EXPERIMENTAL ANALYSIS ON HEAT RECOVERY FROM A PEME STACK: EXPLORING OPERATING TEMPERATURES AND INTEGRATION ASPECTS

Iraj Moradpoor[1]*, Olli Himanen[2], Kaj Nikiforow[2], Sanna Syri[1]

[1]Department of Mechanical Engineering, School of Engineering, Aalto University, Finland
[2]VTT Technical Research Centre of Finland Ltd., Hydrogen production team, P.O. Box 1000, 02044 VTT, Finland

*Corresponding Author: iraj.moradpoor@aalto.fi

ABSTRACT

This study investigates the impact of operating temperature in a real case PEME on the heat recovery process and, in particular, critical parameters such as hydrogen production efficiency, the quantity of generated heat and the specific power consumption. Moreover, it presents experimental polarization curves for a PEME stack consisting of 45 cells across a range of operating temperatures (30°C, 40°C, 50°C, 60°C, 70°C, 80°C), which are essential to conduct analyses on the PEME stack under heat recovery. Furthermore, an analysis is conducted to assess the effectiveness of utilizing the heat generated by the PEME stack at various operating temperatures integrated with heat pumps for supplying district heating (DH) networks. As a result of the study, while the quantity of generated heat by PEME stack is higher in a lower operating temperature, from a hydrogen production point of view, higher operating temperatures are recommended to achieve an optimal operation for the PEME stack. Moreover, the analysis reveals that the integrated heat pump has a higher COP when the PEME stack operates at a higher temperature and identifies 60 °C as an optimal operating temperature for the PEME stack in which the integrated heat pump achieves its highest COP of 3.17, and the hydrogen production efficiency and heat generation efficiency are 66.6% and 33%, respectively, for the PEME stack at full load.

1 INTRODUCTION

Renewable and low-carbon hydrogen is emerging to play a crucial role in determining the direction of the energy landscape of the future, as it provides a more sustainable and cleaner alternative that could reduce our reliance on fossil fuels and help to solve the urgent problem of climate change. This crucial role has been underscored also by the key findings and outcomes of the 28th Session of the UN Climate Change Conference (COP 28) (COP28 Declaration of Intent - Hydrogen, n.d.). Renewable hydrogen or so-called green hydrogen is produced through the water electrolysis process powered by electricity from renewable sources such as wind and solar power. The main technology in this process is electrolyzer which is currently known in four types: Alkaline Electrolyzer (AE), Proton Exchange Membrane Electrolyzer (PEME), Solid Oxide Electrolyzer (SOE), and Anion Exchange Membrane Electrolyzer (AEME). While AE and PEME have been already commercialized on different scales, SOE is in the initial stages of its commercialization on a large scale and AEME is currently available at a laboratory scale (Technology Status: Anion Exchange Membrane (AEM) Electrolysis – Ammonia Energy Association, n.d.).

As an important parameter in assessing electrolyzers, the rate of electricity consumption to hydrogen production or the so-called specific power consumption (kWh/kg H_2) quantifies the amount of electrical energy required to produce one kilogram of hydrogen. Specific power consumption varies in different types of electrolyzers, and it is relatively high in the most common types (i.e. AE and PEME) (Moradpoor et al., 2023). Higher values of specific power consumption mean that more electricity is converted to heat in the electrolyzer, which not only declines the hydrogen production efficiency of the system but also makes it imperative to install specific cooling equipment to control the operating temperature of the electrolyzer. As a practical solution to this challenge, electrolyzers can be integrated with heat pumps to produce both hydrogen and heat which is suitable to be utilized in different

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applications like District Heating (DH) networks. This solution not only improve the overall efficiency of the system but also removes the need for an additional cooling equipment (Integrated Electrolyzer & Heat Pump Solution, n.d.).

