.001.

[5]   Commissariat general au developpement durabl, Chiffres cles de l'energie, 2019.

[6]   ADEME, Climate 2012, 2018.

[7]   F. Sun, J. Li, L. Fu, Y. Li, R. Wang, S. Zhang, New configurations of district heating and cooling system based on absorption and compression chillers driven by waste heat of flue gas from coke ovens, Energy. 193 (2020) 116707. https://doi.org/10.1016/j.energy.2019.116707.

[8]   C.P.-E. de l'Ifri, U. Ifri, U. 2020, Perspectives on a Hydrogen Strategy for the European Union, Ifri.Org. (2020). https://www.ifri.org/sites/default/files/atoms/files/philibert_hydrogen_strategy_2020.pdf.

[9]   Https://www.revolution-energetique.com/la-toute-premiere-batterie-domestique-a-hydrogene-quel-est-son-interet/, La toute premiere batterie domestique a hydrogene : quel est son interet ?, (2021).

[10]   T. Orozco, M. Herrera, J.D. Forero, CFD study of heat exchangers applied in brayton cycles: A case study in supercritical condition using carbon dioxide as working fluid, Int. Rev. Model. Simulations. 12 (2019) 72–82. https://doi.org/10.15866/iremos.v12i2.17221.

[11]   M. De L', H. Fiche, Fiche 3.2.1 Revision : septembre 2019, in: AFHYPAC-Th. Alleau Mémento l'Hydrogene Prod. D'Hydrogene Par Electrolyse l'eau, 2019.

[12]   R.E. Rosli, A.B. Sulong, W.R.W. Daud, M.A. Zulkifley, T. Husaini, M.I. Rosli, E.H. Majlan, M.A. Haque, A review of high-temperature proton exchange membrane fuel cell (HT-PEMFC) system, Int. J. Hydrogen Energy. 42 (2017) 9293–9314. https://doi.org/10.1016/j.ijhydene.2016.06.211.

[13]   K. Maeda, M. Suzuki, H. Aki, R&D and deployment of residential fuel cell cogeneration systems in Japan, in: IEEE Power Energy Soc. 2008 Gen. Meet. Convers. Deliv. Electr. Energy 21st Century, PES, IEEE, 2008: pp. 1–5. https://doi.org/10.1109/PES.2008.4596046.

[14]   L.P. Moulebe, T. Abdelwahed, A.O. Eric, R. Nabila, Mathematical modeling of re-electrification by green hydrogen storage through the PEM fuel cell integrating a 10-year economic study applied to a hotel, E3S Web Conf. 229 (2021) 01038. https://doi.org/10.1051/e3sconf/202122901038.

[15]   L.P. Moulebe, T. Abdelwahed, R. Nabila, Implementation of an Advanced PEM Hydrogen Storage System Based Cogeneration Using Photovoltaic System in a Building, in: 2020 Int. Conf. Control. Autom. Diagnosis, ICCAD 2020 - Proc., IEEE, 2020: pp. 1–6. https://doi.org/10.1109/ICCAD49821.2020.9260552.

[16]   N. Enteria, K. Mizutani, The role of the thermally activated desiccant cooling technologies in the issue of energy and environment, Renew. Sustain. Energy Rev. 15 (2011) 2095–2122. https://doi.org/10.1016/j.rser.2011.01.013.

[17]   K. Knosala, L. Kotzur, F.T.C. Röben, P. Stenzel, L. Blum, M. Robinius, D. Stolten, Hybrid Hydrogen Home Storage for Decentralized Energy Autonomy, Int. J. Hydrogen Energy. 46 (2021) 21748–21763. https://doi.org/10.1016/j.ijhydene.2021.04.036.

[18]   M. Marinelli, M. Santarelli, Hydrogen storage alloys for stationary applications, J. Energy Storage. 32 (2020) 101864. https://doi.org/10.1016/j.est.2020.101864.

[19]   F. Rezaie, R. Roshandel, A.A. Hamidi, Hydrogen management in refineries: Retrofitting of hydrogen networks, electricity and ammonia production, Chem. Eng. Process. - Process Intensif. 157 (2020) 108118. https://doi.org/10.1016/j.cep.2020.108118.

[20]   M. V. Lototskyy, V.A. Yartys, B.G. Pollet, R.C. Bowman, Metal hydride hydrogen compressors: A review, Int. J. Hydrogen Energy. 39 (2014) 5818–5851. https://doi.org/10.1016/j.ijhydene.2014.01.158.

[21]   M. Kayfeci, A. Keçebaş, Hydrogen storage, in: Sol. Hydrog. Prod. Process. Syst. Technol., Elsevier, 2019: pp. 85–110. https://doi.org/10.1016/B978-0-12-814853-2.00004-7.

