Integrated Design for Demonstration of Efficient Liquefaction of Hydrogen (IDEALHY)

Fuel Cells and Hydrogen Joint Undertaking (FCH JU)

Grant Agreement Number 278177

Title:	Hydrogen Liquefaction Report
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Work Package:	Whole Chain Assessment
Deliverable Number:	3.16
Date:	16 December 2013
Report Classification:	Public

New Energy World JU

fuel cells & hydrogen for sustainability

Approvals	
WP Leader	✓
Coordinator	✓
FCH JU	**pending**
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Acknowledgements

The research leading to these results has received funding from the European Union's Seventh Framework Program (FP7/2007–2013) for the Fuel Cells and Hydrogen Joint Technology Initiative, under grant agreement number 278177.

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Publishable Summary

Hydrogen is expected to be an important future clean transport fuel. In the absence of a pipeline network, liquid hydrogen can be the most effective way to supply larger refuelling stations in the medium term. However, at present hydrogen liquefaction is expensive, energy-intensive and limited in capacity.

The IDEALHY project has investigated the different steps in the liquefaction process in detail, using innovations and greater integration in an effort to reduce specific energy consumption by 50 % compared to the state of the art. The project has also developed a strategic plan for prospective large-scale demonstration of efficient hydrogen liquefaction.

An element of the "Whole Chain Assessment" work package of IDEALHY has been Life Cycle and Economic Assessment (LCEA) of hydrogen liquefaction. The objectives of the LCEA are to evaluate and compare the environmental impacts and economic costs and benefits of all relevant pathways for the supply – from selected sources – and delivery of LH_2 to fuelling stations and its subsequent use in road passenger vehicles. This is done relative to current pathways based on crude oil from conventional sources, and relative to delivery of compressed gaseous hydrogen.

Part of the LCEA and the scope of this report is analysis of the "Preferred Process" for hydrogen liquefaction in future large plants, possibly up to 200 tonnes of hydrogen liquefaction capacity per day (tpd). The specific environmental impacts of this assessment are:

- Primary energy (PE) inputs, in the form of energy from depletable resources, such as fossil and nuclear fuels, and
- Prominent greenhouse gas (GHG) emissions consisting of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

The economic costs addressed by this assessment consist of:

- Internal costs, in €, which exclude taxes and financial incentives.

The workbook facilitates the assessment procedures both according to the Renewable Energy Directive (RED) of the European Commission for regulatory purposes, which approximates to attributional life cycle assessment (LCA) and consequential LCA for policy analysis purposes.

To analyse the IDEALHY Preferred Process, an MS Excel Workbook was developed. For the analysis, the Process was split into five stages:

- Compression of the feed hydrogen to 80 bar,
- Chilling of the feed hydrogen and refrigerants to 279 K (6°C), before entering the cold boxes,
- Pre-cooling down to about 130 K,
- Cryogenic cooling with Brayton cycles to 26.8 K, and
- A final expansion and liquefaction step, resulting in LH_2 at 22.8 K and 2 bar.

The specific electricity consumption of the liquefaction *process* at full load operation of a plant with a 40 or 50 tpd capacity is about 6.4 MWh_{el}/t LH_2. A number of auxiliaries, management of flash gas and boil-off as well as a certain amount of hydrogen losses increase specific electricity consumption of the *plant* by some 6% to 6.76 MWh_{el}/t LH_2.

Options such as utilising "waste cold energy", e.g. from re-gasification of liquefied natural gas, if obtainable, or the availability of feed hydrogen at 80 bar can help to reduce the specific electricity consumption of the *plant* to around 6 MWh_{el}/t LH_2.

The specific depletable PE input that is required to liquefy one tonne of hydrogen and the associated GHG emissions vary significantly depending on the location and, therefore, the sources of electricity used, which are assumed to be from the respective national grids. For a 50 tpd plant, the specific total GHG emissions range from 99 kg equivalent CO_2 / t LH_2 for Norway (with a dominant share of hydro power), through around 3,600 kg eq. CO_2 / t LH_2 in Germany and the United Kingdom to 6,737 kg eq. CO_2 / t LH_2 for Australia (with a high share of brown coal power plants).

The specific internal costs amount to about 1.72 €/kg LH_2, based on an estimated investment of 105 million €, a payback period of 20 years, an internal rate of return of 10%, assumed annual fixed costs for operation and maintenance of 4% of the investment, the costs for electricity set to 100 €/MWh_{el} and the operating hours per year to 8,000. When the assumed power costs are halved to 50 €/MWh_{el}, 1.38 €/kg LH_2 follow. For comparison, the costs of hydrogen generation from large-scale steam methane reforming are currently 1.00 – 1.50 €/kg.

It has to be emphasised that a hydrogen liquefaction plant based on the Preferred Process currently is at design stage. All figures stated in this report are thus estimates and based on assumptions to the best knowledge of the IDEALHY partners. Nonetheless, the outcomes of the IDEALHY project bear the potential to revise the notion that liquefaction of hydrogen is inefficient and costly.

Key Words

Life cycle assessment of hydrogen liquefaction

Specific electricity consumption

Depletable primary energy usage

Greenhouse gas emissions

Economic assessment of hydrogen liquefaction

Specific costs of hydrogen liquefaction

Abbreviations

CAPEX	CAPital Expenditure
CCGT	Combined-Cycle Gas Turbine
CCS	Carbon Capture and Storage
EC	European Commission
GH_2	Gaseous Hydrogen
GHG	GreenHouse Gases
H_2	Hydrogen
kW_{el}	kilowatt electrical power
LCA	Life Cycle Assessment
LCEA	Life Cycle and Economic Assessment
eq.	equivalent (in the context of GHG)
LH_2	Liquid Hydrogen / Liquefied Hydrogen
LN_2	Liquid Nitrogen / Liquefied Nitrogen
LNG	Liquefied Natural Gas
LHV	Lower Heating Value
MR	Mixed Refrigerant
MWh_{el}	Megawatthours electrical energy
NG	Natural Gas
PE	Primary Energy (fossil and nuclear)
OPEX	OPerational EXpenditure
t	metric tonne
tpd	tonnes per day
WP	Work Package

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1 Introduction

1.1 IDEALHY Project Objectives

Hydrogen is expected to be an important future clean transport fuel. In the absence of a pipeline network, liquid hydrogen can be the most effective way to supply larger refuelling stations in the medium term. However, at present hydrogen liquefaction is expensive, energy-intensive and limited in capacity.

The IDEALHY project has investigated the different steps in the liquefaction process in detail, using innovations and greater integration in an effort to reduce specific energy consumption by 50 % compared to the state of the art while minimising costs. The project has also developed a strategic plan for prospective large-scale demonstration of efficient hydrogen liquefaction.

1.2 Work Package Scope and Objectives

This report is compiled as part of work package 3 (WP3) "Whole Chain Assessment" of IDEALHY. This WP consists of three tasks:

- 3.1 Scenario Development for Liquid Hydrogen (LH_2),
- 3.2 Safety, and
- 3.3 Life Cycle and Economic Assessment (LCEA).

The overall objective of WP3 is to determine the impact of supplying and distributing significant volumes of liquid hydrogen to a refuelling infrastructure.

1.3 Life Cycle and Economic Assessment

The objectives of the LCEA are to evaluate and compare the environmental impacts and economic costs and benefits of all relevant pathways for the supply – from selected sources – and delivery of LH_2 to fuelling stations and its subsequent use in road passenger vehicles. This is done relative to current pathways based on crude oil from conventional sources, and relative to delivery of compressed gaseous hydrogen.