In recent years, there has been a focused effort on studying heat recovery in electrolyzers primarily aimed at improving efficiency. (van der Roest et al., 2023) investigated heat recovery from a 2.5 MW_{el} PEME to utilize in several different scenarios including utilization by a local heat consumer at the electrolyzer's output temperature, utilization after improving the output temperature with the help of a heat pump and as the third scenario, integrating the electrolyzer with a DH network. They concluded that implementing heat recovery from the electrolyzer in different scenarios can increase the overall efficiency of the system by 14-15%. Moreover, they found that if produced heat by electrolyzer be directly used in a local heat consumption, CO_2 emissions can be declined by 0.28 CO_2/MWh_{heat}, this figure for a case in which the electrolyzer is integrated with a DH network is 0.08 CO_2/MWh_{heat}. (Siecker et al., 2022) studied heat recovery from PEME with the help of SCIP solver in MATLAB software to find an optimal control model that maximizes heat recovery from PEME while hydrogen production remains at a sufficient level. They also studied the impact of controlling the operating temperature on membrane lifespan in PEME and found that by implementing heat recovery, the membrane's degradation time to reach 50% thickness could be extended by 0.68 years. (Burrin et al., 2021) modelled a combined heat and hydrogen (CHH) system based on PEME with the help of Aspen Plus software, in which the combined system provides hydrogen for a refueling station and the generated heat is transferred to a small heat network. They studied this model in different capacities and found that it is possible to generate 312 kW heat when the input electricity to the PEME is 1 MW, which this improves the overall efficiency of the system to 94.6%. They also concluded that heat recovery from PEME and transferring it to a heat network can significantly decline the levelized cost of hydrogen (LCOH) in the system. (Jiarong Li et al., 2019) concluded an increase of almost 15% in the overall efficiency of the system when heat recovery from AE is implemented. (Saxe & Alvfors, 2007) analyzed integrating heat from AE with a DH network and concluded that in addition to economic benefits, heat recovery from AE can improve its overall efficiency by 15.5%. They also considered the oxygen produced by AE as an alternative for oxygen production through cryogenic air separation which is used in pulp and paper industry and concluded that it has potential to improve the efficiency of the system by 5.5%. (Khaligh et al., 2023) found that in addition to improving efficiency, heat recovery from an electrolyzer will help to manage fluctuations in renewable energies more effectively. They studied integrating heat recovered from AE into a DH network which is also supplied by electricity, natural gas, and hydrogen boiler. They achieved an overall efficiency of 90% for AE by capturing heat generated during its operation.

As evident from the existing literature, the focus has primarily been on modeling heat recovery in electrolyzers using various modeling tools and only in a specific operating temperature. However, the lack of an experimental study on a real case PEME to analyze the quantity and quality (i.e., its temperature, and the capability of utilizing it) of the generated heat under various operating temperatures is the gap knowledge that this study is going to fill it. In other words, this study aims to find out how the operating temperature in a real case PEME would affect the heat recovery process and in particular critical parameters such as efficiency, the quantity of generated electrolyzer heat, specific power consumption, etc. Moreover, this study presents experimental polarization curves for a PEME stack consisting of 45 cells across a range of operating temperatures (30°C, 40°C, 50°C, 60°C, 70°C, 80°C), which are essential to conduct analyses on the PEME stack under heat recovery. Furthermore, to evaluate the capability of the generated heat by PEME stack in different operating temperatures in supplying DH networks, an analysis is carried out in which the PEME stack is integrated with a heat pump based on real data from Oilon Selection Tool (OST). Based on the analyses, significant insights and valuable information will be provided for optimizing efficiency and resource utilization in real-world applications.

In overall, the main novelties of this research can be classified as following:

- Analyzing the quantity and quality of the generated heat by a real case PEME across a variety of operating temperatures.
- Identifying the most optimal operating range of temperature for PEME using a real case study approach.

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- Analyzing the effects of heat recovery process in PEME stack on critical parameters with the help of experimental polarization curves under different operating temperatures.
- Assessing the potential of the PEME stack integrated with heat pumps in supplying DH networks and highlighting any possible limitations associated with them.

2 METHODS AND MATERIALS

2.1 System Description

The electrolyzer stack investigated in this study is PEME stack manufactured by Hydrogen Innovation company (PRODUCTS - Hydrogen Innovation GmbH, n.d.), with detailed technical specifications provided in Table 1.

Table 1: Technical specifications of PEME stack investigated by this study (PRODUCTS - Hydrogen Innovation GmbH, n.d.).

General Information	
Number of cells	45
Active Electrode Area (single cell)	28.3 cm^2
Operating Temperature	65 °C – 80 °C
Max. Tested Temperature	85 °C
Stack Current	2.8 – 62.2 A
Stack Voltage at 70 °C and ambient pressure	67.160 – 93.770 V [DC]
Connected Load at 70 °C and ambient pressure	0.187 – 5.826 kW
Length	710 mm
Width	175 mm
Height	175 mm
Mass	Approx. 37 kg
Water Supply	
Max. Pressure	1.5 bar
Min. Flow Rate (BOL / EOL)	9 l · min^{-1} / 12 l · min^{-1}
Max. Temperature Difference Between Input and Output	5 K
Hydrogen Production	
Max. Hydrogen Production	19512 $Nml.min^{-1}$
Max. Pressure	40 bar
Max. Tested Pressure	44 bar
Quality	100% H_2O saturated
Oxygen Production	
Max. Oxygen Production	9756 $Nml.min^{-1}$
Max. Pressure	Ambient
Quality	100% H_2O saturated

2.2 Hydrogen Production in Electrolyzers

The hydrogen production rate in the PEME stack is formulated with the help of Faraday's law of electrolysis. This law states that the amount of hydrogen produced at an electrode is directly proportional to the quantity of electricity passed through the electrolyte (Naimi & Antar, 2018).

$$H_2 = \frac{INM}{zF} \tag{1}$$

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In Eq.1, *I* represent the stack current, and *N, M, z* is number of cells, molar mass of hydrogen (2 g/mole), and number of exchanged electrons (2 electrons), respectively. Additionally, F represents the faraday constant (96485 A.s/mole).
Figure 1 illustrates the hydrogen production rate versus electrical current for the PEME stack investigated by this study.