[22]   J. Deng, R.Z. Wang, G.Y. Han, A review of thermally activated cooling technologies for combined cooling, heating and power systems, Prog. Energy Combust. Sci. 37 (2011) 172–203. https://doi.org/10.1016/j.pecs.2010.05.003.

[23]   Q. Pan, J. Peng, R. Wang, Experimental study of an adsorption chiller for extra low temperature waste heat utilization, Appl. Therm. Eng. 163 (2019) 114341. https://doi.org/10.1016/j.applthermaleng.2019.114341.

[24]   M. Chorowski, P. Pyrka, Modelling and experimental investigation of an adsorption chiller using low-temperature heat from cogeneration, Energy. 92 (2015) 221–229. https://doi.org/10.1016/j.energy.2015.05.079.

[25]   M. V. Lototskyy, I. Tolj, L. Pickering, C. Sita, F. Barbir, V. Yartys, The use of metal hydrides in fuel cell applications, Prog. Nat. Sci. Mater. Int. 27 (2017) 3–20. https://doi.org/10.1016/j.pnsc.2017.01.008.

[26]   B. Han, A. Chakraborty, Adsorption characteristics of methyl-functional ligand MOF-801 and water

systems: Adsorption chiller modelling and performances, Appl. Therm. Eng. 175 (2020) 115393. https://doi.org/10.1016/j.applthermaleng.2020.115393.

[27] H.T. Chua, K.C. Ng, A. Malek, T. Kashiwagi, A. Akisawa, B.B. Saha, Modeling the performance of two-bed, silica gel-water adsorption chillers, Int. J. Refrig. 22 (1999) 194–204. https://doi.org/10.1016/S0140-7007(98)00063-2.

[28] J.G. Wanjiku, M.A. Khan, P.S. Barendse, A.B. Sebitosi, Analytical sizing of an electrolyser for a small scale wind electrolysis plant, 2010 IEEE Int. Energy Conf. Exhib. EnergyCon 2010. (2010) 10–15. https://doi.org/10.1109/ENERGYCON.2010.5771658.

[29] P. Nika, Y. Bailly, F. Lanzetta, Transferts thermiques en écoulements oscillants laminaires incompressibles, Int. J. Refrig. 28 (2005) 353–367. https://doi.org/10.1016/j.ijrefrig.2004.08.012.

[30] Https://normag-glas.de/fr/katalog_neu/prozess/FR-6-WARMEUBERTRAGER_PF-System_140930.pdf, CHAPITRE 6 ÉCHANGEURS DE CHALEUR NORMAG PROZESSTECHNIK 2012 SYSTÈME PF 6.1 Indice A Généralités, (2018).

[31] C. Park, X. Tang, K.J. Kim, Q. Leland, J. Gottschlich, Metal hydride heat storage technology for directed energy weapon systems, ASME Int. Mech. Eng. Congr. Expo. Proc. 8 (2007) 961–969. https://doi.org/10.1115/IMECE2007-42831.

[32] B.P. Tarasov, P. V. Fursikov, A.A. Volodin, M.S. Bocharnikov, Y.Y. Shimkus, A.M. Kashin, V.A. Yartys, S. Chidziva, S. Pasupathi, M. V. Lototskyy, Metal hydride hydrogen storage and compression systems for energy storage technologies, Int. J. Hydrogen Energy. 46 (2021) 13647–13657. https://doi.org/10.1016/j.ijhydene.2020.07.085.

[33] M. V. Lototskyy, V.A. Yartys, B.P. Tarasov, M.W. Davids, R. V. Denys, S. Tai, Modelling of metal hydride hydrogen compressors from thermodynamics of hydrogen – Metal interactions viewpoint: Part I. Assessment of the performance of metal hydride materials, Int. J. Hydrogen Energy. 46 (2021) 2330–2338. https://doi.org/10.1016/j.ijhydene.2020.10.090.

[34] C.S. Wang, J. Brinkerhoff, Advances in mathematical modeling of hydrogen adsorption and desorption in metal hydride beds with lattice Boltzmann method, Int. J. Hydrogen Energy. 45 (2020) 32179–32195. https://doi.org/10.1016/j.ijhydene.2020.08.171.

[35] M. Schicktanz, T. Núñez, Modelling of an adsorption chiller for dynamic system simulation, Int. J. Refrig. 32 (2009) 588–595. https://doi.org/10.1016/j.ijrefrig.2009.02.011.

[36] B. Han, A. Chakraborty, Adsorption characteristics of methyl-functional ligand MOF-801 and water systems: Adsorption chiller modelling and performances, Appl. Therm. Eng. 175 (2020) 115393. https://doi.org/10.1016/j.applthermaleng.2020.115393.

[37] H. El Mghari, J. Huot, J. Xiao, Analysis of hydrogen storage performance of metal hydride reactor with phase change materials, Int. J. Hydrogen Energy. 44 (2019) 28893–28908. https://doi.org/10.1016/j.ijhydene.2019.09.090.