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

Fuel Cells and Hydrogen Joint Undertaking (FCH JU)

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Publishable summary

In work package 1 of the IDEALHY project, existing and proposed processes for hydrogen liquefaction at large scale (>50 tonnes per day) were benchmarked via detailed simulations. The most promising concept was developed further in work package 2 (WP2), working within the same boundary conditions but optimising the process for the lowest possible energy consumption. The investment cost was also a consideration, meaning that the amount and complexity of equipment was kept to a minimum where efficiency would not be compromised.

In parallel with the WP2 work, discussions were held with equipment manufacturers (OEMs) relating to component availability. Since some items will be required at an unprecedentedly large scale, and some turbomachinery with unusually high circumferential speed, close liaison with OEMs is crucial if the right equipment is to be available for plant construction at a later date.

This report summarises the liquefaction process selected and developed in WP1 and WP2, which uses two successive Brayton cycles with a common compressor train. The refrigerant is a helium/neon mixture selected for optimum compressibility and refrigeration efficiency. The pre-cooling to 130K uses a mixed refrigerant, and this MR cycle provides additional cooling needed for the two Brayton cycles. The flash gas is re-liquefied in a final stage via reheating, compression (piston compressors), cooling and throttling back.

The rest of this report describes how this technology could be demonstrated and at what scale; the scale selected for a demonstration plant is 40 tonnes per day (tpd). This is a compromise, in that a minimum size is required in order effectively to test all the novel technical aspects, while an upper limit to the capacity is imposed by the need to develop the infrastructure and market for the liquid hydrogen produced. At the same time close involvement of the OEMs is essential to ensure that the novel components required are designed, tested and brought to market within the appropriate timescale. This is a non-negligible issue given the conservatism of the manufacturers and the lead time for component development, and the selected approach bears this in mind.

It is proposed that before a complete plant is assembled, three (or more) separate test stands will be assembled and used by (consortia of) equipment manufacturers in order to test different sections of the liquefaction process, and draft outlines of these test stands are given. In the short term (three to four years) large sections of the liquefaction process could then be tested in a research (rather than commercial) environment, while plans for a full-scale (40 tpd) demonstration plant are made. This approach would substantially de-risk a commercial demonstration plant for both equipment manufacturers and plant operators, and need not cause excessive costs.

Possible locations for a 40 tpd demonstration plant are assessed considering the current absence of a bulk market for (liquid) hydrogen, the development needed before a large liquefaction plant can be commercially viable and the location of parties potentially interested in such a collaboration. The conclusion is that Norway presents the most advantages as a location for a demonstration plant; the reasoning behind this is outlined and some possible sites in Norway discussed.

Key words

Hydrogen Liquefaction, Brayton Cycle, Mixed Refrigerant Cycle, hydrogen sources, liquid hydrogen market, test of components

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1 Introduction

The aim of the IDEALHY project is to advance the technology for the liquefaction of hydrogen in large plants and especially to reduce the electric power consumption.

In WP1 and WP2 several processes which had been proposed or realised in the past were collected and compared using identical boundary conditions and component efficiencies. From this a preferred process was selected which promises a power consumption of less than 6.3 kWh/kg, compared with about 12 kWh/kg for previously built plants.

One aspect in the selection of the preferred process was the availability of components with which the process could be realised. For some of these components the IDEALHY requirements are new in some respect, implying that a certain amount of development work will be required from component manufacturers. All the component suppliers contacted have agreed, however, that the duty (equipment size) anticipated for a larger plant will be feasible in the near future.

The preferred process has quite a number of internal degrees of freedom which can be adjusted in order to obtain an overall optimization. The optimum choice of parameters will depend mainly on the individual efficiencies of the components. For this reason, a complete optimization can only be performed after the indicated additional development work has been carried out.

For a first specification of the components required, preliminary choices have been made for the principal free process parameters. The power consumption presented is based on these choices, although it is expected that when component development and optimisation has progressed further, the resulting power consumption will be even lower.

In Chapter 2 of this report the preferred process is described and the result of simulation calculations are presented.

Chapter 3 contains proposals for test plants, in which component manufacturers can demonstrate the results of their development work.

Chapter 4 describes a full scale demonstration plant, in which the interplay between the components can be demonstrated. This could already be used for an efficient commercial liquefaction of hydrogen, even if operating at extreme part load capacity.

Possible locations for such a demonstration plant are discussed in chapters 5 and 6.

2 Description of the final process

Based on the process design and optimisation performed in WP1 and WP2, the main process design and parameters have been defined. The process flow diagram is shown in Figure 1. The process can be split into four stages: pre-compression and chilling, pre-cooling with a mixed refrigerant (MR), cryogenic cooling with Brayton cycles and a final expansion and liquefaction stage. The pre-cooling and cryogenic cooling down to 80 K is located in one cold box, while the last cryogenic cooling stage is located in a separate cold box. Both cold boxes are vacuum insulated.