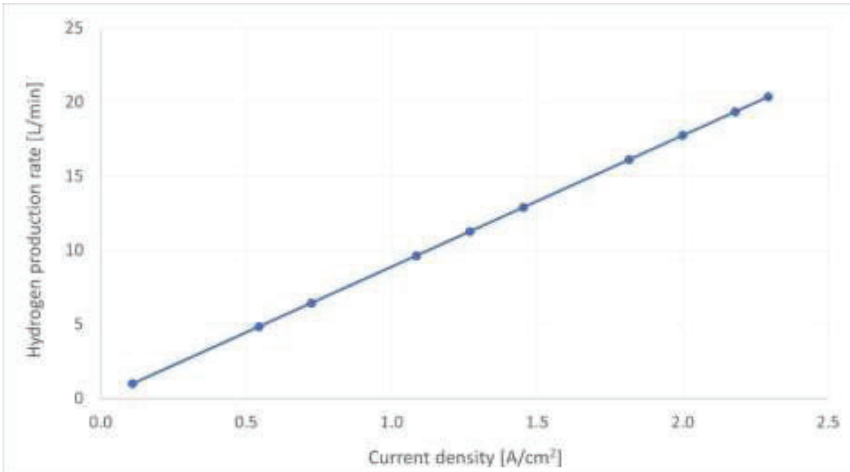

Figure 1: Hydrogen production rate versus electrical current for the PEME stack investigated by this study.

2.3 Thermoneutral Voltage and Excess Heat

Thermoneutral voltage is defined as the voltage at which water is splitting to hydrogen and oxygen without generating excess heat from the reaction (Harrison et al., 2010). In other words, electrolyzers start to generate excess heat when the operating voltage surpasses the thermoneutral voltage. For PEME at 25 °C, the value of thermoneutral voltage is 1.481 (V/cell), and the amount of excess heat generated in operating voltages higher than thermoneutral voltage can be calculated by Eq. 2:

$$Generated\ excess\ heat\ by\ stack = NI\left(V_{operating} - V_{thermoneutral}\right) \quad (2)$$

In which, *I* represent the stack current, *N* is the number of cells, and *V* denotes operating and thermoneutral voltages. It should be noted that this study assumes the thermoneutral voltage as a constant value (1.481 (V/cell)) across the operating temperatures of PEME. This assumption is made due to the weak dependency of the thermoneutral voltage on the operating temperature of electrolyzers (Naimi & Antar, 2018). Figure 2 represents a schematic diagram of the studied PEME and a clear heat generation profile in it based on the cell voltage.

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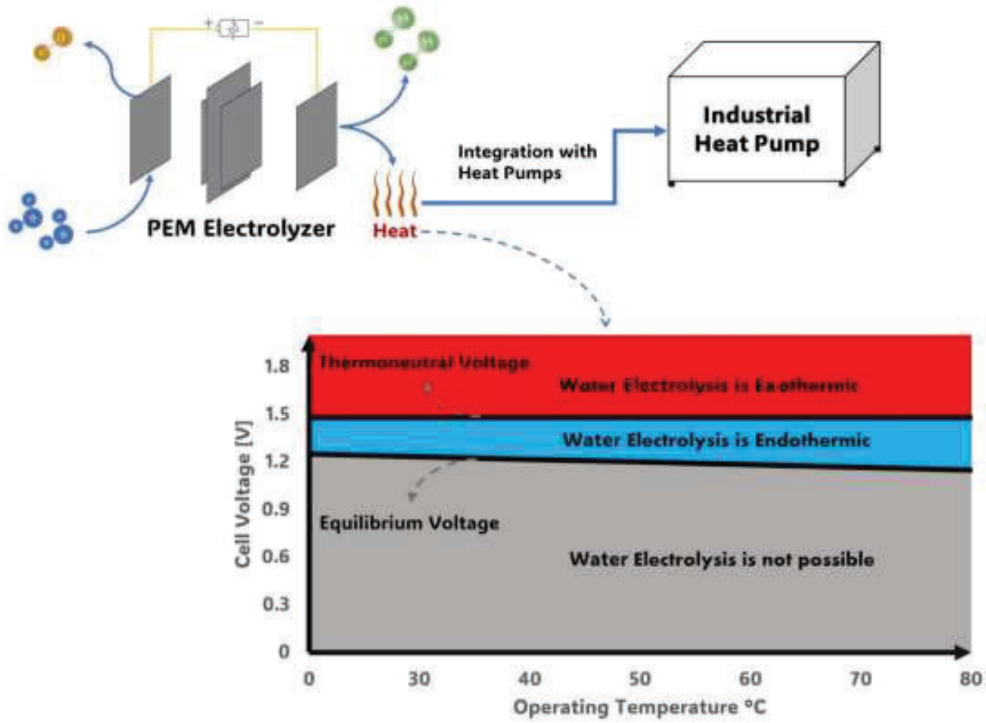

