THE ROLE OF WASTE HEAT RECOVERY IN ENHANCING POWER-TO-HYDROGEN AND POWER-TO-METHANE SYSTEMS

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Abstract

Power-to-Gas technologies offer significant potential to decouple energy demand from supply, enhancing flexibility of future renewable energy systems. This review focuses on Power-to-Hydrogen and Power-to-Methane pathways and examines the impact of waste heat recovery on their exergetic efficiency. In Proton Exchange Membrane (PEM) and Alkaline Water Electrolysers (AWE), approximately 25–40% of the input energy is lost as low-temperature heat (50–90 °C). Solid Oxide Electrolysis Cells (SOEC), operating with water vapor at around 800 °C, requires not only electricity input but also heat input offering potential for thermal integration by utilizing high-temperature waste heat. In Catalytic methanation (CatM) and Biological methanation (BioM), approximately 10–29% of the input energy is lost as high-temperature heat (200-550 °C) respectively 22-24% as low-temperature heat (< 80 °C). Integrating waste heat recovery improves the mean exergetic efficiency by 6.4% for PEM/AWE, 4% for PEM/AWE + BioM, and 6.8% for PEM/AWE + CatM. The highest overall exergetic efficiency for Power-to-Methane, 76.3%, is achieved in integrated SOEC + CatM systems.

Keywords: Green Hydrogen, Solar fuels, Power-To-X, Thermal integration, Waste heat utilisation, Electrolysis, Methanation

1. Introduction

The increasing share of renewable energy in electricity generation leads to greater fluctuations in supply, creating mismatches between supply and demand (Gallo et al., 2016). To mitigate these imbalances, energy storage technologies such as Power-to-Gas (PtG) are essential. PtG processes convert primary and secondary energy into chemical energy carriers such as hydrogen or methane, for later use in electricity generation, industrial applications, or injection into existing gas networks (Stern and Stadler, 2019).

However, PtG systems often suffer from low overall efficiency due to substantial heat losses of 25-35% during electrolysis and 10-28% during methanation (Figure 3). These waste heat streams are frequently underutilized, thus representing a significant potential for efficiency improvement. Despite growing interest in thermal integration, a comprehensive assessment of the impact of waste heat recovery on the exergetic efficiency across different Power-to-Hydrogen (PtH) and Power-to-Methane (PtM) technologies remains lacking in the current literature. Most publications either focus on single case studies or propose isolated conceptual models, but they do not compare the effect of heat integration for different technologies. Furthermore, it remains unclear how far model-based studies overestimate the benefits of waste heat recovery compared to real-world projects. A detailed, quantitative comparison is therefore needed to evaluate these discrepancies and to identify which integration approaches most effectively improve system performance.

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1.1 Research Objective

The objective of this study is to evaluate the impact of waste heat recovery on the exergetic efficiency of PtH and PtM processes. Specifically, this review aims to:

- Compute the exergetic efficiency of PtH and PtM with and without heat utilisation for given models and realized projects
- Compare theoretical models with realized projects to determine discrepancies in exergetic efficiency

By addressing these objectives, this study provides a comprehensive overview of the role of waste heat utilisation in PtG systems and highlights key factors influencing their efficiency. The insights gained from this work can support the development of more efficient PtG systems and inform decision-making for future renewable energy integration.

1.2 Reaction Basics

Electrolysis decomposes water into hydrogen and oxygen (eq. 1), with Alkaline Water Electrolysis (AWE) and Proton Exchange Membrane (PEM) operating around 80°C (Carmo et al., 2013), and Solid Oxide Electrolysis Cells (SOEC) at approximately 800°C (Laguna-Bercero, 2012). The produced hydrogen can be further converted into methane via the Sabatier reaction (eq. 2), with Catalytic Methanation (CatM) occurring at around 200-550°C and Biological Methanation (BioM) at approximately 20-70°C (Götz et al., 2016).

$$H_2O \rightarrow \frac{1}{2}O_2 + H_2 \quad \text{(eq. 1)}$$

$$4\,H_2 + CO_2 \rightarrow CH_4 + 2\,H_2O \quad \text{(eq.2)}$$

1.3 Waste heat usage

Depending on the temperature range of the waste heat, different waste heat usage is feasible. Low temperature waste heat < 80°C, as from PEM, AWE and BioM, can be used for district heating, swimming pool or low temperature industrial heat requirement depending on the specific availability (Figure 1).