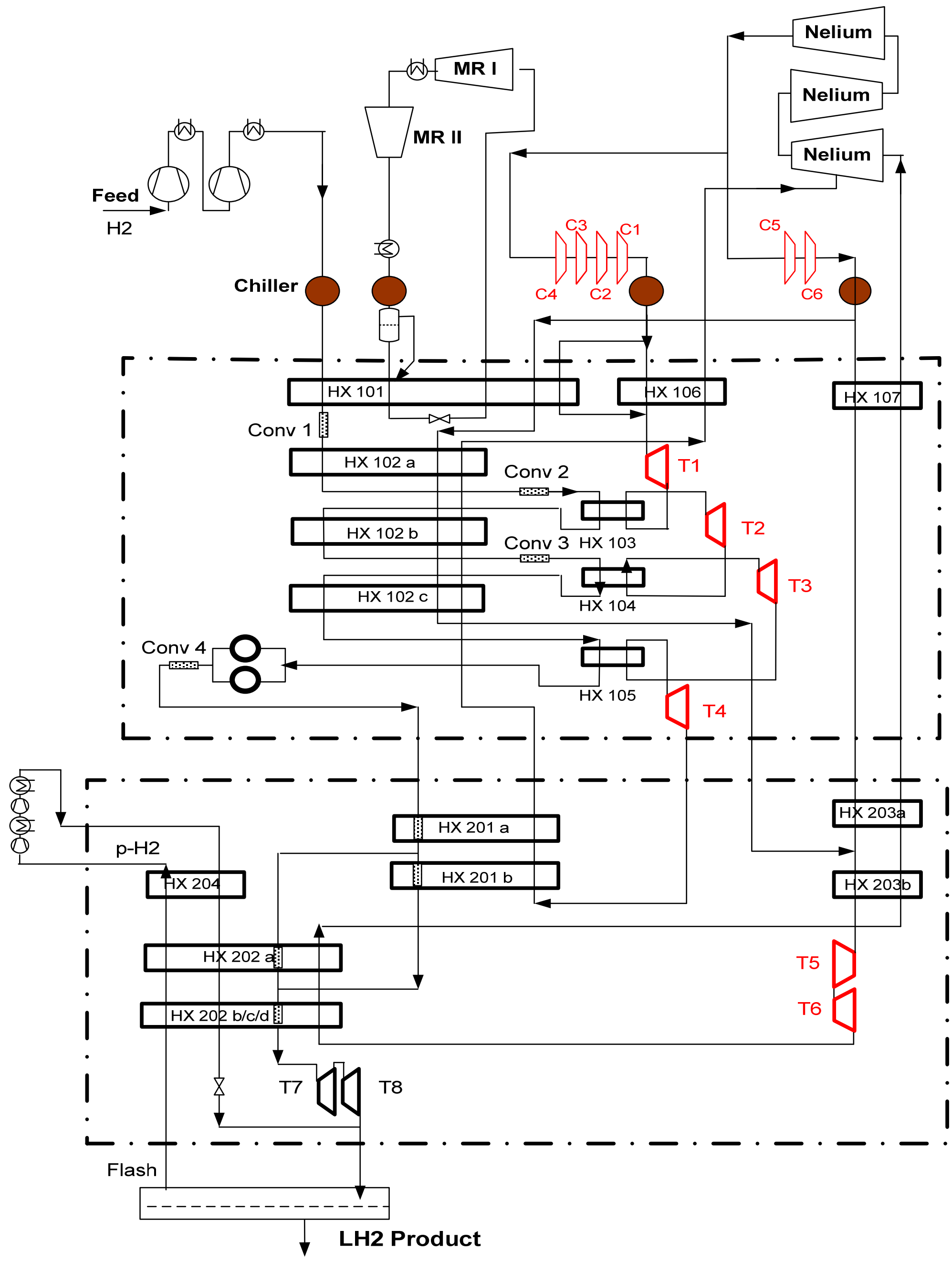


Figure 1: Process flow diagram for the IDEALHY liquefaction process

2.1 Pre-compression and chilling

The hydrogen feed enters the liquefaction process at a pressure of 20 bar following purification using pressure-swing adsorption (PSA), with a pressure of 20 bar, and is compressed with a two stage piston compressor up to 82 bar. All gas streams entering the cold box are pre-chilled with a single component refrigerator down to 279 K.

2.2 Pre-cooling

The feed is then further pre-cooled down to 130 K with a single MR cycle. The 130 K temperature split was chosen following an energy optimization procedure described in D2.7. The MR process also provides additional cooling needed for the two Brayton cycles, and the process details are shown in Table 1.

Cooling temperature [K]	130
Inlet temperature [K]	279
Chiller inlet condition	two phase
MR Pressure [bar]	
Low pressure	2.8
High pressure	26.6
Pressure ratio	9.5
Flow Rate	
Molar flow [kmol/h]	705.6
Mass flow [kg/s]	6.3
Composition [%mol]	
Nitrogen	4.8 %
Methane	33.1 %
Ethane	35.4 %
Propane	4.5 %
n-Butane	22.2 %
Shaft power [kW]	
Two-stage (80 %)[a]	1346.2
Chiller	
COP	5.5
MR duty [kW]	584.8
H_2 feed duty [kW]	159.3
Nelium duty [kW]	20.8
Power [kW]	139.1
Total power [kW]	1485.3

Table 1: Details of the MR pre-cooling process ([a] Isentropic stage efficiency)

A challenge of the MR cycle is the distribution of the two-phase mixed refrigerant in the heat exchangers. This requires sophisticated header design, and it is desirable to avoid two-phase distribution when possible.

The following arrangement for the combined water cooler and chiller cooler and cryogenic cold box is proposed, as shown in Figure 2; the water cooler and the chiller cooler are vertical tube and shell exchangers with the MR high pressure stream inside the tubes. Both exchangers have exactly the same number of tubes with exactly the same tube pattern. The two exchangers are stacked directly above each other without refrigerant collectors, so that the two-phase fluid flows directly from each upper tube into the corresponding lower tube.