Figure 2: A detailed schematic of heat generation in PEME cell based on the cell voltage (Naimi & Antar, 2018).

2.4 Polarization Curve

Figure 3 illustrates the polarization curve (i.e., the graph showing the relationship between operating voltage and current in electrolyzers) for the investigated PEME stack by this study over a range of operating temperatures. It is important to mention that the polarization curves depicted in Figure 3 are based on data which has been supplied by the electrolyzer manufacturer specifically for the use of this study (PRODUCTS - Hydrogen Innovation GmbH, n.d.). With the help of polarization curves across varying operating temperatures and employing Eq. 2, it becomes possible to accurately calculate and analyze the quantity of excess heat generated by the stack.

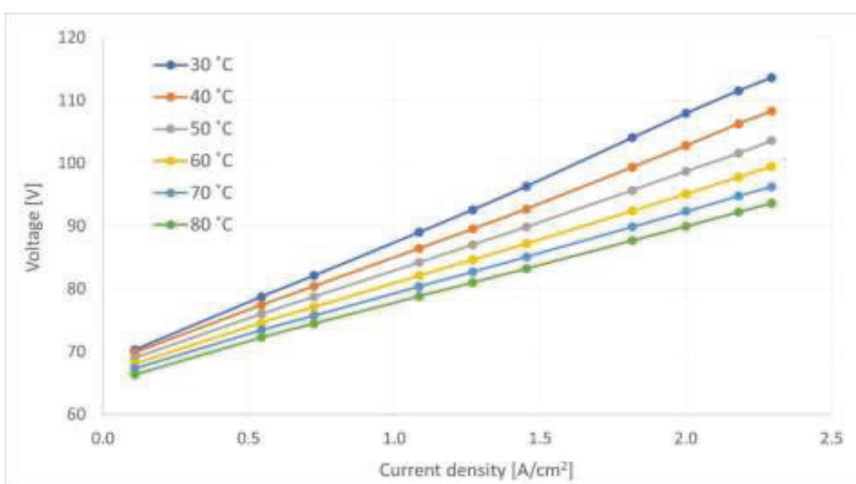

Figure 3: Polarization curve for the investigated PEME stack across a range of operating temperatures (*PRODUCTS - Hydrogen Innovation GmbH*, n.d.).

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2.5 Integration with Heat Pumps

One of the most practical solutions to implement heat recovery in electrolyzer stacks is integrating them with heat pumps. The Coefficient of Performance (COP) of a heat pump represents its efficiency in transferring heat from a heat source (here electrolyzer stacks) to a specific heat sink (for example supply side of a DH network). In heat pumps, COP is defined as the ratio of the useful heat output from condenser to the power consumption by compressor, therefore, a higher COP indicates greater efficiency for heat pumps (COP Heat Pump | Industrialheatpumps.Nl, n.d.).

In this study, Oilon Selection Tool (OST) is used to evaluate the integration of the PEME stack with heat pumps in different operating temperatures of PEME. OST is a flexible design tool facilitating quick and straightforward matching of products to specific applications (Oilon Selection Tool - Valintaohjelma - Oilon, n.d.). The evaluated heat sink in this study is the supply side of a hypothetical DH network in three different scenarios based on its temperature (90 °C, 100 °C, and 110 °C). The output data from this analysis typically includes COP values corresponding to each scenario, providing insight into how operating temperature in PEME stack would affect its integration with heat pumps. Table 2 presents technical data and settings of the heat pump in OST to integrate with the PEME stack.

Table 2: Technical data and settings of the heat pump in OST to integrate with the PEME stack.