For waste heat from Catalytic methanation, around 200-550°C has a higher exergtic value and coupling with SOEC for the waste heat utilisation is favorable to increase overall efficiency. However, the waste heat can be used also for industrial processes pyrolysis, gasification or all other processes where lower temperatures are required (Figure 1).

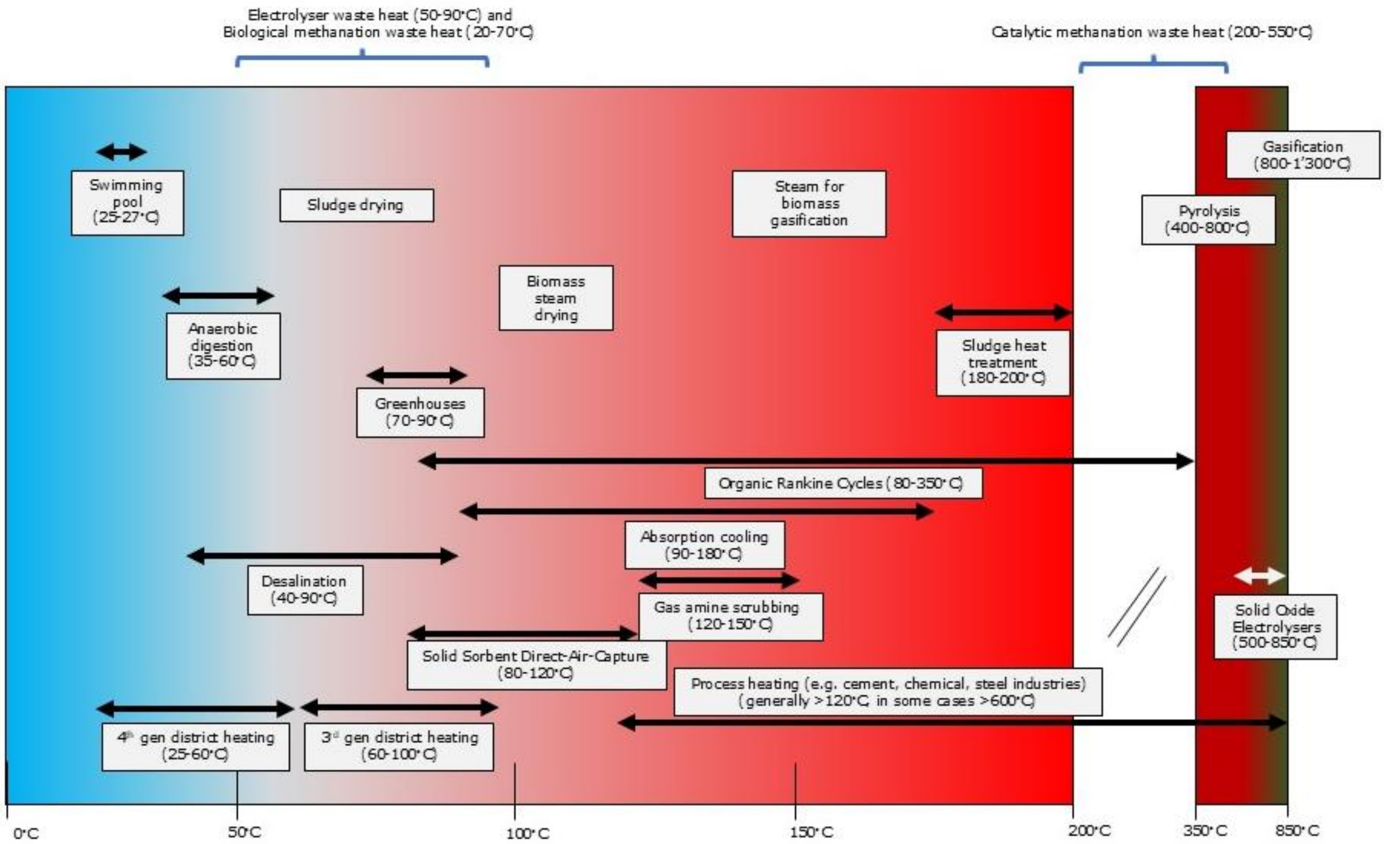

Figure 1: Overview of potential utilisation of waste heat from electrolysis and methanation (own illustration)

2. Methodology

53 publications on PtH and PtM systems were reviewed. A subset of 12 provided sufficient data (e.g., waste heat quantity, temperature level, input electricity, gas output) for exergetic analysis and were selected for detailed exergetic analysis.

2.1 Efficiency Metrics

For energy systems with different energy carriers, it is highly relevant to find optimal and representative comparisons. Therefore, the exergetic efficiency of the PtH and PtM systems with and without heat utilisation was chosen. Further assumptions are summarized in Table 1.

Exergetic efficiency without heat utilisation (w/oHU) is defined the following way, taking the nomenclature from the system diagram below (**Figure *2***, ***list of symbols: Appendix A***):

$$\eta_{H2,w/oHU} = \frac{m_{H2} \cdot LHV_{H2}}{E_{El,in} + Q_{in,el}(1-\frac{T_{amb}}{T_{Qin}})} \quad \text{(eq. 3)}$$

$$\eta_{H2\&CH4,w/oHU} = \frac{m_{CH4} \cdot LHV_{CH4}}{E_{El,in} + Q_{in,el}(1-\frac{T_{amb}}{T_{Qin}})} \quad \text{(eq. 4)}$$

The exergetic efficiency for the electrolysis with heat utilisation (wHU) is defined the following way, taking the nomenclature from the system diagram below (**Figure *2***, ***list of symbols: Appendix A***):

$$\eta_{H2,wHU} = \frac{m_{H2} \cdot LHV_{H2} + Q_{wH,el} \cdot (1-\frac{T_{amb}}{T_{use,wH,el}})}{E_{El,in} + Q_{in,el}(1-\frac{T_{amb}}{T_{Qin}})} \quad \text{(eq. 5)}$$