The specific environmental impacts of this assessment are:

- Primary energy (PE) inputs, in the form of energy from depletable resources, such as fossil and nuclear fuels, and
- Prominent greenhouse gas (GHG) emissions consisting of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

The economic costs addressed by this assessment consist of:

- Internal costs, in €, which exclude taxes and financial incentives.

1.4 Methodology

Assessment is performed by means of MS Excel workbooks which have a standardised structure and format to accommodate necessary functionality (for investigating the effect of key parameters) and transparency (by documenting all assumptions and sources of data). Chapter 2 of this report provides details on the workbook concept.

1.5 Context and Scope of the Deliverable Report

This report is part of a series of reports related to LCEA under IDEALHY:

- The "Baseline Results Report" (Ref. 1) documents work on the baseline for the LCEA in the project.
- The "Liquid Hydrogen Pathway Report" (Ref. 2) defines the pathways for hydrogen generation, conditioning, liquefaction, distribution and end use that are analysed and compared in the LCEA.
- The "Hydrogen Production and Utilisation Report" (Ref. 3) documents work on the development of workbooks for the production and utilisation of hydrogen, i.e. upstream and downstream the liquefaction plant.
- The "Hydrogen Liquefaction Report" – this deliverable – summarises work on the development of the workbook that represents the hydrogen liquefaction plant and presents results from the related LCEA activities.
- The "Techno-Economic Analysis and Comparison Report" will provide results from LCEA analysis with respect to complete chains of hydrogen generation, conditioning, delivery and usage.

The first three items have been published on the website of the IDEALHY project. From the final report, a summary with key findings is going to be uploaded.

Development of the liquefaction workbook has been based on the results from other work packages, in particular WP2 "Component assessment and optimisation of feasible large-scale liquefaction process" and WP5 "Planning and preparation of a large scale demonstration".

This report compiles the main features and key assumptions incorporated into the hydrogen liquefaction workbook, which is based on the "Preferred Process" identified in the course of the project: The Preferred Process is described in Chapter 3. Further specifications are introduced in Chapter 4. Chapter 5 presents and discusses illustrative results for PE consumption, GHG emissions and internal costs.

2 Workbooks

2.1 Assessment Procedures

The assessment procedures incorporated in the MS Excel workbooks for the IDEALHY Project were detailed previously in the Baseline Results Report (Ref. 1)[1]. In particular, the workbooks comprise assessment procedures which are consistent:

- With the EC Renewable Energy Directive (RED; Ref. 4) for regulatory purposes, approximating to attributional life cycle assessment (LCA) and
- With consequential LCA for policy analysis purposes.

The essential features for the EC RED methodology are:

- Exclusion of total GHG emissions associated with the construction, maintenance and decommissioning of plant, equipment, machinery and vehicles.
- Co-product allocation based on energy content.
- Where relevant (in situations where biomass is a feedstock), exclusion or inclusion of total GHG emissions associated with indirect land use change (iLUC) depending on the possible introduction of "iLUC factors" by the EC.

The essential features for policy analysis with consequential LCA are:

- Inclusion of total GHG emissions associated with the construction, maintenance and decommissioning of plant, equipment, machinery and vehicles.
- Co-product allocation based on substitution credits although this presents significant practical challenges due to the need to model the complete and global consequences of product displacement.
- Where relevant (in situations where biomass is a feedstock), inclusion of total GHG emissions associated with iLUC, if possible, although necessary global modelling is another major practical challenge with no broadly agreed approach and estimates at the moment.

The MS Excel workbooks provide clear specification of the goal and scope of the evaluation, as required by the ELCD (Refs. 5 to 8) and the FC-HyGuide (Refs. 9 and 10).

It should be noted that the results depend on certain critical assumptions including the following considerations:

- Primary energy is defined as an indicator of energy resource depletion and, as such incorporates the energy contained in fossil and nuclear sources. It would be possible to determine the energy provided by renewable sources when these are the main feedstocks for hydrogen production and liquefaction. However, this is not realised in the workbooks created in the course of this project.
- Estimated emissions of CO_2, CH_4 and N_2O can be converted to equivalent (eq.) CO_2 by means of Global Warming Potentials (GWPs). Values of GWPs depend on the chosen time horizon under consideration. Additionally, these values are subject to

[1] This chapter is based on a corresponding section in Ref. 1 by North Energy Associates Ltd.

revision from time-to-time by the Intergovernmental Panel on Climate Change (IPCC) as scientific understanding improves. In the context of LCA, the GWPs adopted are governed by the choice of methodology. Currently, the RED specifies GWPs of 23 kg eq. CO_2/kg CH_4 and 296 kg eq. CO_2/kg N_2O for a 100 year time horizon based on the IPCC Third Assessment Report (Ref. 11).
More recent equivalent GWPs of 25 kg eq. CO_2/kg CH_4 and 298 kg eq. CO_2/kg N_2O are given in the IPCC Fourth Assessment Report (Ref. 12).
Throughout this report, the GWPs as stipulated in the RED are applied.

- The internal economic cost estimates generated by the MS Excel workbooks are in €. These results are intended to reflect economic evaluation across the European Union (EU). However, the limitations of this are recognised and results should only be considered as approximations. This is because, apart from inherent extrapolation across 28 Member States with different internal economic conditions, it has also been necessary to incorporate cost data from countries outside the EU and for years other than 2013.

2.2 Basic Workbook Features

Each MS Excel workbook has a standard structure, consisting of a series of worksheets, which was described and presented previously in the Baseline Results Report (Ref. 1). In particular, the main elements of this structure are:

- An Input worksheet which enables the values of specified parameters to be altered,
- A Unit Flow worksheet (Unit Flow Chart) which provides a visual presentation of the process chain represented by the workbook,
- Individual Process Stage worksheets where detailed calculations are performed,
- Summary worksheets which present the results, and
- Worksheets that contain factors for PE usage and emission of GHGs related to the provision of electricity, water and materials.

This structure was adopted from North Energy Associates Ltd and has been used in numerous other projects making it is possible to ensure that the workbooks accommodate necessary functionality to model the effects of variations in specified parameters and contain adequate transparency to promote confidence in the subsequent results.

3 The IDEALHY Hydrogen Liquefaction Process

3.1 Process Characteristics and Stages

The Preferred Process for hydrogen liquefaction at large scale was developed under WP1 and WP2 of the IDEALHY project. Based on this, WP5 established the schedule for a demonstration plant (Ref. 13, which provides more details of the Preferred Process). Key boundary conditions of this process are summarised in Table 1.

Table 1: Key boundary conditions of the IDEALHY liquefaction process.

Parameter	Unit	Value
Feed hydrogen temperature	K	293
Feed hydrogen gas purity	%	99.99
Feed para-hydrogen fraction	%	25
Feed hydrogen pressure	bar	20
Operating pressure up to final expansion	bar	82
Final liquid hydrogen temperature	K	22.8
Final liquid hydrogen purity	%	100
Final liquid hydrogen para-fraction (minimum)	%	98
Final liquid hydrogen pressure	bar	2

The process flow diagram is shown in Figure 1. For the analysis, the process stages can be outlined as follows.

3.1.1 Compression of feed hydrogen

The feed hydrogen gas at assumed 20 bar is compressed through a two stage piston compressor to reach 82 bar. In the following, the pressure level is referred to as 80 bar for simplicity.