Parameter	Value
Heat Pump model	Industrial heat pump, model P30
Refrigerant	R1233zd(E)
Condenser Fluid	Ethylene glycol-Water mixture (40 %)
Evaporator Fluid	Ethylene glycol-Water mixture (40 %)
Subcooler	on
VFD	100%
Evaporator inlet temperature	5 °C less than operating temperature in the PEME stack
Evaporator outlet temperature	10 °C less than operating temperature in the PEME stack
Condenser inlet temperature	5 °C more than heat sink temperature
Condenser outlet temperature	10 °C more than heat sink temperature

3 RESULTS AND DISCUSSION

3.1 Specific Power Consumption

Figure 4 illustrates power consumption by PEME stack versus the stack currents under different operating temperatures. This figure which results directly from polarization curves shows how power consumption in electrolyzer decreases by increasing the operating temperature of PEME stack.

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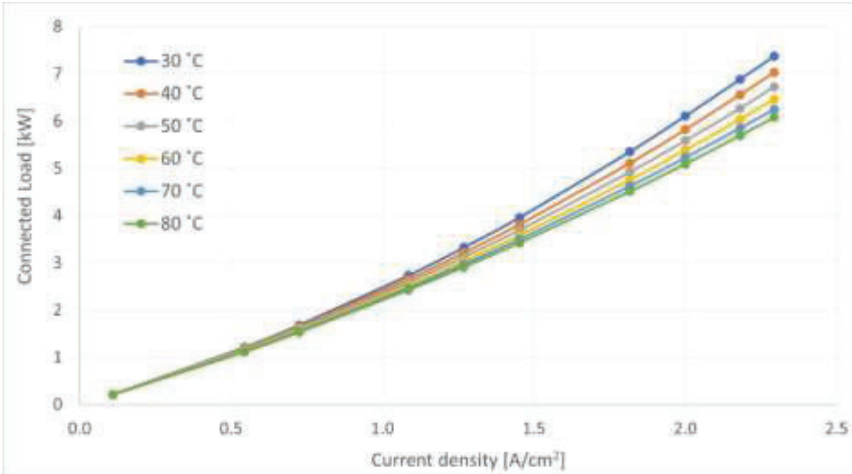

Figure 4: Power consumption by PEME stack versus the stack current density under different operating temperatures.

While Figure 4 shows the power consumption of the PEME stack, it may not serve as a comprehensive parameter for evaluating the stack's performance when compared to other electrolyzers. Specific power consumption, defined as the ratio of power consumption to hydrogen production by the electrolyzer, is considered as a significant metric for assessing performance in electrolyzers. This parameter accounts for the efficiency of hydrogen production relative to the energy input, providing a clearer indication of the electrolyzer's effectiveness. Figure 5 depicts specific power consumption by PEME stack versus the stack current across a range of operating temperature.

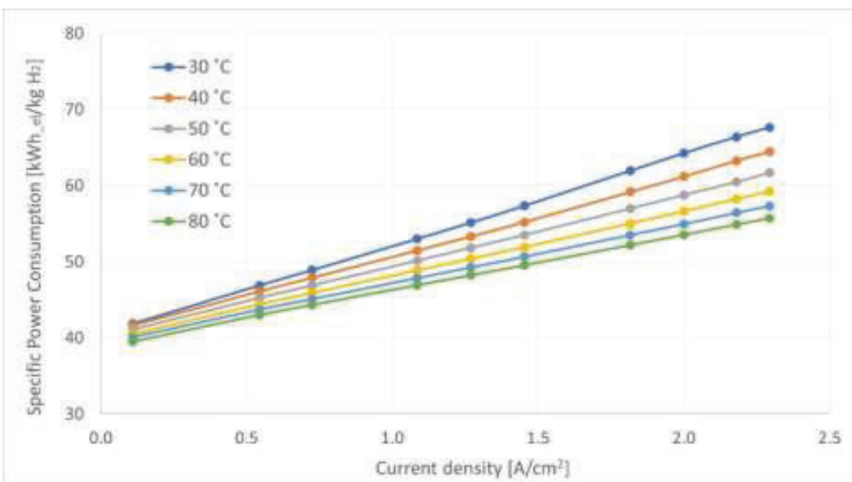

Figure 5: Specific power consumption versus the stack current density under different operating temperatures.

As can be seen, by increasing the operating temperature in PEME, a significant decline in its specific power consumption occurs, especially when it operates under higher values of electrical current (i.e., in the full load point). The effects of operating temperature on power consumption can be explained more clearly with the help of thermodynamic principles like Gibbs free energy and Nernst equation. In a higher temperature, the reaction of water electrolysis is more thermodynamically favorable as breaking the chemical bonds would be easier. Therefore, considering this fact that the Gibbs free energy change of a reaction determines its spontaneity, increasing operating temperature in electrolyzers cause a reduction in Gibbs free energy and consequently in the required input energy. Moreover, according to Nernst equation, increasing the operating temperature in electrolyzers, declines the cell potential which leads to reduction in the input energy required to drive the electrolysis process forward (Naimi & Antar, 2018).