The exergetic efficiency for the electrolysis combined with the methanation including heat utilisation (wHU) is defined as follows, using the nomenclature from the system diagram below (**Figure *2***, ***list of symbols: Appendix A***):

$$\eta_{H2\&CH4,wHU} = \frac{m_{CH4} \cdot LHV_{CH4} + Q_{wH,el} \cdot \left(1-\frac{T_{amb}}{T_{use,wH,el}}\right) + Q_{wH,me} \cdot (1-\frac{T_{amb}}{T_{use,wH,me}})}{E_{El,in} + Q_{in,el}(1-\frac{T_{amb}}{T_{Qin}})} \quad \text{(eq. 6)}$$

Table 1: Assumption of energetic efficiency calculations

Assumptions	Electrolysis	Methanation
Auxiliary energy needs (sensors and pumps)	Neglected. Since for the electrolysis, the additional energy input for auxiliaries 3% of the total energy input (Candelaresi et al.), justifying the assumption to neglect this part for simplicity and limited data availability.	Neglected. Since for the methanation, the additional energy input for compressions and pumps are below 6% of the total energy input (Wang et al., 2019, Giglio et al., 2018), justifying the assumption to neglect this part for simplicity and limited data availability.
Feedstock temperature	The temperature of water was assumed to be room temperature (25°C).	The temperature of hydrogen and CO_2 was assumed to be room temperature (25°C).
Heat input electrolysis	Neglected for AWE and PEM. For AWE and PEM, this heat input ($Q_{in,el}$) typically accounts for less than 3% of the energy compared to the electricity input (Candelaresi et al., 2021, Giglio et al., 2018). Due to lack of data and only minor influence on the overall efficiency, the required heat input was neglected for PEM and AWE electrolysis ($Q_{in,el}$ for AWE/PEM ≈ 0) For SOEC not neglected.	-
Energy to get CO_2 neglected	-	Neglected.

