Energy modeling of a cascade cycle for hydrogen liquefaction applications

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ABSTRACT –
This study analyzes the energy performance of green hydrogen pre-cooling at ultra-low temperatures. For a fixed refrigerated load, the decrease in evaporation temperature leads to a collapse of the COP of the low-temperature cycle and a sharp increase in the work of the compressors, reflecting a high energy cost of cryogenic temperatures. The optimization of intermediate pressure in cascade cycles significantly improves COP and reduces power consumption. The results highlight the importance of designing efficient refrigerants and compressors, as well as high-performance heat transfer, to minimize specific pre-cooling energy. These conclusions provide clear guidance for the design of more efficient and sustainable green hydrogen liquefaction systems.

1. INTRODUCTION

In recent years, the demand for low-temperature cooling systems, such as rapid freezing and food storage, has increased significantly due to stricter performance and environmental standards [1]. Cascade refrigeration systems (CRS) present themselves as an efficient alternative to single or two-stage cycles for very low temperatures (-30°C to -85°C). They overcome the limitations of conventional systems, including high pressures, high discharge temperatures, and low volumetric efficiency, by using different refrigerants at each stage, which improves efficiency and reliability [2], [3]. Among the possible combinations of refrigerants, the combination of carbon dioxide (CO_2) for the low-temperature cycle (LTC) and propane (R290) for the high-temperature cycle (HTC) has aroused particular interest. This configuration leverages the low global warming potential (GWP) and environmental benefits of these natural refrigerants while maximizing the operational efficiency of the CRS [4]. Hydrogen liquefaction, a key step in the development of a competitive green hydrogen sector, is a typical application for CRS, particularly for pre-cooling before liquefaction. Liquid hydrogen has an energy density nearly 800 times higher than that of compressed gas, facilitating its transport, storage and industrial use and for large-scale mobility [5]. However, this process remains energetically intensive, requiring temperatures below 20 K and a typical consumption of 10 to 15 kWh/kg H_2, of which 20 to 30% is attributed to the pre-cooling step [6],[7].
The present work analyzes a CO/propane cascade refrigeration system applied to hydrogen pre-cooling. The study focuses on energy performances, notably compressor powers, coefficient of performance (COP) and specific pre-cooling energy. The objective is to evaluate the feasibility of integrating this system into a green hydrogen production line and to identify the parameters influencing energy consumption in order to reach the recommended industrial values for the pre-cooling step (2 to 4 kWh/kg H_2).

2. METHODOLOGY

a. System description

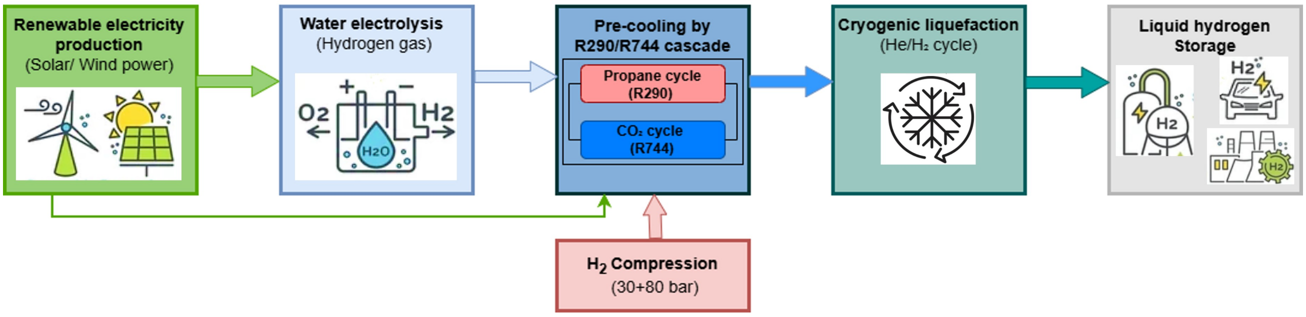

Figure 1: Integrated Process Chain for Green Hydrogen Production, Pre-Cooling, Liquefaction, and Cryogenic Storage

Figure 1 gives an overview of the green hydrogen value chain, from its production to its liquid storage. It highlights the main steps: renewable energy production, electrolysis, hydrogen treatment and drying, then compression. The study focuses specifically on the pre-cooling step, represented by the CO_2/propane cascade system, highlighted in green. This system, composed of a R290 cycle and a R744 cycle, is placed upstream of cryogenic liquefaction in order to effectively lower the temperature of hydrogen before it enters deep cycles (He/H_2). It thus contributes to improving overall energy efficiency. Once liquefied, hydrogen is directed towards cryogenic storage.