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3.2 Excess Heat Generation

As explained in 2.3, the quantity of excess heat generated by electrolyzers can be calculated with the help of polarization curve and applying Eq.2 for different points of operation. Figure 6 illustrates the excess heat generation by the PEME stack under different operating temperatures.

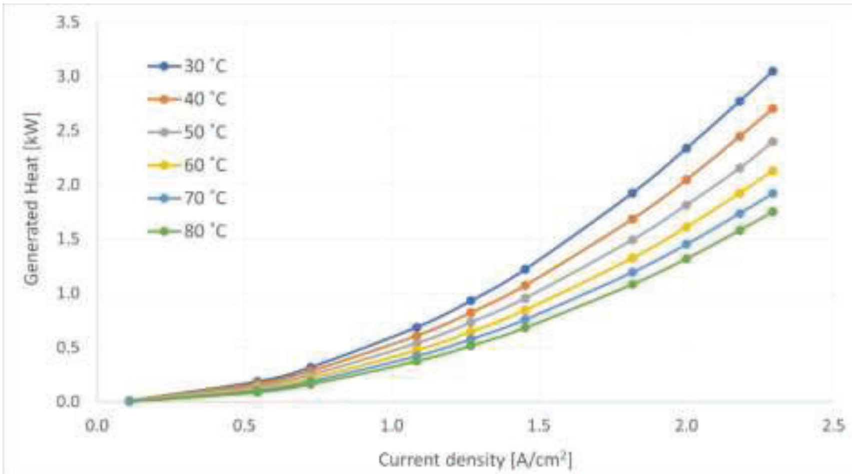

Figure 6: Excess heat generation by PEME stack versus its current density under different operating temperatures.

As can be seen, the PEME stack generates more excess heat at full load, however, the quantity of generated heat is higher when the temperature is lower. Figure 7 shows it more clearly that how the changing in the operating temperature affects the connected load to the PEME and the quantity of heat produced by it, however, the hydrogen production rate in this figure remains unchanged since the current density is kept at 2.3 A/cm^2. As it is evident from this figure, by raising the operating temperature in PEME, the required power to produce the same amount of hydrogen declines and consequently the quantity of heat generated in water electrolysis process decreases.

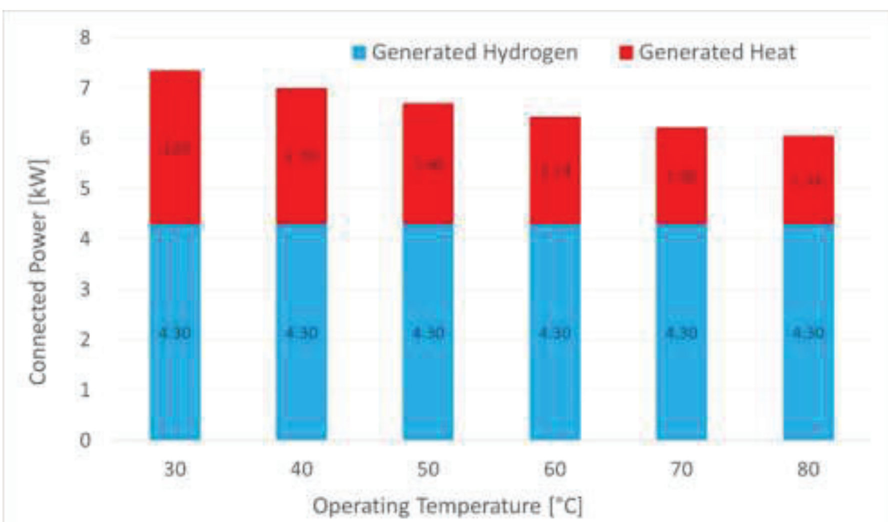

Figure 7: Connected power and generated heat in PEME under different operating temperature and the electrical current density of 2.3 A/cm^2.

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3.3 Heat and Hydrogen Production Efficiency

Figure 8 shows the hydrogen production efficiency of the PEME stack in different operating temperatures. Hydrogen production efficiency was defined as the ratio of hydrogen produced in kW (based on HHV) to the power input in kW. As can be seen the hydrogen production efficiency of the PEME stack is higher at higher operating temperatures. An efficiency of almost 100% for hydrogen production can be achieved when PEME is operating at the thermoneutral voltage. To clarify more, at this voltage the amount of generated heat is zero (see figures 2 and 6), therefore all the input power is efficiently converted into hydrogen.