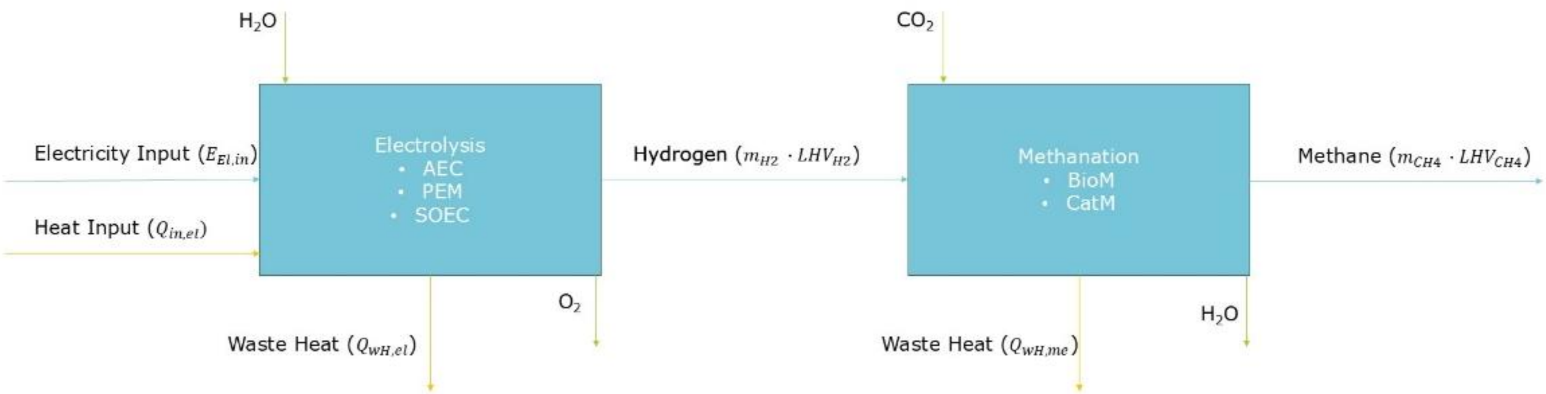

Figure 2: System Diagram, Power to Hydrogen to Methane, Definitions (own illustration, list of symbols: Appendix A)

3. Results

3.1. Exergy analysis of P2H and P2M systems with and without heat recovery

The aim was to compare performance with and without heat recovery for different PtH and PtM technologies.

For AWE and PEM, the exergetic efficiency without heat recovery shows a wide range, spanning from about 60% to 75%, with a mean value of 67.84 ± 4.82% (Figure 3). Considering waste heat utilisation, the exergetic efficiency increases ranging from 68.83% to 78.18% with a mean value of 74.24 ± 3.87 %. Thus, the mean exergetic efficiency is 6.4% higher when heat utilisation is considered for AWE and PEM (Figure 3).

SOEC reaches a mean exergetic efficiency without heat recovery of 68.85 ± 4.81 %. With heat recovery, SOEC exhibits the highest average exergetic efficiencies among the electrolysis technologies of 86.37 ± 7.35 % (Figure 3). Thus, the mean exergetic efficiency is 17.52% higher when heat utilisation is considered (Figure 3).