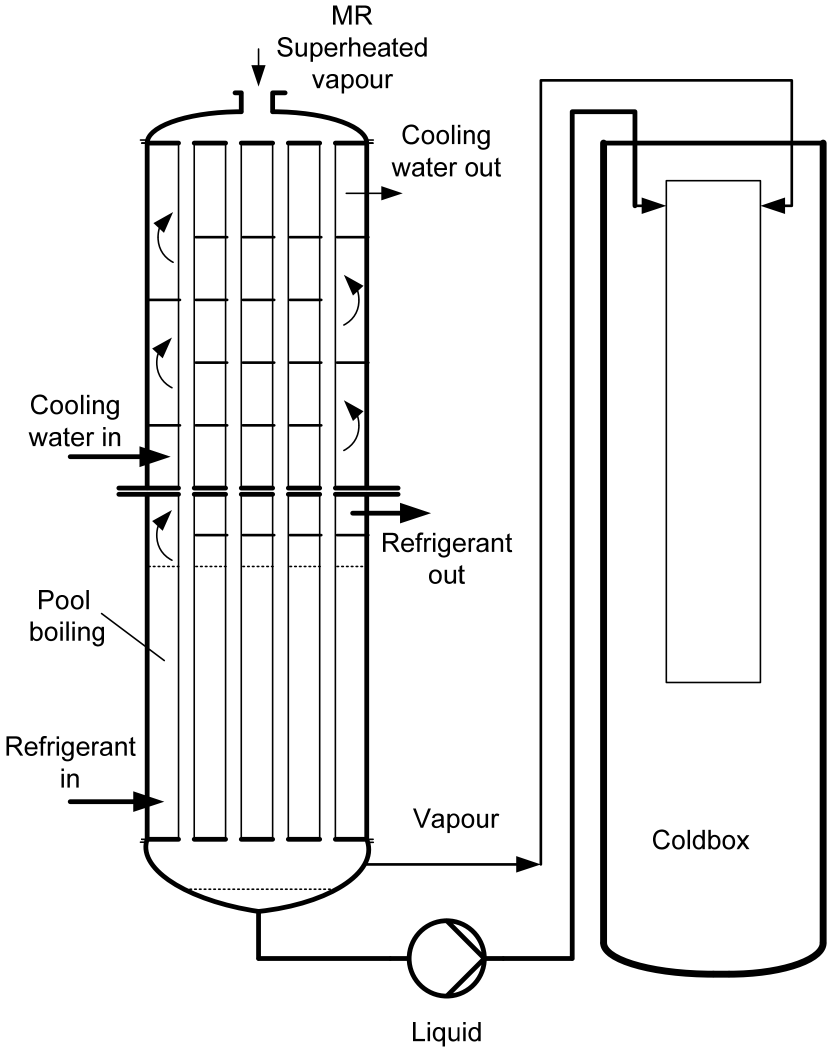


Figure 2: Proposed arrangement for the water cooler/chiller and cold box

At the bottom of the chiller, MR liquid condensed in the heat exchanger and MR vapour are separated and guided individually into the cold box and the MR plate-fin heat exchanger. The vapour flows by itself, but for the liquid a pump is needed.

2.3 Brayton refrigerator

The cooling of the hydrogen feed down to the final expansion and liquefaction stage is performed by two Brayton cycles with a common compression train. A 75%/25% (mol basis) mixture of helium and neon ('Nelium') was chosen as refrigerant to give the optimum trade-off between refrigeration efficiency and compressibility.

An option for the Nelium compression train (Figure 3) consists of three hermetically sealed compressors with two intercooled stages each, with a total power consumption of 10.1 MW.

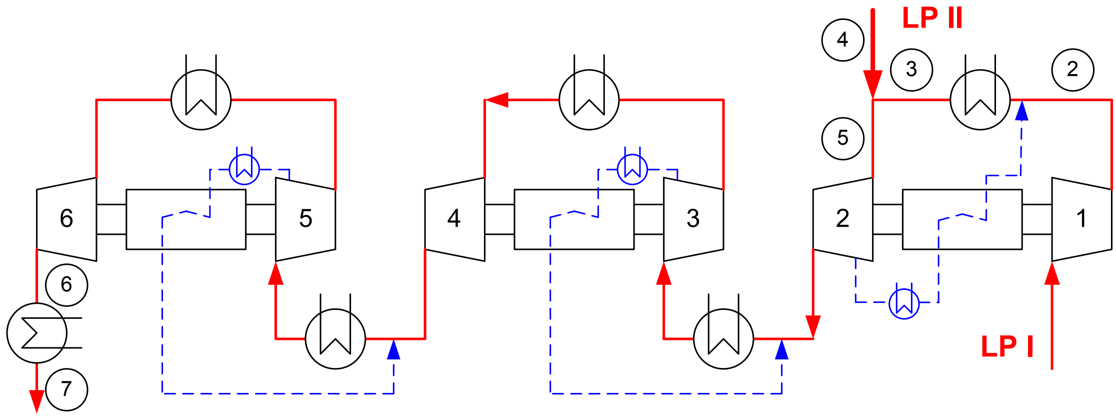


Figure 3: Nelium compression train

The high temperature Brayton cycle consists of four compressor/expander stages, and cools the hydrogen feed down to 70 K, with four adiabatic converters down to 85 K and heat exchanger integrated catalyst from there on.

The low temperature Brayton cycle has two compressor/expander stages, and cools the feed further down to the final expansion at 26.8 K.

The details of the compressor/expander units in the two Brayton cycles are shown in Table 2.

	T1	**T2**	**T3**	**T4**	**T5**	**T6**
P_{in} (MPa)	6.34	4.59	2.97	1.21	4.90	1.67
T_{in} (K)	131.9	120.1	105.9	84.9	68.0	47.9
P_{out} (MPa)	4.61	2.99	1.23	0.38	1.67	0.27
T_{out} (K)	119.2	104.6	79.8	58.1	47.9	26.3
Efficiency	0.81	82	0.83	0.85	0.83	0.85
Power (kW)	116.1	138.7	229.6	231.9	259.7	267.2
	C1	**C2**	**C3**	**C4**	**C5**	**C6**
Pin (MPa)	5.93	5.38	4.57	5.88	4.41	3.88
Tin (K)	298	298	298	298	298	298
Pout (MPa)	6.44	5.95	5.40	4.59	5.00	4.43
Tout (K)	310.7	310.2	323.8	323.9	317.2	318.1
Efficiency	0.79	0.79	0.80	0.80	0.80	0.81
Power (kW)	112.4	137.4	227.0	227.9	254.9	265.4

Table 2: Detail of Brayton cycle expander/compressor units

2.4 The final expansion and liquefaction

From 80 bar and 26.8 K the hydrogen feed is expanded down to 2.1 bar in a two-stage gas bearing turbo expander (Figure 4) . The outlet vapour quality is about 0.05 as the feed enters a flash tank. The liquid outlet from the flash tank is lead to the liquid hydrogen storage tanks.

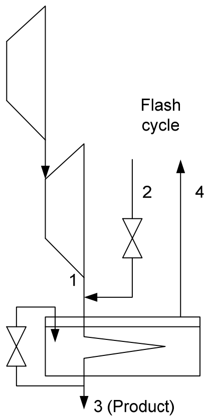


Figure 4: Final expansion and liquefaction stage.

2.5 The flash gas cycle

Due to the limited minimum temperature of the Nelium cycle, some flash gas is produced in the final expansion of the feed. This flash gas must be re-liquefied, and in this sub-process it is reheated up to ambient temperature and subsequently compressed to 7.4 bar in a two stage piston compressor. The flash gas is then cooled back down to 26.8 K in parts of the heat exchanger network, and throttled back to low pressure and into the feed before entering the flash tank with the main stream of liquefied hydrogen.