3.1.2 Chilling of feed hydrogen and refrigerants

The hydrogen feed, a mixed refrigerant high-pressure stream and two Brayton cycle high-pressure streams entering the first cold box are chilled with a single-component refrigerator from assumed ambient 293 K (20°C) to 279 K (6°C), depicted by the brown circles in Figure 1.

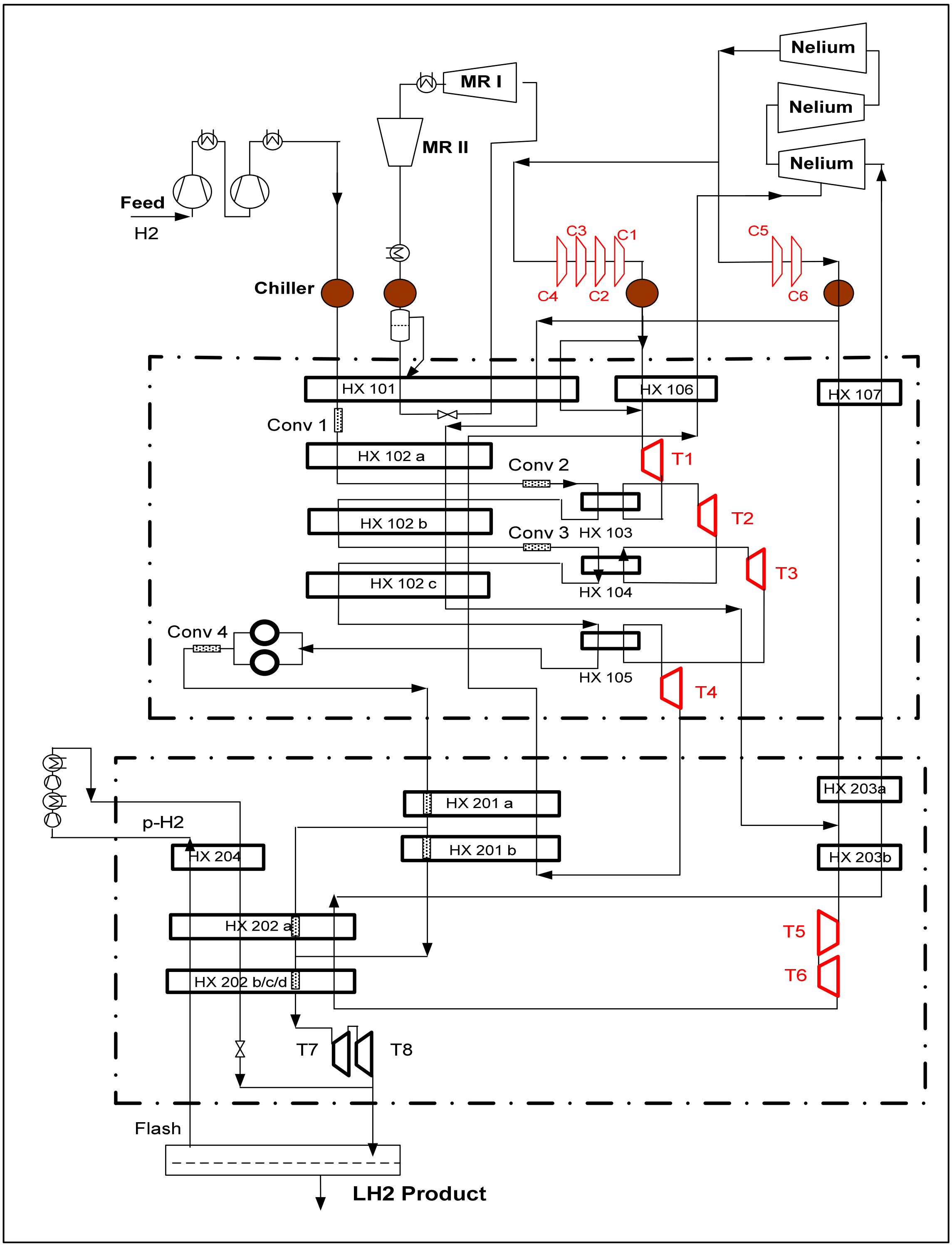

Figure 1: IDEALHY liquefaction process flow diagram (Ref. 13).
The upper rectangle depicts the cold box for components above 80 K; the lower one represents the cold box for lower temperatures. Both are vacuum insulated. C = turbo compressor, HX = heat exchanger, p-H2 = para-hydrogen, T = turbo expander.

3.1.3 Pre-cooling

During pre-cooling, the high-pressure hydrogen is cooled through heat exchangers, using a mixed refrigerant (MR, consisting of nitrogen, methane, ethane, propane and butane) down to a temperature of about 130 K. Also small portions of the two Nelium 25 streams (75% helium, 25% neon, mol-based fractions) receive cooling from the MR cycle.

In the process, the hydrogen is led through converter vessels, where the catalytic ortho-to-para conversion ("Conv 1" to "Conv 4" in Figure 1) takes place. Any residual contaminants are removed in two switchable adsorbers before the hydrogen leaves the first cold box.

3.1.4 Cryo-cooling

In cryo-cooling, the temperature of the hydrogen is further reduced to 26.8K. The cooling is performed by two overlapping Brayton cycles with a common compression train. As mentioned, the Brayton cycles receive some pre-cooling from the MR cycle. Ortho-para conversion continues.

3.1.5 Final expansion and flash gas cycle

In the final step, the hydrogen is liquefied through two expansion stages, from 80 bar to 2 bar. A vapour of 5% is left and it enters a flash gas cycle for reheating, cooling and then liquefaction through a throttle valve.

3.2 Liquefaction Capacity and Power Requirement

In the course of determining the IDEALHY Preferred Process and components needed, a plant with 50 tonnes of liquefied product per day (50 tpd) was focussed on. As regards realising a demonstration plant, however, a smaller capacity appeared to be advisable, given the limited demand for LH_2 expected in the near future. As explained in the schedule for the demonstration plant (Ref. 13), the high investment requires that such a plant should be commercial.

It was therefore decided to plan for a 40 tpd plant that additionally can operate at part load down to 25% of the rated capacity. This will still facilitate demonstrating the capabilities of the IDEALHY concept (Ref. 13)[2].

Table 2 shows the expected power requirements per process step as derived in Ref. 13. The values for 40 tpd at 100% load were derived by multiplying those for 50 tpd by 0.8. The figures for smaller load factors are based on technical considerations.

Since the scaling factor of 0.8 is the same for capacity and power requirements, the resulting specific electricity consumption at full load operation is 6.4 $kWh_{el}/kg\ LH_2$ for both plant sizes.

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[2] Operation at part load is accounted for regarding a 50 tpd plant throughout this report as well.

Table 2: Expected power requirements for the IDEALHY liquefaction process at 40 and 50 tpd rated capacity.
(Source: Ref. 13, Table 6; modified).