For AWE or PEM combined with CatM the exergetic efficiencies range from 44.39% to 70.52% with a mean of 54.38 ± 8.17 % (Figure 3). Considering the utilisation of the waste heat, the exergetic efficiency ranges from 52.17% to 80.96% with a mean of 61.22 ± 10.04 % (Figure 3). The mean exergetic efficiency increase due to heat utilisation is 6.84%.

For AWE or PEM combined with BioM the exergetic efficiencies range from 45.14% to 53.30% with a mean of 46.48 ± 0.94 %. Considering the utilisation of the waste heat, the exergetic efficiency ranges from 49.07% to 57.81% with a mean of 52.34 ± 0.76 %. The mean exergetic efficiency increase due to heat utilisation is 3.67%. (Figure 3)

The exergetic efficiency with heat integration from the combination of SOEC and CatM ranges from 66.9% to 81% with a mean of 76.33 ± 5.42 % (Figure 3). This is due to the internal heat integration of the waste heat from CatM to preheat the reactants (water) for the SOEC. There is no data available for this system without heat integration.

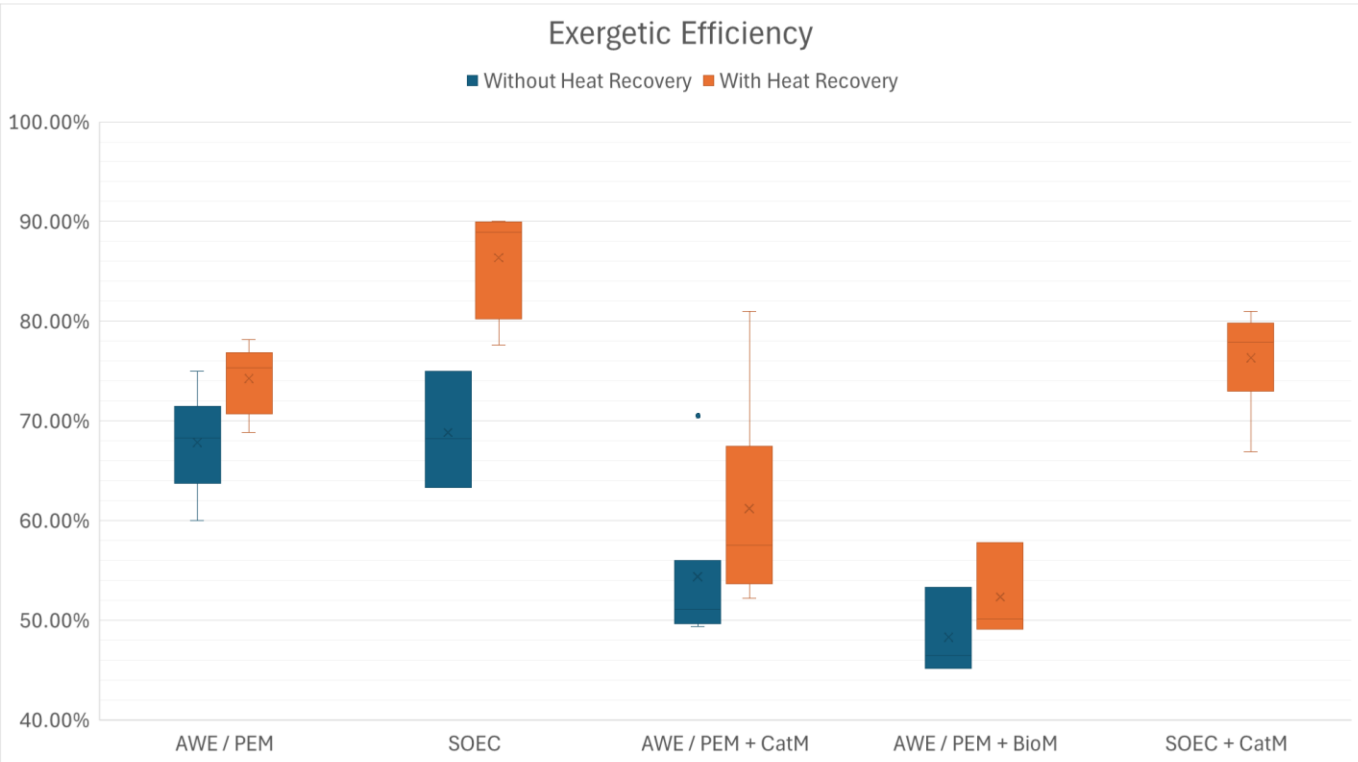

Figure 3: Exergetic efficiency of PtH and PtM process with and without heat integration (Data: Appendix B)