3 Test plants

3.1 Components requiring further development work

As mentioned in the introduction, the task of the IDEALHY project was to identify the best process and the components needed to build a high-efficiency large-scale plant for the liquefaction of hydrogen. This plant was to be of low investment cost, easy to operate, safe and with a positive cash flow over its life cycle. The project participants are convinced that all of these objectives have been reached in the technical solution identified in section 2 above.

It should be noted that as far as technology goes, the changes proposed are not particularly revolutionary, although for a number of components the limits of present-day technology have been stretched. To make this total plant a reality, some R&D will be required from component suppliers, but this will be more 'D' than 'R'.

The liquefaction flow diagram is shown in Figure 5, highlighting the components for which development work is needed and for which a demonstration plant would be of particular value. The table below gives further information about these areas, identifying the limits of current knowledge and drawing attention to the aspects which need further development.

A	Plate-fin heat exchangers have been built for a pressure level of 8 MPa. Catalyst has been filled into heat exchanger channels at lower pressures, but never filled into 8 MPa exchangers. The absolute size of heat exchangers with 8 MPa channels is limited.
B	Gas bearing turbines have been used for hydrogen cryogenic expansion but only for pressures below 2.5 MPa. Here they are needed for an inlet pressure of 8 MPa.
C	The piston compressor for the flash gas cycle has many references. It has, however, never before been a requirement that no re-conversion from para- to ortho-hydrogen occur during this compression process.
D	Mixed refrigerant cycles have been used for very large plants and for small laboratory systems. But only very few companies have experience for mid-size systems with multi-channel plate-fin heat exchangers.
E	Coupled expanders and compressors with magnetic bearings have been used for air on perlite coldboxes. Here they are needed for vacuum insulated coldboxes and at higher speeds than ever before. In the flow diagram the machine C1/T1 has been marked, as the speed increase required for this pair is larger than for the other machines.
F	Hermetic turbo compressors with magnetic bearings and integrated motors have been built for heavier gases with lower circumferential speed. Here also higher circumferential speeds are needed than ever before. The last stage compressor has been marked, as the speed increase demanded for this stage is higher than for the other stages.

Table 3: Description of process areas needing development work

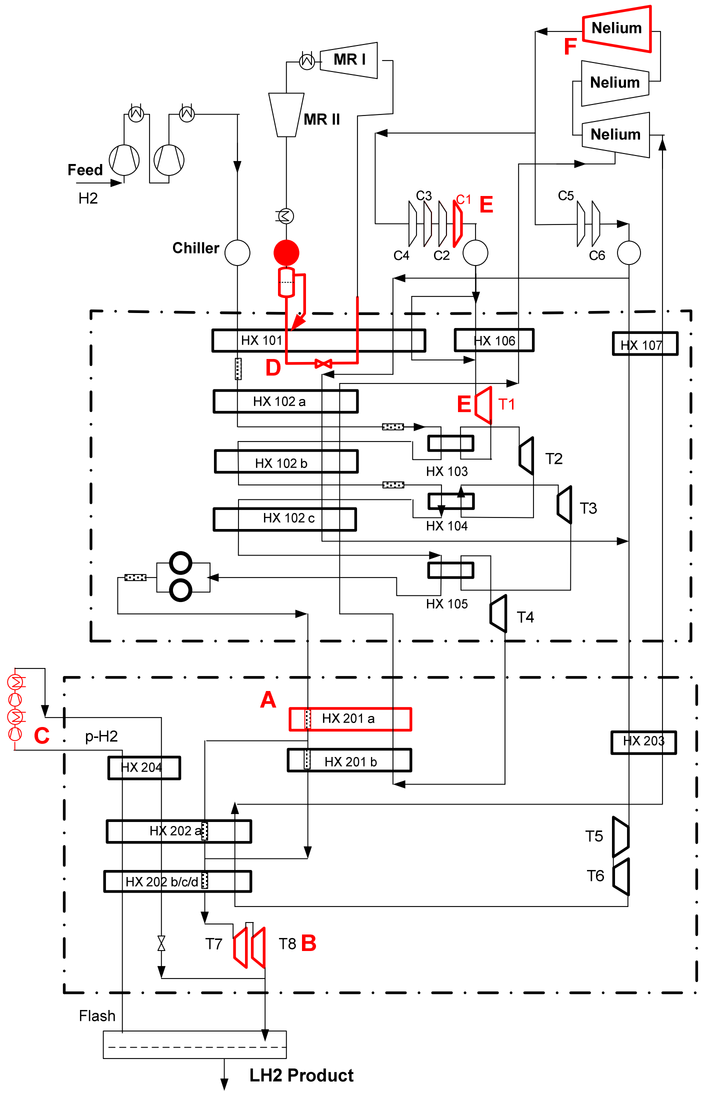


Figure 5: IDEALHY process flow scheme, highlighting components which need further development

The need for R&D and demonstration of reliability depends on the size of the liquefier. This dependence is different for different components, as illustrated in the schematic diagram overleaf.

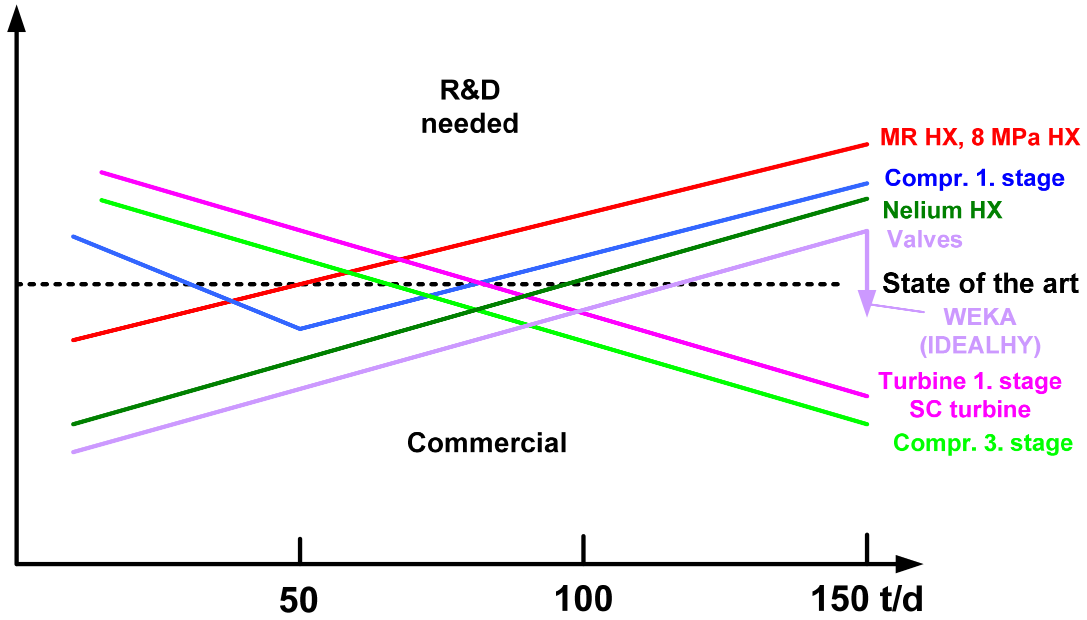


Figure 6: Graphical illustration of the development trajectory for different parts of the liquefaction process