Plant Capacity	**Unit**	**50 tpd**	**40 tpd**		
Operating load factor		**100%**	**100%**	**50%**	**25%**
Feed compressor	kW_{el}	1,520	1,216	630	330
Chiller	kW_{el}	230	184	92	46
Mixed refrigerant cycle	kW_{el}	1,382	1,106	553	276
Brayton cycles	kW_{el}	10,100	8,080	4,753	3,228
Flash gas cycle	kW_{el}	100	80	45	30
Total liquefaction process	kW_{el}	13,332	10,666	6, 073	3,911

3.2.1 Options for Reducing the Power Requirement

There are two major options to reduce the power requirement of the Preferred Process:

- The possibility of having feed hydrogen delivered at higher pressure, requiring either only one stage or no pre-compression at all, as opposed to the normal two stage pre-compression set-up.
- Pre-cooling can be alternatively be accomplished using "waste cold" from re-gasifying liquefied natural gas (LNG), for example when the hydrogen feed is generated by methane steam reforming and this natural gas is shipped to the site in its liquid state. This could replace the mixed refrigerants pre-cooling circle, only a pump circulating nitrogen as a secondary refrigerant would be needed (100 kW_{el}).

Both options are considered in the LCEA.

3.3 Plant Layout

A layout of the liquefaction plant has been proposed (Ref. 13) as shown in Figure 2. The following considerations have been taken into account:

- All cryogenic components are to be housed in the two vacuum insulated cold boxes. Each cold box is a cylinder of about 4.5 m diameter and 10 m length. They are to be installed vertically and are to hang in a steel construction. On site, the two cold boxes are to be connected by a "tunnel", through which 5 process lines pass.
- All compressors are to be installed in a compressor building which is to be equipped with a crane for installation and servicing.
- The liquefied hydrogen will be stored in a storage vessel, which can hold the production of up to three weeks. From there the liquid hydrogen will be filled into transport trucks, containers or ships.

Also considered on the plant premises are:

- The possibility of a gaseous hydrogen buffer,
- Buffers for the refrigerants of the two refrigeration cycles: the mixed refrigerant and Nelium,
- A liquid nitrogen dewar, as nitrogen will be needed for a number of reasons including inerting, purging and catalyst regeneration purposes.

A flare is needed to vent hydrogen-containing gases e.g. from purging or adsorber regeneration.

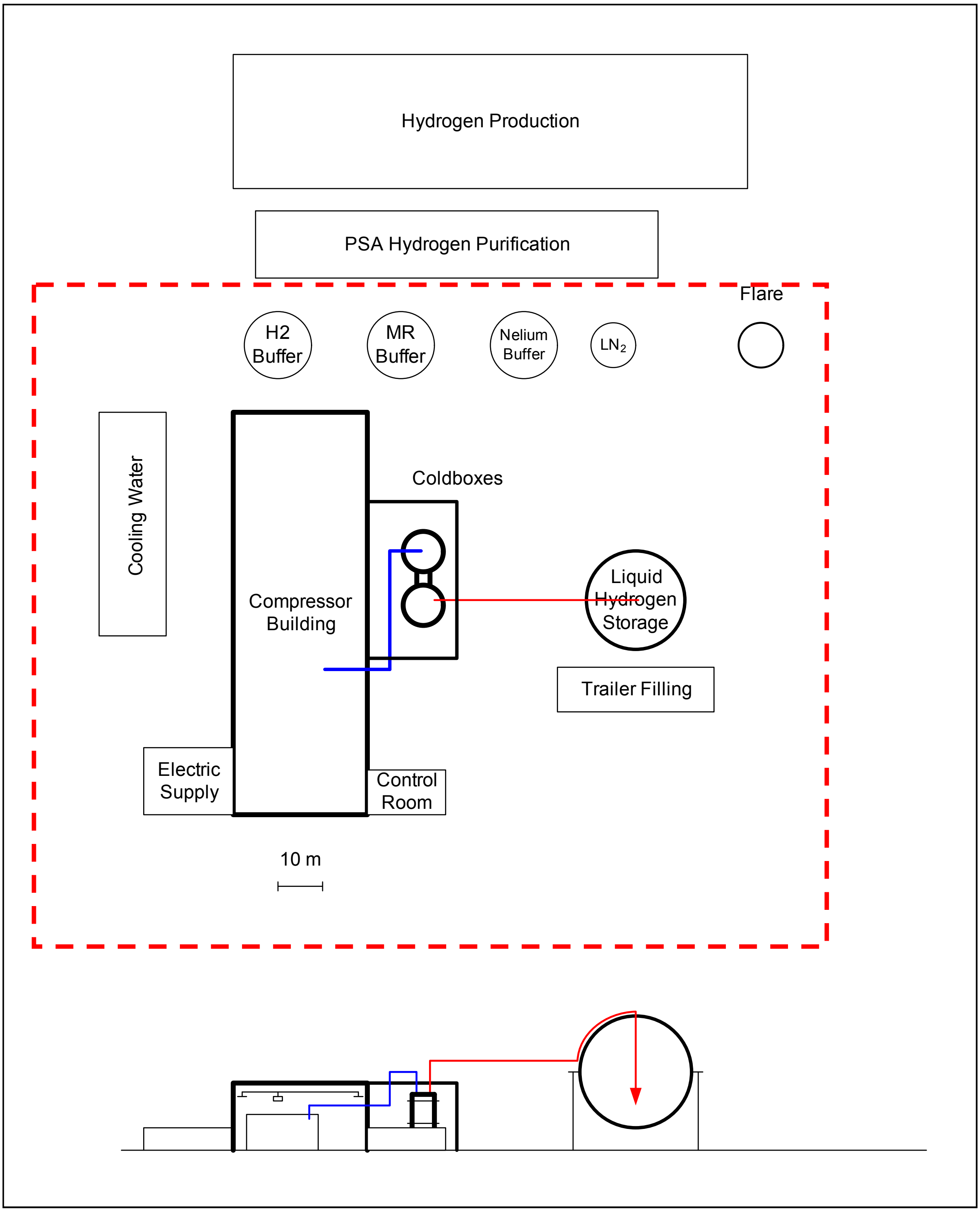

Figure 2: The suggested liquefaction plant with a side elevation for a 40 tpd demonstration plant. The red square defines the system boundary for the LCEA (Source: Ref. 13, LCEA system boundary added).

4 Specifications for the LCEA

The hydrogen liquefaction workbook maps the process as outlined in Chapter 3 to the extent required for the LCEA. It has to be emphasised that a hydrogen liquefaction plant based on the Preferred Process currently is at design stage. All figures stated above and in the following are thus estimates and based on assumptions to the best knowledge of the IDEALHY partners.

In addition to the liquefaction *process* as introduced in sections 3.1 and 3.2, operation of the liquefaction plant causes additional power consumption, as explained in section 4.3.

4.1 General Specifications

- The red square in Figure 2 defines the system boundaries for the LCEA.
- The functional unit is defined as 1 tonne of LH_2 in the on-site storage ready for dispatch.
- The reference flow is 1 tonne of LH_2 at 100% purity, 2 bar, 22.8 K with a share of para-H_2 of more than 98%.

4.2 Technical Specifications

The default values of the main technical specifications (i.e. input parameters in the workbook) are listed in Table 3. Where the table does not state preset options for a parameter, any alternative figure can be chosen.

- Besides 50 tpd capacity, the workbook also facilitates a 40 tpd plant size.
- For both plant sizes, part load factors of 75%, 50% and 25% can be selected, so that e.g. for the option with nominal 40 tpd an actual output of down to 10 tpd can be realised.
- The estimated hydrogen loss rate for the flash gas compressor is significantly lower than that of the feed gas compressor chiefly because only part of all hydrogen passes through the flash gas cycle and the percentages in Table 3 are relative to the entire hydrogen stream.

Table 3 Default values of the main technical input parameters.