3.2 Comparison of Exergetic Efficiencies in Modeled and Realized Systems

The literature was divided in models and realized project in order to understand whether there is a difference and whether models tend to overestimate the influence of heat integration.

Considering AWE/PEM models, the mean exergetic efficiency increases from 68.41% to 70.93% due to heat integration, a mean exergetic efficiency increase by 2.51%. Whereas the mean exergetic efficiency of realized projects with AWE/PEM is 66.48% without heat integration and 73.18% with heat integration, a mean exergetic efficiency increase by 6.7%. Demonstrating that the mean exergetic efficiency value with heat integration and increase compared to without heat integration are higher for realized projects than models. (Figure 4)

For models of AWE/PEM combined with CatM the mean exergetic efficiency is 50.36% without heat integration and 58.77% with heat integration, an increase by 8.41%. Looking at realized projects, the mean exergetic efficiency is 56.94% without heat integration and 63.56% with heat integration, an increase by 6.64%. Demonstrating that the mean exergetic efficiency value with heat integration is higher for realized projects, however the exergetic efficiency increase is higher for the models. (Figure 4)

For models of AWE/PEM combined with BioM the mean exergetic efficiency is 49.22% without heat integration and 53.44% with heat integration, an increase by 4.22%. Looking at realized projects where only one data point was found, the mean exergetic efficiency is 46.48% without heat integration and 50.15% with heat integration, an increase by 3.68%. Demonstrating that the mean exergetic efficiency value with heat integration and increase compared to without heat integration are higher for models than for realized projects. (Figure 4)

For SOEC and SOEC+CatM the comparison could not be made, due to lack of data for realized projects.