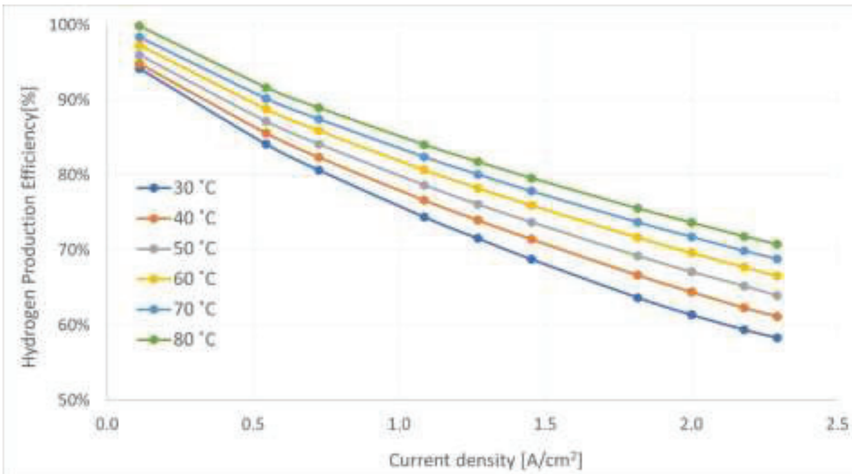

Figure 8: Hydrogen production efficiency of the PEME stack versus the stack current density under different operating temperatures.

This figure also shows how at full load operation the hydrogen production efficiency declines. As an argument behind this, according to figure 3, at full operation, PEME is operating at voltages higher than thermoneutral voltages where the water electrolysis process is exothermic, therefore a significant part of the input electricity is converted to waste heat. As a result, the amount of heat generated by PEME is higher at full load operation and consequently the hydrogen production efficiency would be lower. Moreover, at full operation, the electrolyzer will be under an increased stress caused by higher flow rates and longer operating hours, which can lead to greater energy losses and reduced efficiency.

Similarly, the efficiency for the excess heat generated by the PEME stack at different operating temperatures can be defined. Figure 9 shows how the heat generation efficiency of the PEME stack changes by operating temperature of the PEME stack. As can be seen, higher efficiency is achievable at lower operating temperatures where according to Figure 8 hydrogen production efficiency is lower.

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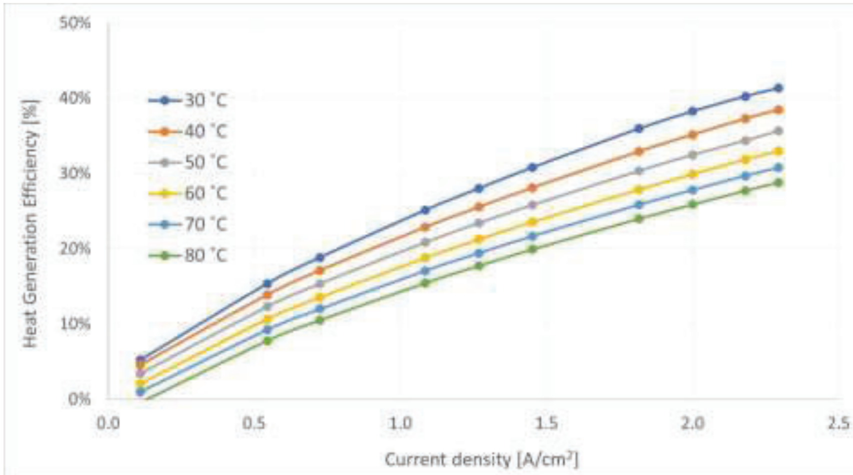

Figure 9: Heat generated efficiency of PEME stack versus the stack current density under different operating temperatures.

3.4 Integration with Heat Pumps

Figure 10 illustrates the COP of a heat pump integrated with PEME stack versus the temperature of heat source (i.e., the operating temperature of the PEME stack) at different temperatures for the heat sink (i.e., the supply side temperature of a hypothetical DH network). Table 3 presents this result in more detail. As can be seen, certain scenarios may encounter limitations due to inherent constraints associated with evaporator, condenser, and the refrigerant. Moreover, the maximum allowed temperature for the evaporator inlet is 55 °C, therefore, as can be seen in Figure 10, in operating temperatures lower than 60 °C, increasing operating temperature in the PEME stack leads to higher COP for the integrated heat pump, however, at operating temperatures higher than 60 °C, COP remains at the same level.

