



## **Integrated design for demonstration of efficient liquefaction of hydrogen (IDEALHY)**

### **Fuel Cells and Hydrogen Joint Undertaking (FCH JU)**

Grant Agreement Number 278177

Title: Large-Scale Hydrogen Liquefaction Concepts and Pre-Cooling Alternatives  
*(Publishable Summary)*

Authors / Project Partner: David Berstad, Petter Nekså, Harald T. Walnum / SINTEF Energi AS  
Lutz Decker / Linde Kryotechnik AG  
Alice Elliott / Shell Global Solutions International B.V.  
Christoph Haberstroh, Hans Quack, Ilka Seemann / Technische Universität Dresden

Work Package: Technology Analysis and Conceptual Liquefaction Process Assessment

Deliverable Number: 1.3

Date: 29 October 2012

Report Classification: Restricted (here: *Publishable Summary*)

<b>Approvals</b>	
<b>WP Leader</b>	✓
<b>Coordinator</b>	✓
<b>FCH JU</b>	<b>pending</b>
<b>Contacts</b>	
<b>David.Berstad@sintef.no</b>	
<b>info@idealhy.eu</b>	

## Disclaimer

Despite the care that was taken while preparing this document the following disclaimer applies: The information in this document is provided as is and no guarantee or warranty is given that the information is fit for any particular purpose. The user thereof employs the information at his/her sole risk and liability.

The document reflects only the authors' views. The FCH JU and the European Union are not liable for any use that may be made of the information contained therein.

## Publishable summary

This report documents the outcomes from Task 1.3 in the IDEALHY project.

It is important to have an understanding of the properties of existing processes and concepts in order to evaluate new liquefaction concepts. To create a level playing field for process benchmarking, the concepts found in the open literature (already described in deliverable D1.1) require modelling and simulation with the common IDEALHY boundary conditions and process parameters described in D1.2.

A reference case, the standard Linde large-scale cycle, was simulated by all institutions and the results compared, to ensure that the different institutions in IDEALHY could produce consistent results while using different simulation tools. Most of the stream states compared were within 1 % deviation and all results were within a 4 % margin.

Including the Linde reference case, seven different processes were modelled and simulated. The differences between the cycles were examined using exergy analysis, as breaking the process efficiency losses down by this method reveals to what magnitude the different components and sub-processes contribute to irreversibilities and thus to efficiency losses. Key observations from this analysis include the severe penalty of utilising liquid nitrogen for hydrogen pre-cooling, and the importance of efficient turbomachinery.

The liquefaction process was divided into four stages, to elaborate further on the different concepts and develop a new and more efficient cycle:

1. Pre-compression of the feed
2. Pre-cooling down to about 80 K
3. Cryogenic cooling down to 20–30 K
4. Final expansion and liquefaction.

From a process point of view, it was concluded that a higher pressure is advantageous, primarily because of reduced variation in the hydrogen heat capacity, but this pressure is limited by the efficiency of heat exchangers. This and other consequences of elevated hydrogen pressure will be investigated further in WP2.

For pre-cooling it was found that mixed refrigerant (MR) cycles have a thermodynamic advantage compared to Brayton cycles in higher temperature intervals. The optimum temperature split between MR (pre-cooling) and Brayton (cryogenic cooling) in a liquefier will also be investigated further in WP2.

For cryogenic cooling, Brayton cycles are the main process option. The choice of possible working fluids is primarily a question of the targeted temperature before expansion/liquefaction of hydrogen, as well as of the ease of compression. A helium/neon mixture seems to be the most promising solution; it is a compromise between low temperature and high molecular mass to enable efficient compression.

For the final expansion and liquefaction stage, a power-generating liquid expander is the only viable solution for high efficiency. It would also be beneficial to have a once-through configuration, i.e. one with no flash gas at the liquid expander outlet. This, however, depends on a sufficiently low temperature at the expander inlet, which in turn depends on the cryogenic cooling cycle being able to provide required low temperature.

Based on the evaluation described in this document the stated goal of 45–48 % reduction in specific power consumption should be achievable.

### **Key words**

efficient hydrogen liquefaction, pre-compression, pre-cooling, cryogenic cooling, flash gas, mixed refrigerant

### **List of abbreviations**

UA:	Product of heat transfer coefficient and heat transfer area
MITA:	Minimum internal temperature approach
LMTD:	Logarithmic mean temperature difference
NTU:	Nephelometric turbidity unit

## Table of Contents

<b>Disclaimer</b> .....	<b>iii</b>
<b>Publishable summary</b> .....	<b>iv</b>
<b>Key words:</b> .....	<b>v</b>
<b>List of abbreviations</b> .....	<b>v</b>
<b>1. Introduction</b> .....	<b>1</b>
1.1 IDEALHY Project Objectives .....	1
1.2 Work Package Scope and Objectives .....	1
1.3 Deliverable Objective in relation to the WP .....	1
<b>2. Hydrogen thermodynamics in simulation tools</b> .....	<b>2</b>
2.1 Implementation of equations of state for hydrogen .....	2
2.1.1 Microsoft Excel .....	2
2.1.2 PROII.....	2
2.1.3 HYSYS .....	2
2.2 Comparison with Reference case.....	3
<b>3. Recalculation of published processes</b> .....	<b>8</b>
3.1 Results from recalculated processes.....	8
3.1.1 Valenti et al. [6].....	8
3.1.2 Shimko [7] .....	13
3.1.3 SINTEF Mixed Refrigerant (MR) [8] .....	16
3.1.4 WE-NET: hydrogen Claude cycle.....	22
3.1.5 WE-NET: Brayton cycles.....	26
3.2 Comparison .....	34
3.2.1 Cycle key performance index and other central parameters .....	34
3.2.2 Exergy losses comparison .....	39
<b>4. Developing new concepts</b> .....	<b>40</b>
4.1 Pre-compression .....	41
4.2 Pre-cooling .....	42
4.2.1 Closed nitrogen loop .....	43
4.2.2 Helium/hydrogen Brayton.....	43
4.2.3 Mixed refrigerant systems .....	44
4.2.4 Comparison of preliminary results.....	45
4.3 Cryo-cooling .....	46

4.4	Final expansion and liquefaction .....	48
4.5	Power recovery/integration .....	49
<b>5.</b>	<b>Concept for further investigation .....</b>	<b>50</b>
5.1	Pre-compression .....	50
5.2	Pre-cooling .....	50
5.3	Cryo-cooling .....	51
5.4	Liquefaction .....	51
5.5	Full cycle layout and initial calculations .....	51
<b>6.</b>	<b>Impact of results on WP objectives and overall project .....</b>	<b>53</b>
<b>7.</b>	<b>Conclusions and recommendations .....</b>	<b>53</b>
	<b>References .....</b>	<b>55</b>
	<b>Acknowledgements .....</b>	<b>56</b>
	<b>Appendices .....</b>	<b>57</b>
	<b>Appendix A: Heat exchanger inlet and outlet temperatures comparison .....</b>	<b>57</b>
	<b>Appendix B: Sankey diagrams for WE-NET cycles .....</b>	<b>58</b>