Parameter	Unit	Default Value	Preset Options
Liquefaction capacity	tonnes LH_2 output/d	50	40
Operating load factor	%	100	75 / 50 / 25
Lifetime of plant	a	30	
Annual operating time	h/a	8,000	
Pre-cooling via LNG evaporation?	No / Yes	No	Yes
Hydrogen feed pressure	bar	20	40 / 80
Hydrogen losses - Feed gas compressor - Regeneration of adsorber at pre-cooling step - Flash gas compressor	 % % %	 1.500 0.100 0.025	

4.3 Specific Power Requirements

Table 4 reproduces the power requirement figures from Table 2 for the 40 tpd plant. Values for 75% part-load have been estimated in addition. Moreover, further power consumers are considered in the second-last line of the table. They are not part of the liquefaction *process* as such but related to operation of the *plant*. In the workbook, they are subsumed as auxiliaries:

- Components such as an instruments air compressor, a vacuum pump for the cold boxes, the control system, safety devices, lighting, etc. involve additional power use.
- In order to operate a cooling system that mainly serves the inter- and after-coolers of the compressors, water pumps and /or the fans of a wet cooling tower will consume further electrical power. Water will be evaporated.
- A tank for the liquefied hydrogen is necessary with a storage capacity of up to three weeks of production at full load. Although it will be very well insulated, a certain influx of heat will occur and result in boil-off, causing a higher mass flow through the flash gas cycle than induced by the Preferred Process.

Some of these factors scale in a linear fashion with plant size and capacity factor (e.g. power required by the cooling system), others remain constant independent of the capacity factor (such as lighting and the control system).

Analogous data for the 50 tpd plant are provided in Table 5.

Table 4: Expected power requirements for the 40 tpd liquefaction plant at full and part load.

	Unit	Plant Capacity: 40 tpd			
Operating load factor		**100%**	**75%**	**50%**	**25%**
Feed compression	kW_{el}	1,216	936	630	330
Chilling	kW_{el}	184	138	92	46
Mixed refrigerant cycle	kW_{el}	1,106	829	553	276
Brayton cycles	kW_{el}	8,080	6,498	4,753	3,228
Flash gas cycle	kW_{el}	80	61	45	30
Total liquefaction *process*	kW_{el}	10,666	8,462	6, 073	3,911
Auxiliaries	kW_{el}	610	529	442	361
Total liquefaction *plant*	kW_{el}	11,276	8,991	6,515	4,272

Table 5: Expected power requirements for the 50 tpd liquefaction plant at full and part load.

	Unit	Plant Capacity: 50 tpd			
Operating load factor		**100%**	**75%**	**50%**	**25%**
Feed compressor	kW_{el}	1,520	1,170	788	413
Chiller	kW_{el}	230	173	115	58
Mixed refrigerant cycle	kW_{el}	1,382	1,037	691	346
Brayton cycles	kW_{el}	10,100	8,123	5,941	4,035
Flash gas cycle	kW_{el}	100	76	56	38
Total liquefaction *process*	kW_{el}	13,332	10,579	7,591	4,890
Auxiliaries	kW_{el}	725	623	514	414
Total liquefaction *plant*	kW_{el}	14,057	11,202	8,105	5,304

As introduced in section 3.2.1, two options can serve to reduce the power requirement:

- The standard assumption is that hydrogen is supplied at 20 bar. The feed compressor will then increase the pressure to 80 bar, as required for the Preferred Process.
  - When alternatively the feed is available at 40 bar or 80 bar, respectively, the first stage of the feed compressor is obsolete or the compressor can be left out entirely.
  - It is assumed that omitting the first stage will halve the power requirement.
- When hydrogen is generated from natural gas reforming, this gas may be delivered in liquid state. Cold from re-gasification may thus be available for pre-cooling. This would substitute cooling energy from the mixed refrigerant cycle.
  - In the case of utilising cold from LNG re-gasification, it is assumed that for a 50 tpd plant that the power requirement reduces to about 100 kW for operating a closed nitrogen cycle between the LNG terminal and the liquefaction plant.
  - In accordance with previous scaling, the figure for a 40 tpd unit is determined as 80 kW.

4.4 Sources of Electricity

As introduced in section 1.3, the environmental impact assessment considers PE inputs from depletable resources and the emission of prominent greenhouse gases. In order to quantify these, so-called multipliers are used that specify the level PE use and GHG emissions associated with the consumption of one unit of electricity. These multipliers vary from country to country and depend on time. Based on energy balances for 2009 provided by the International Energy Agency (Ref. 14), multipliers for the following regions are employed, with individual data sets in line with the RED methodology on the one hand and with consequential LCA on the other hand[3]:

- EU-27 on average,
- Australia
- Germany
- The Netherlands,
- Norway, and
- The United Kingdom.

For EU-27, projected figures for 2030 are used in addition, based on data for “el-generation-mix-EU-27-2030 (PRIMES)” from GEMIS (Ref. 15).

The effort for the provision of water is considered as well, however in a simple manner because the impact is far less significant than that of electricity.

4.5 Plant Construction, Maintenance and Decommissioning

For consequential LCA, the inclusion of total GHG emissions associated with the construction, maintenance and decommissioning of plant, equipment, machinery and vehicles is required.

[3] For consequential LCA, the IEA data were modified with results from GEMIS (Ref. 15).

In order to account for this at the current concept stage of the Preferred Process, the IDEALHY partners have estimated the amount of key materials required for plant construction. Table 6 shows the resulting masses for a 50 tpd unit. Most of the stainless steel is expected to be required for a LH_2 storage vessel, for example. The figure for concrete is based on an assumed fenced area of 252 m * 185 m with a base plate of the same dimensions with an average thickness of 0.5 m and a density of 2 tonnes per cubic metres of concrete.

Table 6: Estimated inventory of major materials with respect to plant construction.

Material	**Unit**	**Mass**
Carbon steel	tonne	380
Stainless steel	tonne	595
Copper	tonne	150
Aluminium	tonne	140
Concrete	tonne	46,620

Figures for Maintenance and Decommissioning are derived in this way:

- Maintenance is assumed to cause 2.5% of the PE input and GHG emissions per year that stem from construction.
- Decommissioning is assumed to result in 4% of the PE input and GHG emissions from construction.

4.6 Unit Flow Chart

Figure 3 shows the Unit Flow Chart that represents operation of a liquefaction plant based on the Preferred Process with 50 tpd rated capacity. The numbers in this figure correspond to operation at full load.