The abscissa shows the capacity of the plant. In the IDEALHY project we have concentrated on the plant with a capacity of 50 tpd, but we have kept in mind that smaller and larger plants may be needed. The vertical axis is divided by the state-of-the-art line into two areas:

- Below the line: the “commercial” area, where products can be specified and purchased from several suppliers.
- Above the line: the upper area, i.e. the “R&D” area, shows, where little experience is available, and where development work and some kind of demonstration plant would be extremely desirable.

There seem to be two groups of components: those which need development for larger capacity plants, and those which need development for lower capacity plants. It is unsurprising that the smallest distances from the state-of-the-art are in the 50 tpd capacity range, as this was the target range of the IDEALHY project.

There are three components for which at 50 tpd we have stretched the state-of-the-art: the third stage of the main Nelium compressor, the first stage of the expansion turbine and the gas bearing supercritical (SC) turbine. It is interesting to note that these components have far fewer problems in higher capacity plants.

The other group of components – those already commercially available – comprises the cryogenic valves, the Nelium heat exchanger, the first stage of the Nelium compressor, the MR heat exchanger and the 8 MPa heat exchanger.

Concerning the cryogenic valves the development work by WEKA within the IDEALHY project has resulted in the fact that even for plants with 150 tpd capacity, such valves can now be considered as “commercial”. For the other four components the main question is now what their size limit is, i.e. at what capacity should the number of units be increased rather than their individual size.

The purpose of development work, test plants and/or a non-commercial demonstration plant is to move all lines downwards relative to the state-of-the-art, into the commercial zone. When building large-scale commercial hydrogen liquefiers, only components whose status is below the state-of-the-art line should be used.

It should be remembered that there are a few components or partial systems, whose development status is not capacity-related, e.g. the choice of the best catalyst and also the blocked re-conversion in the flash gas cycle

3.2 Liquefaction capacity of demonstration plant

Presently about one commercial hydrogen liquefier is built per year worldwide with a capacity of 5-10 tpd. Plants with a capacity up to about 20 tpd will probably be built in the foreseeable future, and will be based on the technology currently available. The inherent conservatism of customers (and/or OEMs) relating to such plants encourages this use of established and proven technology. Table 4 shows some aspects of the liquefaction process and describes both the 'conventional' approach and the method used by IDEALHY.

	Currently used technology	**IDEALHY technology**
Hydrogen pressure in process	2 MPa	8 MPa
Precooling	Open LN_2	Mixed refrigerant closed loop
Brayton cycle refrigerant	Hydrogen	Nelium
Brayton cycle compressor	Dry piston compressor or oil lubricated screw compressor	Turbo compressor
Final expansion	Throttle valve or ejector	Gas bearing turbines

Table 4: Comparison between IDEALHY and existing processes

The technology proposed in the IDEALHY project is intended for larger plants, where power efficiency becomes more and more important. It should be usable in plants up to 100 or even 150 tpd. For higher capacities one will probably opt for multiple plants.

3.3 Involvement of component manufacturers in demonstration plant

To make good progress in bringing all needed components into the "commercial" status one needs the active participation of qualified component manufacturers. Not many of these component suppliers share the conviction that such plants – and thus their components – will be needed in the near future.

To convince them to cooperate in an eventual demonstration plant, a first stage of separate test stands is proposed, which would allow a combination carrot-and-stick approach in dealings with OEMs:

- Suppliers would benefit from (a) test facility/facilities jointly funded by a partnership / consortium, in which they could develop their components and demonstrate their capabilities without the immediate threat of penalties. Probably few of them could alone afford a test facility of this capacity.

- Competition would be encouraged by building the test stands (or the demonstration plant) in such a way that components of different suppliers could be installed side by side, so that a direct comparison would be possible.

An important difference between "test facility" and "demonstration plant" is that for a test stand one would require from manufacturers machines only "as good as possible", i.e. without performance guarantees and penalties. This means that the manufacturers would not have to include technical and commercial margins in their proposals for participation in the test stands. It is expected that this test stand stage would last approximately four years, during which time manufacturers would in parallel have the chance to progress with commercialisation of the components under test.

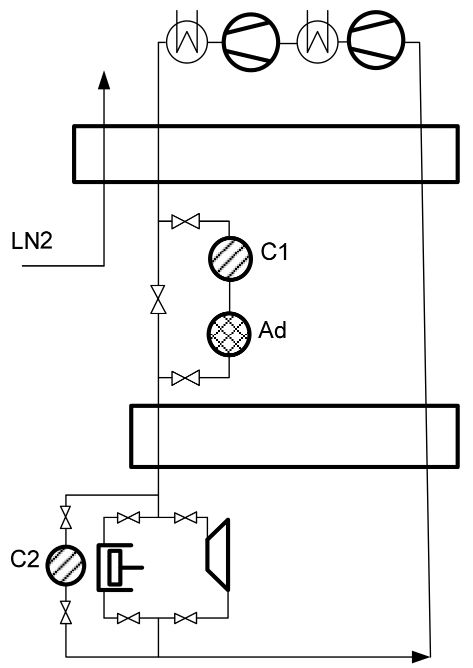
3.4 Proposal for test stands

The demonstration of the novel IDEALHY hydrogen liquefaction technology can be divided into three different sections. These alternatives are presented below.