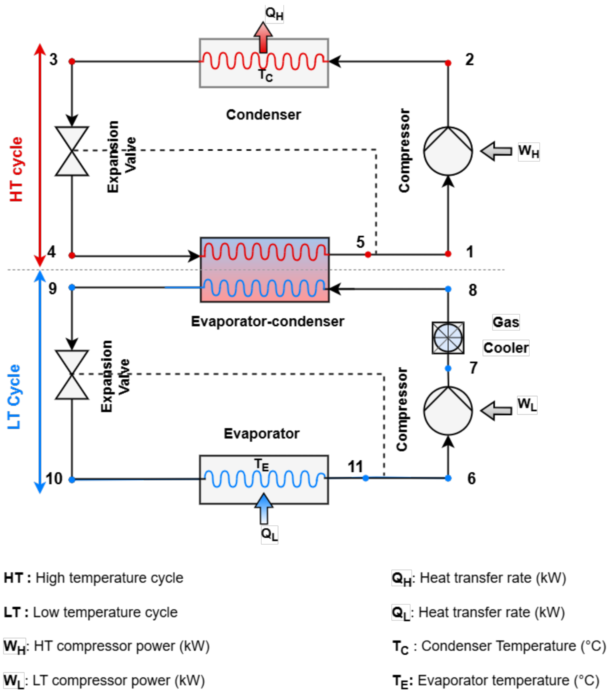

Figure 2: Schematic of a cascade refrigeration system

Figure 2 illustrates the principle of the cascade system: two independent cycles optimized for different temperature ranges (HT and LT), each with a compressor, condenser, expander and evaporator. The two circuits exchange heat via a cascade condenser, which serves as both an evaporator for the HV cycle and a condenser for the LT cycle.

In this configuration, CO_2 (LT) provides performance at very low temperatures while propane (HT) benefits from moderate pressures and good energy efficiency. Their combination allows to optimize the pre-cooling, an essential step to reduce energy consumption before liquefaction. The two cycles finally comply with the mass and energy balances specific to cascade refrigeration systems.

a. Thermodynamic study

Table 1: Thermodynamic Equations for the HT/LT Cascade Refrigeration System

Cycle Component	Equation / Relation	Description
	High-Temperature (HT) Cycle	
Mass flow rate	$\dot{m}_1=\dot{m}_2 = \dot{m}_3=\dot{m}_4=\dot{m}_H$	Constant mass flow rate throughout the HT cycle
HT Condenser	$Q_{Cond} = \dot{m} * (h[2] - h[3])$	Heat rejected in the condenser
HT Expansion Valve	$h[3] = h[4]$	Enthalpy remains constant across the valve

HT Compressor	$W_H = \dot{m}_H * (h[2]-h[1])$ $P_H = \frac{W_H}{\eta_H}$	Work input to the HT compressor compressor power for HT cycle
Cascade Condenser	$Q_{cc} = \dot{m}_L (h[6]-h[7]) = \dot{m}_H * (h[1]-h[4])$	Heat transfer between the HT and LT cycles
Low-Temperature (LT) Cycle		
Mass flow rate	$\dot{m}_5 = \dot{m}_6 = \dot{m}_7 = \dot{m}_8 = \dot{m}_9 = \dot{m}_L$	Constant mass flow rate throughout the LT cycle
LT Expansion Valve	$(h[7]=h[8])$.	Enthalpy remains constant across the valve
LT Evaporator	$Q_{evap} = \dot{m} * (h[1] - h[4])$	Cooling load absorbed in the evaporator
LT Compressor	$W_L = \dot{m}_L * (h[6]-h[5])$ $P_L = \frac{W_L}{\eta_L}$	Work input to the LT compressor compressor power for LT cycle
System Performance		
HT Cycle COP	$COP_H = \frac{Q_{CC}}{W_H}$	Coefficient of performance of the HT cycle
LT Cycle COP	$COP_L = \frac{Q_{evap}}{W_L}$	Coefficient of performance of the LT cycle
Overall COP	$COP_{Total} = \frac{Q_L}{(W_L + W_H)}$	Overall performance of the cascade system
	$E_{precool} = \frac{(P_H + P_L)}{\dot{m}_{H2}}$	specific energy consumed for hydrogen pre-cooling