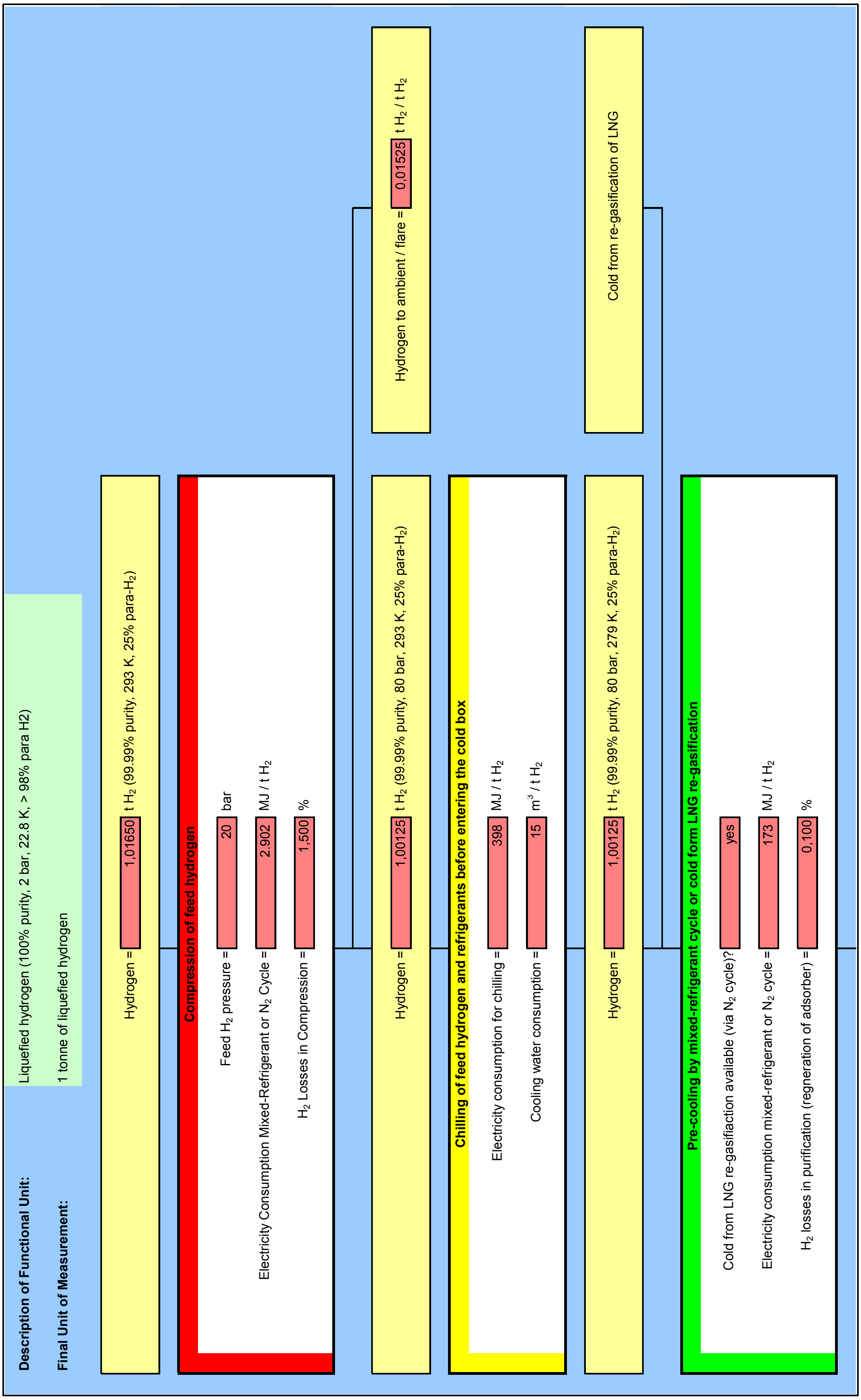

Figure 3: Unit Flow Chart of the IDEALHY hydrogen liquefaction process.

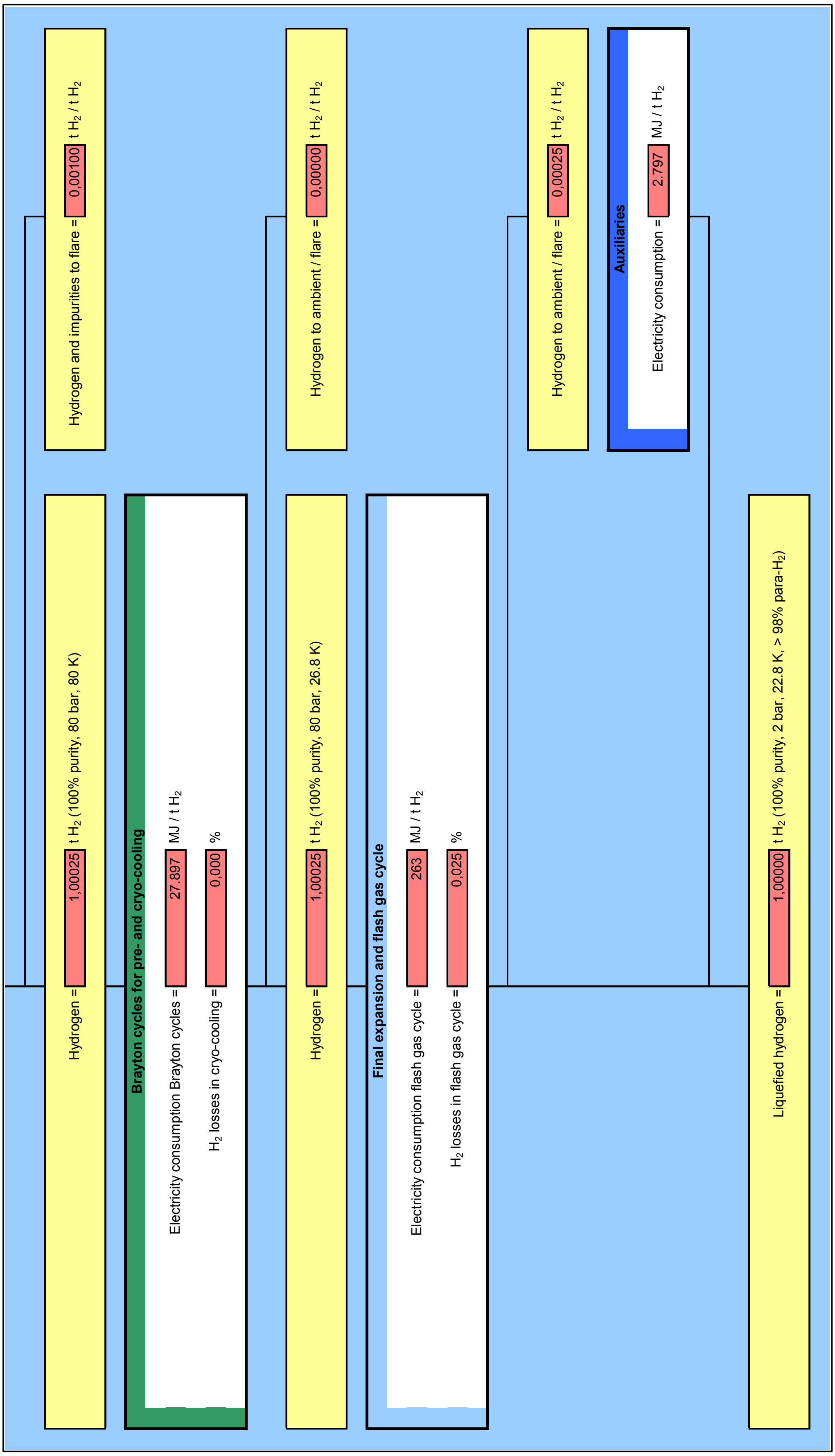

Figure 3: Unit Flow Chart of the IDEALHY hydrogen liquefaction process (continued).

4.7 Economic Specifications

The default values of parameters for the economic analysis are shown in Table 7.

Table 7: Economic default values.