	Test Stand 1	Test Stand 2	Test Stand 3
To be tested	Feed compressor Catalyst Poisoning of catalyst Turbine in sc region Cryogenic valves Reconversion in flash cycle	MR cycle Distribution of two phases in HX Part load operation Temperature dependence	Main turbocompressor Cryogenic expander/compressor

3.4.1 Hydrogen cycle test stand

Test stand 1 would allow testing of components of the hydrogen feed stream and the flash gas cycle.



Two-stage piston compressor (same as in full plant)

Possibility to inject specified amounts of impurities (e.g. N2, A, CO, CH4)

An LN2 precooled heat exchanger

An adiabatic op-converter C1

An adsorber

A gas bearing turbine, which is identical to turbine T7 of the full plant

Possibility to test a piston expander as alternative

A second adiabatic converter, which allows the whole cycle to be brought near to 99 % para-hydrogen

Reliability of 8 MPa cryogenic valves

Figure 7: Process sketch and outline of possible test stand 1

3.4.1.1 Topics investigated in test stand 1

- Performance and reliability of the feed gas compressor
- Heat transfer of the 8 MPa fins of the heat exchanger
- NCU (number of conversion units) of the adiabatic converter for different catalysts
- Drop in performance of the converter in function of the adsorbed impurities
- Holding time of the adsorber at different operating temperatures
- Reliability and performance of the gas bearing turbine
- Reliability and performance of a piston expander as alternative
- The flash cycle mode in which the converter C1 is bypassed

3.4.2 The mixed refrigerant test stand

Test stand 2 would allow testing of components in the mixed refrigerant cycle. It would consist of the original MR loop with compressor, coolers, heat exchanger and throttle valve. The hydrogen and Nelium streams will be replaced by a nitrogen cycle, which carries the refrigeration produced out of the system.

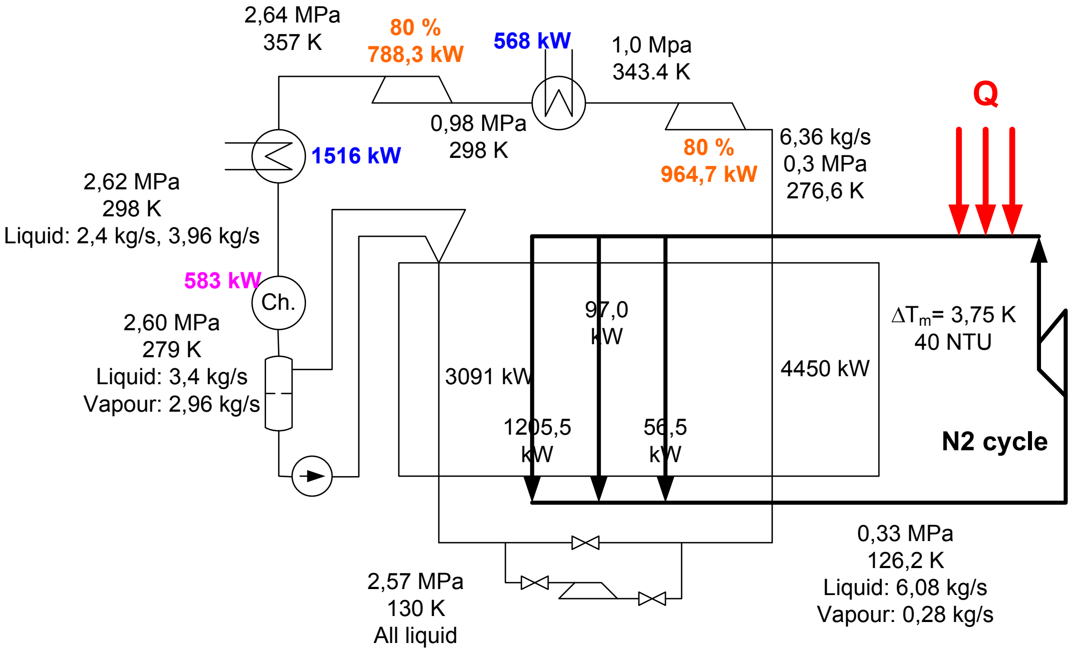


Figure 8: Process sketch and outline of possible test stand 2. NTU = Net Transfer Units, a characteristic of heat exchangers.

3.4.2.1 Topics investigated in test stand 2

- Reliability and performance of MR compressor
- Performance of plate-fin heat exchanger (avoidance of mal-distribution of two-phase flow
- Variation of MR composition, pressure levels, low temperature level
- Part load operation e.g. by variation of refrigerant composition
- Expander as alternative to throttle valve

3.4.3 Brayton cycle test stand

Test stand 3 allows the test of components of the Brayton cycle. It would contain the third stage of the main turbocompressor, compressing Nelium from 2 to 4 MPa. It would further include two expander/compressors from two different manufacturers, a plate fin heat exchanger and a nitrogen cycle to bring the refrigeration to the outside.

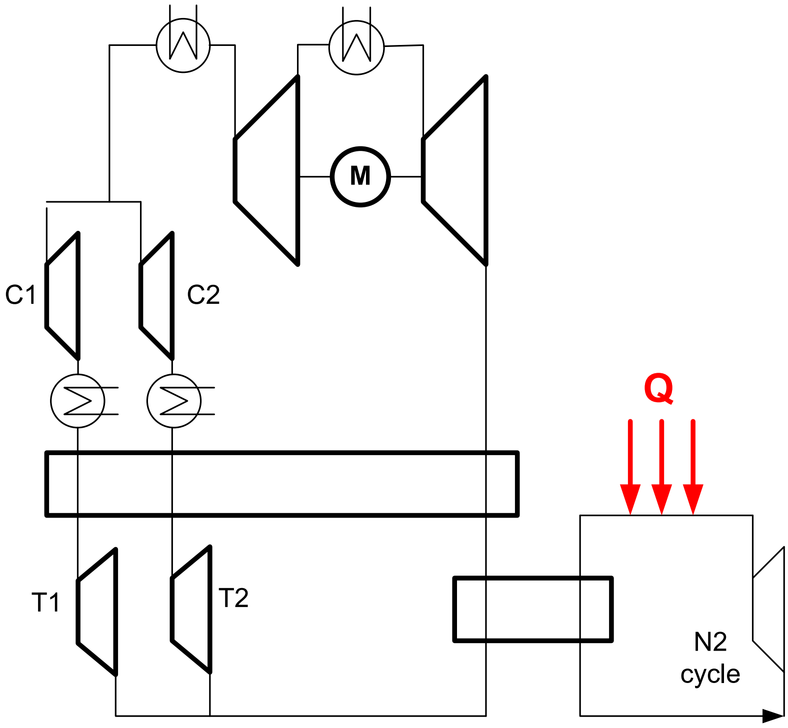


Figure 9: Process sketch and outline of possible test stand 3

3.4.3.1 Topics investigated in test stand 3

- Reliability and performance of the main compressor with magnetic bearings: A speed increase of at least 20 % above present state-of-the-art is desired
- Reliability and performance of the turbine-compressors with magnetic bearings: A speed increase of at least 20 % above present state-of-the-art is desired