b. Validation model

In this study, the thermodynamic model equations, which are highly nonlinear, are solved using the Engineering Equation Solver (EES) [8], commonly used for refrigeration system modeling. Previous work on CO2-propane cascade refrigeration systems is based on numerical approaches. The system is validated by comparing predicted performance with experimental results. EES simultaneously solves the equations using a variant of Newton's method, ensuring that the number of equations and that of variables are equal.

A parametric study was conducted to evaluate the effect of key design and operational parameters on the system's COP. Each variable has been adjusted within a defined range to identify the factors that most influence performance. The conditions retained are: LT evaporation temperature of 30 °C, superheat of 5 K, subcooling of 2 K, temperature difference of 7 °C at the condenser and 4 °C at the cascade exchanger. The isentropic efficiencies of the compressors are 0.3 (LT) and 0.6 (HT). The ambient temperature is set at 40 °C and the refrigeration capacity at 1.5 kW. The model is validated by comparing it to the results of Cabello and Andreu-Nacher [9] for a CO_2 –propane system, with the correspondence of input variables and results summarized in Table 2.

Table 2 :Validation results

Parameters	R.cabello model	Present model	Erreur %
q_H	254,9	253,8	0,43
q_L	249,8	240,8	3,60
W_H	87,3	87,62	-0,37
W_L	110,8	110,4	0,36
COP_H	2,92	2,897	0,79
COP	2,25	2,178	3,22
COP_{tot}	1,18	1,18	0

3. RESULTS AND DISCUSSION

The analysis of the results shows that the COP of the high temperature cycle (COPH) remains constant at 2.89, while that of the low temperature cycle (COPL) drops sharply, by 2,17 to 0.40, when the evaporation temperature changes from 30°C to 85°C. This decrease results in a similar decrease in overall COP (1.18 0.34), reflecting the increase in low-temperature compressor work required to liquefy hydrogen. For green hydrogen, this highlights the high energy cost of very low temperatures and the importance of optimizing the cascade cycle via efficient refrigerants and efficient compressors, in order to reduce pre-cooling energy and improve the durability of the process. In summary, the inverse relationship between Tevap and global COP guides the optimization choices for a more efficient and environmentally friendly H_2 system.

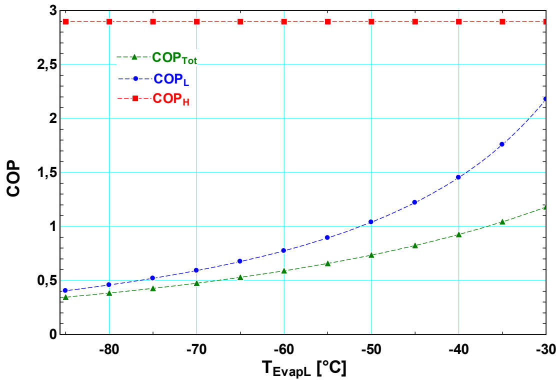

Figure 3: COP Vs Evaporation temperature

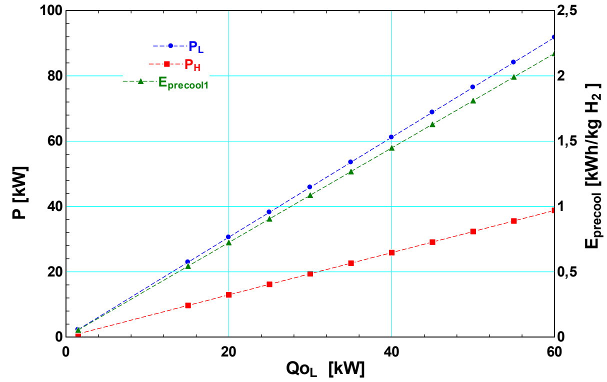

Figure 4: variation of the Q_{OL} with compressor powers and hydrogen

The analysis shows that the increase in the Q_{oL} refrigeration load leads to a proportional increase in compressor powers and specific energy consumed. Thus, to obtain a realistic modeling of pre-cooling in a green hydrogen context, it is necessary to increase Q_{oL}, either by a higher hydrogen flow rate, or by an improved heat transfer in the evaporator, allowing to achieve an Eprecool in the industrial range of 2–4 kWh/kg H_2 and ensuring consistent and reliable modeling.