Parameter	Unit	50 tpd	40 tpd
Investment	million €	105	90.5
Payback period	a	20	
Internal rate of return	%	10	
Fixed annual costs for operation and maintenance	% of investment	4	
Specific variable costs - Electricity - Water - Feed hydrogen	 €/MWh$_{el}$ €/m^3 €/t H_2	 100 1.25 2,000	

The quoted investment for a 50 tpd plant is the estimate that was available when the liquefaction workbook had to be finalised, pending the "Report on efficiency and cost calculations" (IDEALHY Deliverable D2.7, Ref. 16). The final version of D2.7 may thus contain a different figure.

The figures for investment, payback period and internal rate of return do not apply to a first-of-its-kind demonstration installation which is described in Ref. 13 but to a second or third plant. They are going to be influenced by the country, region and exact location where such as site is going to be built, too.

The investment for the 40 tpd plant is about 90.5 million €. This amount was calculated using the formula

$$C = A*(P)\hat{}2/3 \qquad (1)$$

where C is the investment and P the plant capacity in tpd. Constant A was determined to be 7.37 from the investment for 50 tpd and zero investment for a "0 tpd plant".

The default specific power costs represent a conservative estimate.

1.65% of the feed hydrogen are lost in the liquefaction process (see the upper end of the Unit Flow Chart in Figure 3) caused by the mechanisms as listed in Table 3. This loss must be accounted for with respect to the overall costs of liquefaction plant operation[4].

[4] The same is true concerning an additional burden in terms of PE depletion and GHG emissions on the "remaining" hydrogen caused by the hydrogen losses. This is facilitated in the liquefaction workbook as well. However, since the level of GHG emissions is strongly dependent on the type of hydrogen generation process, the default value for PE input and emissions of CO_2, CH_4 and N_2O from upstream processes are set to zero.

The default specific hydrogen cost figure is a conservative estimate based on data for hydrogen generated from steam methane reforming in Ref. 17.

When feed hydrogen is available at 40 or 80 bar and when cold from LNG re-gasification can be utilised, the investment will be smaller than stated in Table 7. The expected reductions range between about 1.8 million € for a 40 tpd plant when feed hydrogen is available at 40 bar so that the first stage of feed compressor can be omitted, and 5 million € for a 50 tpd plant when external cold energy is available and the MR cycle is redundant.

5 Illustrative Results and Discussion

All results in this chapter were obtained applying the RED methodology.

5.1 Specific Electricity Consumption

From the power requirements in Table 4 and Table 5, respectively, specific electricity consumptions per tonne of liquefied hydrogen can be calculated. For a 50 tpd plant, they are shown in Table 8. At full load operation, 6.41 $MWh_{el}/t\ LH_2$ will be consumed in the liquefaction *process* and 6.76 $MWh_{el}/t\ LH_2$ for operating the complete *plant*, respectively. The auxiliaries therefore increase the specific electricity consumption by about 6%.

For comparison, the existing liquefaction plant in Leuna/Germany, put into operation in 2007, has a capacity of 5 tpd and displays a specific liquefaction energy of approximately 11.9 MWh/t LH_2, for the *process* including an estimated penalty for employing cold from LN_2 of 0.4 kWh/l LN_2 (Ref. 18).

Table 8 shows how the total specific electricity consumption changes with diminishing utilisation of the plant. It is worth noting that for load factors down to 50% (correspon-ding to 25 tpd actual output), the increase in specific consumption is moderate.

Table 8: Specific electricity consumption at full and part load operation for a 50 tpd plant.

	Unit	Plant Capacity: 50 tpd			
Operating load factor		**100%**	**75%**	**50%**	**25%**
Feed compressor	MWh_{el} / t LH_2	0.74	0.76	0.77	0.81
Chiller	MWh_{el} / t LH_2	0.11	0.11	0.11	0.11
Mixed refrigerant cycle	MWh_{el} / t LH_2	0.66	0.66	0.66	0.66
Brayton cycles	MWh_{el} / t LH_2	4.85	5.20	5.70	7.75
Flash gas cycle	MWh_{el} / t LH_2	0.05	0.05	0.05	0.07
Total liquefaction *process*	MWh_{el} / t LH_2	6.41	6.78	7.30	9.40
Auxiliaries	MWh_{el} / t LH_2	0.35	0.40	0.49	0.79
Total liquefaction *plant*	MWh_{el} / t LH_2	6.76	7.18	7.40	10.20

Table 9 shows the corresponding figure for a plant with 40 tpd rated capacity. Due to the assumed linear changes when downsizing the facility from 50 tpd with respect to power requirements for the *process*, these numbers are the same as in Table 8 whereas those for the auxiliaries and thus for the *plant* are slightly higher.

Table 9: Specific electricity consumption at full and part load operation for a 40 tpd plant.

	Unit	Plant Capacity: 40 tpd			
Operating load factor		**100%**	**75%**	**50%**	**25%**
Total liquefaction *process*	MWh_{el} / t LH_2	6.41	6.78	7.30	9.40
Auxiliaries	MWh_{el} / t LH_2	0.37	0.42	0.53	0.87
Total liquefaction *plant*	MWh_{el} / t LH_2	6.78	7.21	7.83	10.27

Table 10 studies the effect of feed hydrogen pressures of 40 and 80 bar as well as utilising cold energy from LNG re-gasification with respect to specific electricity consumptions, compared with the standard case. These alternative cases are sorted with respect to their performance.

Table 10: Specific electricity requirement of the liquefaction *plant* at higher feed pressure and utilisation of external cooling energy. Details for the standard case can be found in Table 8.

	Unit	Plant Capacity: 50 tpd			
Operating load factor		**100%**	**75%**	**50%**	**25%**
Standard case	MWh_{el} / t LH_2	6.76	7.18	7.80	10.20
40 bar feed pressure	MWh_{el} / t LH_2	6.38	6.79	7.40	9.78
LNG pre-cooling	MWh_{el} / t LH_2	6.13	6.55	7.16	9.56
80 bar feed pressure	MWh_{el} / t LH_2	6.00	6.40	7.01	9.37

- When a feed compressor is not required because hydrogen is available at 80 bar, 0.74 MWh_{el}/t LH_2 can be saved, reducing the power consumption of the *plant* to just above 6 MWh_{el}/t LH_2. Hydrogen at 80 bar could be provided, for example, by high-pressure electrolysers that are expected to come on the market in the future.
- When cold from LNG re-gasification can be utilised (in the context of generating hydrogen from natural gas by methane steam reforming), this will reduce the specific electricity consumption of the *plant* by about 0.62 kWh_{el}/kg LH_2 to around 6.13 kWh_{el}/kg LH_2.

In order to further reduce electricity consumption, a combination of both options would be desirable, of course. However, steam reformers operate at only 20 – 30 bar.

5.2 Primary Energy Input and Greenhouse Gas Emissions

Based on the standard case and full load operation of a 50 tpd plant, Table 11 shows the specific depletable PE input that is required to liquefy one tonne of hydrogen in different settings and the associated GHG emissions. It demonstrates that the location of the plant is very important since these results are strongly influenced by the actual sources of electricity used, which are assumed to be from the respective national grids. Obviously, the primary energy mixes for producing electricity vary significantly[5].

Since the figures in Table 11 need to be considered as estimates, the significant differences between possible sites for a plant (country or region) should be noted rather than the absolute values.