3.4.4 Rationale behind test stand approach

Inclusion of a test stand stage would substantially reduce the (technical and commercial) risk involved for all participants in the eventual construction of an actual demonstration plant. This de-risking will reduce reluctance of potential participants in a demo plant initiative and increase the likelihood of successful plant construction.

This approach also brings further advantages, some of which are given below.

- Different companies can participate in the different test stands, which can also run on different schedules and carry out a wide range of tests.

- Component manufacturers can contribute (financially and/or in-kind) to the test stands, reducing the cost involved in this stage.
- Competing component manufacturers could be invited to participate, so that one would have competitive bids for the demo plant.
- The test programme will be efficient, as there will be less waiting for installation, repair and testing of other components. This will also give easier cost control.
- The three test stands could be located anywhere and do not all need to be at the same location.
- Following this stage, the demonstration plant could have a lower nominal capacity should this be more appropriate for the market, e.g. 40 tpd.
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3.4.5 Technology status after completion of the test plants

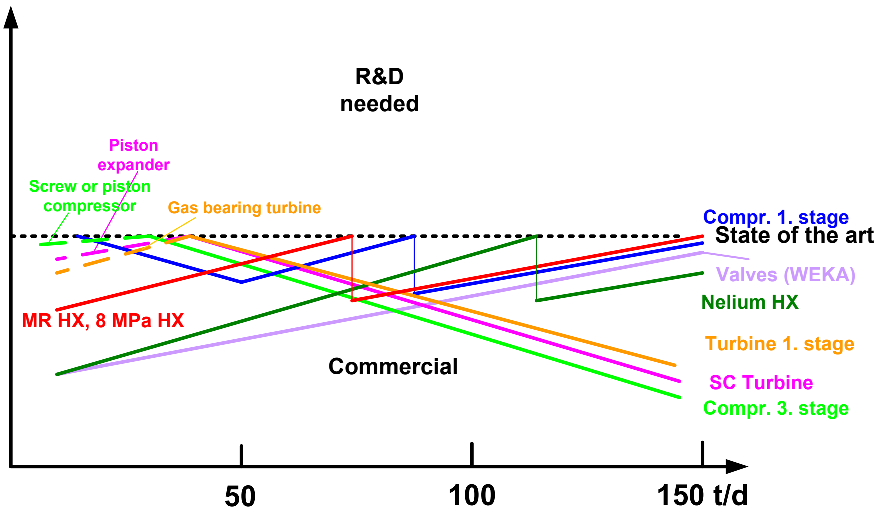

Figure 10: Graphical illustration of the development trajectory following the 'test stand' stage

The figure shows that after the successful completion of development and tests in the three test plants, the IDEALHY technology proposed will be available for commercial hydrogen liquefiers in the capacity range between 40 and 150 tpd. For some components (MR, 8 MPa heat exchanger, first stage of the Brayton cycle compressor and some Nelium heat exchangers) it will be necessary to use two units in parallel in the higher capacity plants.

Below a capacity of about 40 tpd it is necessary to replace the first Brayton expansion turbine by a gas bearing turbine, the last stage of the Brayton compressor has to be replaced by a piston or screw compressor and the SC gas bearing turbine has to be replaced by a piston expander.

4 Demonstration plant options

4.1 Non-commercial technology demonstration plant

A non-commercial demonstration plant has the advantage that component suppliers can be asked to deliver components stretching the state-of-the-art.

This would be a plant with no net output and is shown schematically in Figure 11. Cold supercritical hydrogen (about 2.1 MPa) would be taken from the outlet of expander T7. It is further cooled by the flash gas cycle and subsequently warmed up to ambient temperature and re-converted to normal hydrogen.