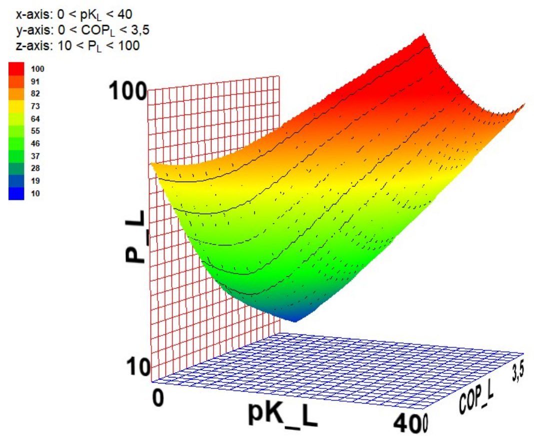

Figure 5: Impact of intermediate pressure on COP and P_L

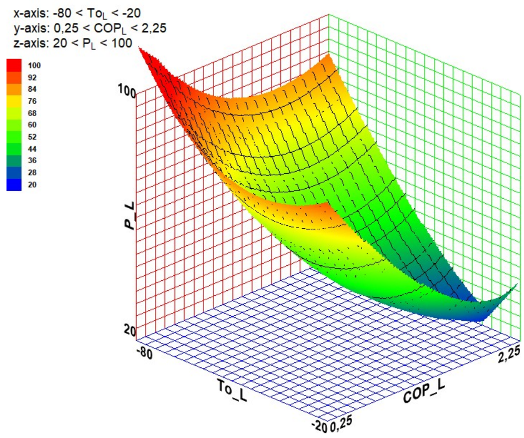

Figure 6: Evolution of COP as a function of the T_{OL} for a fixed refrigerated load

Figure 5 illustrates the crucial importance of the intermediate pressure configuration p_{KL} for the intermediate pressure of the pre-cooling system. For a fixed load of 15 kW at the cryogenic temperature of -80 °C required by hydrogen, the analysis reveals a decisive compromise. A reduction of p_{KL} from 40 bar to 4 bar results in a significant improvement in the coefficient of performance, from 0.46 to 3.25, accompanied by a substantial decrease in compressor power consumption from 109.5 kW to 15.4 kW. This configuration, favoring a smaller and less energy-consuming cascade exchanger, is therefore much more efficient for this demanding application. In green hydrogen production, where every kilowatt hour counts, operating at low p_{KL} to maximize COP is essential in order to reduce the specific pre-cooling energy and preserve the environmental efficiency of liquefaction.

Figure 6 illustrates the high energy penalty associated with pre-cooling hydrogen to ultra-low temperatures. For a refrigeration load of 15 kW, lowering the evaporation temperature from 30°C to 80°C results in a collapse of the COP from 2.18 to 0.46 and a five-fold increase in compressor power (from 23 kW to 109.1 kW). This shows that achieving cryogenic temperatures is highly energy-intensive, highlighting the importance of optimizing refrigeration cycles to reduce electricity consumption and ensure the viability and sustainability of liquefied green hydrogen.

4. CONCLUSION

The study highlights the major energy challenges related to the production of ultra-low temperature cooling for green hydrogen pre-cooling. The results show that the COP of the low-temperature cycle strongly decreases when the evaporation temperature falls, leading to a substantial increase in the work of the compressors and overall electrical consumption. The intermediate pressure configuration plays a determining role: a reduction of p_{KL} significantly improves COP and reduces power consumption, highlighting the importance of precise sizing of cascade cycles and exchangers. The study confirms that, even for low experimental loads, the inverse relationship between evaporation temperature and energy efficiency guides optimization choices. To ensure the sustainability and viability of green hydrogen liquefaction, it is imperative to optimize refrigerants, compressors, and heat transfer in order to minimize the specific pre-cooling energy.

5. References

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