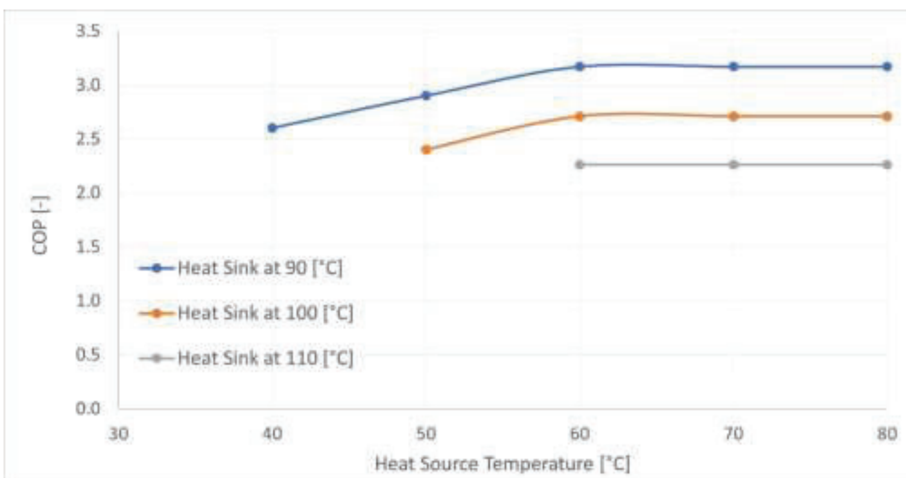

Figure 10: COP of heat pump integrated with the PEME stack versus heat source temperature (i.e., the operating temperature of the PEME stack) in different temperature for the heat sink (i.e., the supply side of a hypothetical DH network).

Table 3: More details on the results from OST. L1 represents the error indicating evaporation temperature too low, and L2 represents the error indicating that Condensation temperature too high.

Heat Source [°C]	Heat Sink [°C]	Evaporator Inlet [°C]	Evaporator Outlet [°C]	Condenser Inlet [°C]	Condenser Outlet [°C]	COP [-]
30	90	25	20	95	100	L1, L2
40	90	35	30	95	100	2.60
50	90	45	40	95	100	2.90
60	90	55	50	95	100	3.17

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70	90	55	50	95	100	3.17
80	90	55	50	95	100	3.17
30	100	25	20	105	110	L1, L2
40	100	35	30	105	110	L2
50	100	45	40	105	110	2.40
60	100	55	50	105	110	2.71
70	100	55	50	105	110	2.71
80	100	55	50	105	110	2.71
30	110	25	20	115	120	L1, L2
40	110	35	30	115	120	L2
50	110	45	40	115	120	L2
60	110	55	50	115	120	2.26
70	110	55	50	115	120	2.26
80	110	55	50	115	120	2.26

4 CONCLUSION

This study aimed to find out how the efficiency, specific power consumption, the quantity, and the quality of the captured heat in heat recovery from a PEME stack would be affected by the operating temperature using a real case study approach. Experimental polarization curves were generated for a PEME stack consisting of 45 cells across a range of operating temperatures (30°C, 40°C, 50°C, 60°C, 70°C, 80°C). Subsequently, analyses were conducted to evaluate the PEME stack's capability with heat pumps to supply DH networks. Based on the analyses, insights and new information are provided for optimizing efficiency and resource utilization in real-world applications.
According to the results, the specific power consumption for the PEME stack is lower at higher operating temperatures, however, the quantity of heat generated declines when the PEME stack operates at a higher operating temperature. Based on the output results, the hydrogen production efficiency increases from 58.3% to 70.8% when the operating temperature of the PEME stack (at full load) changes from 30 °C to 80 °C. Conversely, the heat generation efficiency declines from 41.3% to 28.8% over the same temperature range. Therefore, from a hydrogen production efficiency, higher operating temperature is beneficial.
Furthermore, based on the analysis assessing the capability of integrating the PEME stack with heat pumps to supply DH networks, limitations associated with evaporation and condensation temperatures affect the feasibility of integrating the PEME stack with heat pump at any operating temperature. According to this analysis's findings, the integrated heat pump has a higher COP when the PEME stack operates at a higher temperature, however, for operating temperatures higher than 60 °C, COP remains at the same level due to limitations imposed by the evaporation inlet temperature. Therefore, the optimal operating temperature from heat production efficiency point of view is dependent on the heat pump technology and operating conditions.

NOMENCLATURE

F	faraday constant	(As/mol)
I	electrical current	(A)
M	molar mass	(g/mol)
N	number of cells (–)	
V	Voltage	(V)
z	number of exchanged electrons (–)	

Subscript

AE	Alkaline Electrolyzer
AEME	Anion Exchange Membrane Electrolyzer
COP	Coefficient of Performance

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DH District Heating
OST Oilon Selection Tool
PEME Proton Exchange Membrane Electrolyzer
SOE Solid Oxide Electrolyzer

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