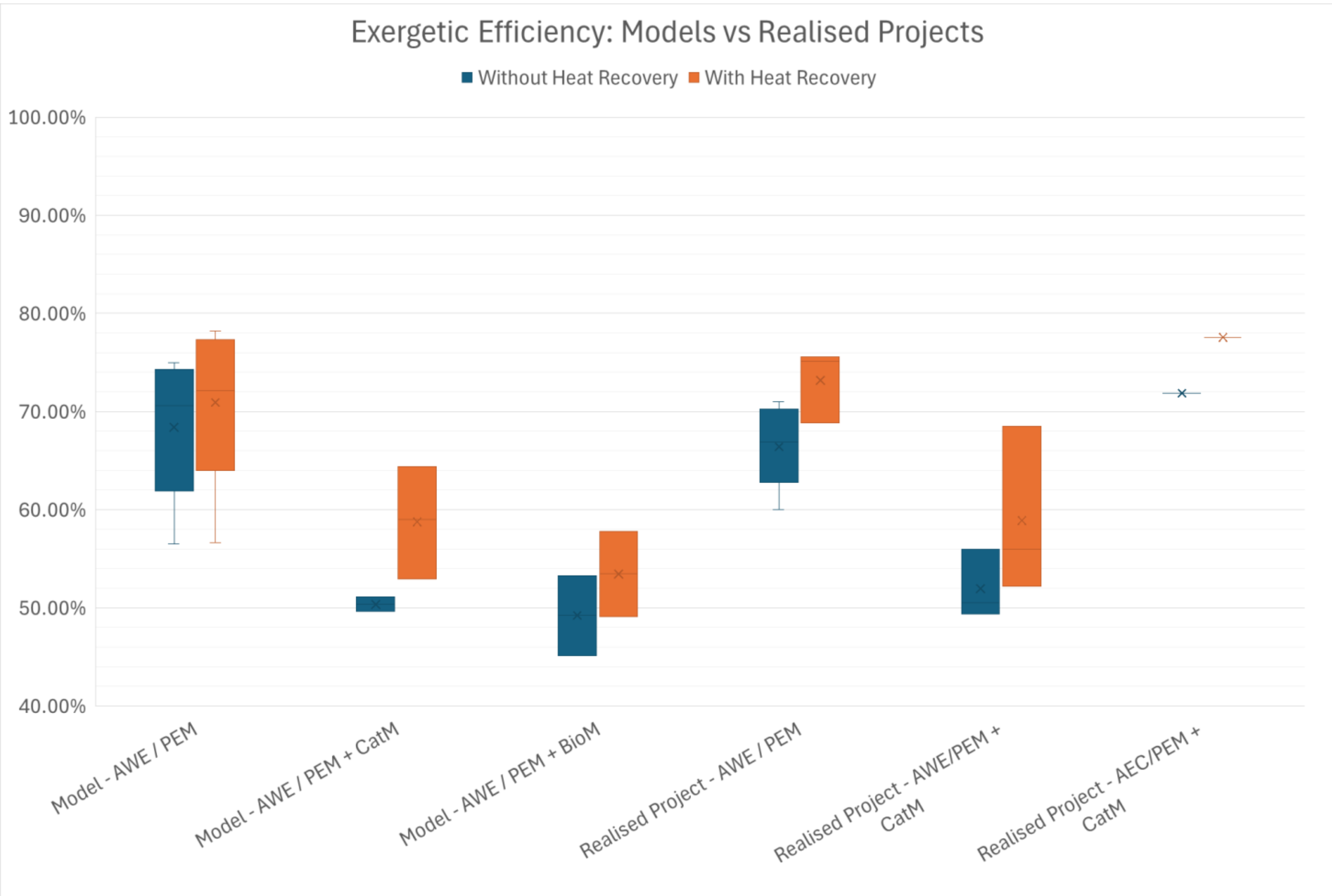

Figure 4: Exergetic Efficiency, comparison Models vs Realised Projects (Data: Appendix B)

4. Conclusion

This review highlights the critical role of waste heat utilisation in improving PtG system efficiency. Key findings include:

- Heat recovery increases the mean exergetic efficiency of PtH technologies between 6-18%.
- The highest PtH exergetic efficiency can be achieved by SOEC with a mean exergetic efficiency of 74%
- Heat recovery increases the mean exergetic efficiency of PtM combined with AWE/PEM between 4-7%.
- PtM with SOEC and CtM can reach high exergetic efficiency through heat integration
- No ambiguous trend in over or underestimation of models compared to realized projects was found.

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Appendix

A: Units and Symbols

This section provides guidance on the use of units and symbols in your paper. Please follow these guidelines.

Symbol	Unit	Description
$\eta_{H2,w/oHU}$	[ ]	Exergetic efficiency of hydrogen electrolysis without heat utilizaiton
$\eta_{H2\&CH4,w/oHU}$	[ ]	Exergetic efficiency of hydrogen electrolysis and methantion without heat utilizaiton
$\eta_{H2,wHU}$	[ ]	Exergetic efficiency of hydrogen electrolysis with heat utilizaiton
$\eta_{H2\&CH4,wHU}$	[ ]	Exergetic efficiency of hydrogen electrolysis and methantion with heat utilizaiton
LHV_{H2}	kWh/kg	Lower heating value hydrogen
LHV_{CH4}	kWh/kg	Lower heating value methane
m_{H2}	Kg	Mass hydrogen
m_{CH4}	Kg	Mass methane
$E_{El,in}$	kWh	Electricity input for electrolysis
$Q_{in,el}$	kWh	Heat input electrolysis
T_{Qin}	K	Temperature of required heat input
T_{amb}	K	Ambient temperature – Assumed to be 25°C
$Q_{wH,el}$	kWh	Heat output from electrolysis
$T_{use,wH,el}$	K	Temperature at which the waste heat from the electrolysis is used
$Q_{wH,me}$	kWh	Heat output from methanation
$T_{use,wH,me}$	K	Temperature at which the waste heat from the methanation is used