- For example, the PE mix for producing electricity in Norway is largely based on hydro. Therefore, the resulting burden related to these two impact categories is low, in particular compared to Australia with a large share of brown coal power plants.
- Regarding Germany, the share of renewable energy in electricity generation has increased from 16.4% in 2009 to 22.9% in 2012. Therefore, the specific PE input and GHG emissions related to operating a liquefaction plant would be lower today and will be even lower when a large-scale plant based on the Preferred Process becomes operational.
- It is sometimes argued, however, that the European electricity grid is integrated so closely that it is advisable to refer to EU averages rather than national figures. Comparing the 2009 and 2030 figures for EU-27 in Table 11 establishes a reduction of PE input by about 30% and of GHG emissions by about 20%.

[5] The impact of water provision on PE depletion and GHG emissions is minor, as mentioned earlier, and therefore not discussed here.
In addition, since no particular source of hydrogen is considered in the context of this report, an additional burden in terms of PE depletion and GHG emissions because of hydrogen losses (see previous footnote) is not taken into account.

Table 11: Primary energy input and greenhouse gas emissions related to the standard case (50 tpd plant operating at full load) in various settings.

Impact Category	Unit	2009				2009	2030
		Norway	Germany	United Kingdom	Australia	EU-27	
Specific depletable PE input	MWh / t LH_2	0.49	17.32	18.34	22.39	16.85	11.57
Specific total GHG emissions	kg eq. CO_2 / t LH_2	99	3,572	3,597	6,737	2,442	1,958

5.3 Specific Internal Costs

Table 12 exemplifies the contributions to the specific internal costs for the standard case.

With assumed power costs of 100 €/MWh_{el}, (see Table 7), the total internal costs of hydrogen liquefaction amount to about 1.72 €/kg LH_2. When the power costs are halved, 1.38 €/kg LH_2 follow. For comparison, the costs of hydrogen generation from large-scale steam methane reforming are currently 1.00 – 1.50 €/kg (Ref. 17).

Table 12: Specific internal costs associated with the standard case.

Cost Factor	Unit	Costs	Unit	Specific costs	Share in costs
Annuity	million € / a	12.33	€ / kg LH_2	0.74	43%
Fixed O&M costs	million € / a	4.20	€ / kg LH_2	0.25	15%
Variable costs - Electricity - Water - Hydrogen	million € / a	 11.27 0.55 0.24	€ / kg LH_2	 0.68 0.03 0.01	 39% 2% 1%
Total costs	million € / a	28.60			
Total specific costs			€ / kg LH_2	1.72	
			€ cent / kWh LH_2 (LHV)	0.05	

Electricity and capital investment play major roles with respect to costs of hydrogen liquefaction plants. Concerning the former, on-site power generation could be an option, given the high load factor. This would save grid fees and de-couple GHG emissions from the national or EU-mix.

6 Conclusions

The outcomes from the IDEALHY project appear to revise the notion that the liquefaction of hydrogen is necessarily inefficient and costly; a promising technical concept has been developed which is economically feasible. The crucial next step is raising support for a demonstration plant, along with working with manufacturers to ensure that key components are improved.

The economic competitiveness of highly efficient large-scale hydrogen liquefaction and its overall benefits with respect to PE input and GHG emissions will depend on the results of comparison with other pathways for road fuel production, delivery and use, which are currently in progress (see the “Techno-Economic Analysis and Comparison Report” mentioned in section 1.5 \r \h 1.5).

Acknowledgements

The research leading to these results has received funding from the European Union’s Seventh Framework Programme (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant agreement n° 278177.

The authors would like to thank the IDEALHY partners for providing information for the LCEA and for many fruitful discussions. Special thanks go to Nigel Mortimer from North Energy Associates Ltd. and Hans Quack from Technische Universität Dresden for their intense support.

References

1. "Baseline Results Report", N. D. Mortimer, O. Mwabonje and J. H. R. Rix, Deliverable 3.13 of the IDEALHY Project, May 2012, www.idealhy.eu.

2. "Liquid Hydrogen Pathway Report", K. Stolzenburg and R. Mubbala, Deliverable 3.14 of the IDEALHY Project, June 2012, www.idealhy.eu.

3. "Hydrogen Production and Utilisation Report", N. D. Mortimer, C. Hatto, O. Mwabonje and J. H. R. Rix, Deliverable 3.15 of the IDEALHY Project, November 2013, www.idealhy.eu.

4. "Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC" European Commission, Brussels, Belgium, 5 June 2009.

5. "European Life Cycle Assessment Platform" Institute for the Environment and Sustainability, European Commission Joint Research Centre, Ispra, Italy, http://lct.jrc.ec.europa.eu/assessment, accessed 30 March 2012.

6. "International Reference Life Cycle Data System (ILCD) Handbook – General Guide for Life Cycle Assessment – Provisions and Action Steps" First Edition, EUR24378, Luxembourg, March 2010.

7. "International Reference Life Cycle Data System (ILCD) Handbook – General Guide for Life Cycle Assessment – Detailed Guidance" First Edition, EUR24708, Luxembourg, March 2010.

8. "International Reference Life Cycle Data System (ILCD) Handbook – Specific Guide for Life Cycle Inventory Data Sets" First Edition, EUR24709, Luxembourg, March 2010.

9. "FC-HyGuide: Guidance Document for Performing LCAs on Fuel Cells and Hydrogen Technologies – Guidance Document for Performing LCA on Hydrogen Production Systems" by A. Lozanovski, O. Schuller and M. Faltenbacher, 2011-09-30 Final, 30 September 2011.

10. "FC-HyGuide: Guidance Document for Performing LCAs on Fuel Cells and Hydrogen Technologies – Critical Review Statement and Response Summary – Review According to the ILCD-Handbook and ISO 14040 and ISO 14044" by P. Fullana i Palmer, M. Finkbeiner and M. Bode, 2011-09-30 Final, 30 September 2011.

11. "Climate Change 2001: The Scientific Basis; Contribution of Working Group 1 to the Third Assessment Report of the IPCC" Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom, 2001, www.ipcc.ch/ipccreports/assessment-reports.php.

12. "Climate Change 2007: Synthesis Report: Fourth Assessment Report", Intergovernmental Panel on Climate Change, 2007, www.ipcc.ch/pdf/assessment-report/ar4/ar-syn.pdf.

13. "Schedule for demonstration plant including options for location", D. Berstad, L. Decker, A. Elliott, H. Quack, H. T. Walnum and P. Nekså. Deliverable 5.22 of the IDEALHY Project, July 2013, www.idealhy.eu.

14. Approximate analysis of electricity generation statistics based on: International Energy Agency, Energy Balances, Paris, France; e.g. link for Germany: http://www.iea.org/statistics/ statisticssearch/report/?country=NORWAY &product=balances&year=2009, last access 23 September 2013.

15. "Global Emissions Model for Integrated Systems: GEMIS Version 4.81", Internationales Institut für Nachhaltigkeitsanalysen und -Strategien, Darmstadt, Germany, 2013, www.iinas.org.

16. "Report on efficiency and cost calculations", D. Berstad, L. Decker, A. Elliott, P. Nekså, H. Quack and H. T. Walnum. Deliverable 2.7 of the IDEALHY Project, November 2013, www.idealhy.eu.

17. References quoted in: "Kosten der Wasserstoffbereitstellung in Versorgungssystemen auf Basis erneuerbarer Energien", T. Grube, B. Höhlein, in: "Wasserstoff und Brennstoffzelle – Technologien und Marktperspektiven", J. Töpler, J. Lehmann (Editors), Springer, Berlin, Oktober 2013.

18. "Großtechnische Wasserstoffverflüssigung in Leuna", M. Bracha, L. Decker, Deutsche Kälte-Klima-Tagung, 2008.