B: Data and Reference

Reference	Model / Realised Project	AWE / PEM	AWE	PEM	SOEC	CatM	BioM	Usage	Without Heat Recovery - Exergetic	With Heat Recovery Exergetic efficiency based on LHV
(Mezzera et al., 2021)	Model			x		x		Electricity Generation (ORC)	70.52%	80.96%
(Mezzera et al., 2021)	Model			x				DHN	74.07%	72.12%
(Candelaresi et al., 2021)	Model			x		x		Preheating CatM	53.56%	55.76%
(Candelaresi et al., 2021)	Model			x					56.53%	56.63%
(Benjaminsson et al., 2013)	Realised Project	x				x		Steam generation	56.00%	68.51%
(Benjaminsson et al., 2013)	Realised Project	x							70.00%	75.10%
(van Leeuwen and Zauner, 2018)	Realised Project		x			x		Not defined	49.39%	52.17%
(van Leeuwen and Zauner, 2018)	Realised Project		x					Not defined	63.70%	
(van Leeuwen and Zauner, 2018)	Model		x			x		Not defined	49.62%	52.92%
(van Leeuwen and Zauner, 2018)	Model		x					Not defined	63.70%	
(van Leeuwen and Zauner, 2018)	Realised Project			x			x	DHN	46.48%	50.15%
(van Leeuwen and Zauner, 2018)	Realised Project			x				Not defined	60.00%	
(van Leeuwen and Zauner, 2018)	Model			x			x	DHN	45.14%	49.07%
(van Leeuwen and Zauner, 2018)	Model			x				Not defined		
(van Leeuwen and Zauner, 2018)	Realised Project		x			x		DAC	50.51%	56.00%
(van Leeuwen and Zauner, 2018)	Realised Project		x					Not defined	65.60%	
(van Leeuwen and Zauner, 2018)	Model		x			x		DAC	51.09%	59.00%
(van Leeuwen and Zauner, 2018)	Model		x					Not defined		
(Gaul et al., 2015)	Realised Project			x				gas pressure regulation station	71.00%	75.60%
(Vidal Vázquez et al., 2018)	Realised Project			x				DAC	68.23%	68.83%
(Wang et al., 2019)	Model				x	x		SOEC		79.40%
(Wang et al., 2019)	Model				x	x		SOEC		78.90%
(Wang et al., 2019)	Model				x	x		SOEC		75.00%
(Wang et al., 2019)	Model				x	x		SOEC		66.90%
(Giglio et al., 2018)	Model				x	x		SOEC		76.80%
(Anghilante et al., 2019)	Model			x		x		Electricity Generation (ORC)		64.40%
(Anghilante et al., 2019)	Model				x	x		SOEC		81.00%
(Groniewsky et al., 2022)	Model		x				x	Electricity Generation (ORC)	53.30%	57.81%
(Groniewsky et al., 2022)	Model		x					Electricity Generation (ORC)	68.40%	71.32%
(Nastasi and Lo Basso, 2016)	Model	x						Metal Hydride Heat Pump	75.00%	78.18%
(Nastasi and Lo Basso, 2016)	Model	x						Metal Hydride Heat Pump	72.73%	76.44%
(Zhao et al., 2021)	Model				x			SOEC	63.34%	89.87%
(Shamsi et al., 2024)	Model				x			SOEC	68.20%	77.60%
(Reza et al., 2023)	Model				x			SOEC	75.00%	88.00%
(Bui et al., 2023)	Model				x			SOEC		90.00%