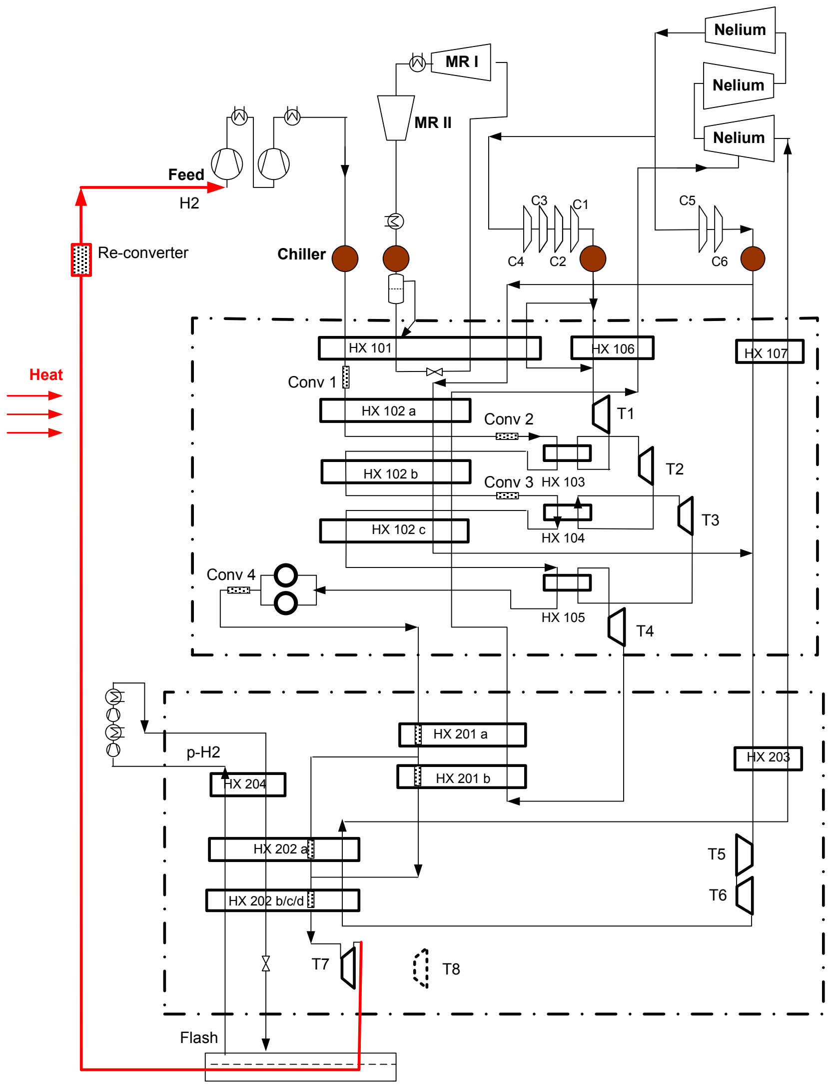

Figure 11: Process flow diagram of non-commercial demonstration plant

For this non-commercial demonstration plant one would not need:

- a source of hydrogen raw gas;
- a large liquid hydrogen storage vessel;
- customers to buy the product.

Such a technology demonstration plant could be located anywhere. The components of such a demonstration plant would have a lifetime of over 30 years, so the most sensible approach would be to install the plant at a location where commercial hydrogen liquefaction would be needed at a later stage.

4.2 A commercial hydrogen liquefaction plant

This would comprise hydrogen production, hydrogen liquefaction, liquid hydrogen storage and a means of hydrogen off-take by the customer such as a hydrogen refuelling station.

The lowest capacity, for which the IDEALHY technology would be fully usable is about 40 tpd. There is currently no market for a liquid hydrogen production rate in this order of magnitude. Such a plant would however have a lifetime of at least 30 years, during which time the market size will grow. In the meantime there is profit to be made from the excellent part-load efficiency of the proposed IDEALHY process, down to about 25 % of the nominal capacity. So if one chose a nominal capacity of 40 tpd, one can expect a very efficient operation down to about 10 tpd. As mentioned before, successful completion of the test program in the three proposed test stands is an important prerequisite for such a commercial demonstration plant.

This section further elaborates on aspects of the planning of such a demonstration plant.

4.2.1 Impact of scale on efficiency

The chosen plant size for the IDEALHY project was originally 50 tpd, because in the planning stage we were of the opinion that plants in this size range would be needed in the mid-range future. The cost of such a plant is estimated to be of the order of €100 million, meaning that its construction without a commercial goal is not justifiable. It is highly debatable, however, whether a commercial plant of that order of magnitude is necessary for LH_2 supply within the next 5 years.

If such high volumes of liquid hydrogen cannot as yet be commercially used, then a logical step would be to construct a smaller plant (e.g. 5 – 10 tpd), having identified which of the novel technical concepts developed could be of value in such a plant. In the table below the principal novel solutions identified during the IDEALHY project are listed, together with comments as to whether they could and should be demonstrated in a smaller capacity plant.

Compression of the feed to 80 bar	Suitable for 10 tpd plant
Precooling by MR cycle	Suitable for 10 tpd plant
Use of He/Ne mixture as working gas for Brayton section	Could be used in smaller capacity plant, but probably no advantage compared to pure helium or pure hydrogen
Use of turbo compressor as recycle compressor in Brayton cycle	May be possible for lowest pressure stage of Brayton cycle compression with nelium as refrigerant; for higher pressure stages piston or screw compressors would be needed. Would be associated with relatively high investment cost.
Power recovery of Brayton cycle expanders	Turbines needed for a smaller plant would have much smaller wheels and would run faster than the turbines in the 50 tpd plant. Turbines of that size with power recovery would be a development project in itself.
High pressure "wet" hydrogen expanders with gas bearings	Potentially reducible to 20 tpd. One could use a piston expander; but what would be the "demonstration"?
Catalyst in heat exchanger	Only a new type of catalyst would have a "demonstration" feature.

Table 5: Application of novel concepts at scales smaller than 50 tpd

With the IDEALHY process in a 50 tpd capacity plant the indication is that the power consumption would be about 6 kWh/kg.

- A smaller (5 – 10 tpd) plant could be realised with a power consumption of 8-9 kWh/kg (already much better than the state-of-the-art), using just compression to 80 bar, MR precooling and nelium (or helium or hydrogen) as refrigerant for the Brayton cycle.
- Using Nelium as the refrigerant for a plant size below 20 tpd would mean reverting to screw compressors / gas bearing turbines instead of turbocompressors / power recovery from turbines, and the demonstration value would be lost.
- The Brayton cycle works between (suction pressure) 2.4bar and 60bar, and the efficiency of such a 50 tpd plant would be unimpaired down as low as 25% capacity i.e. 12.5 tpd.

The main reason why the proposed IDEALHY liquefier has such a good part-load efficiency is the "unloading" feature of the Brayton cycle, which is the largest power consumer of the overall system.

"Unloading" means that the inventory of refrigerant is reduced in the cycle. At nominal capacity the main Brayton turbo compressor works between the pressures 0.27 and 4 MPa with a mass flow rate of 8.4 kg/s. If one releases 75 % of the inventory into the external gas buffer, the plant would operate between 0.068 and 1 MPa with a mass flow rate of 2.1 kg/s. All velocities in the cycle will remain constant, i.e. also the speed of all turbo compressors and all turbines.

The conclusion was that a **40 tpd** plant capable of efficient part-loading down to approximately 10 tpd would be a sound proposition. Such a plant would incorporate all the novel technical steps already listed, as the Brayton cycle has the advantage that this is possible without seriously compromising plant efficiency, as demonstrated in Table 6 below.

	50 tpd (IDEALHY)	**40 tpd 100%**	**20 tpd 50%**	**10 tpd 25%**	
Feed compressor	1520	**1216**	630	330	kW
Flash gas	100	**80**	45	30	kW
Chiller	230	**184**	92	46	kW
MR	1382	**1106**	1106	1106	kW
Brayton	10100	**8080**	4200	2400	kW
Total	13332	**10666**	6073	3912	kW
Mass flow rate	0.579	**0.463**	0.232	0.116	kg/s
Specific power requirement	6.4	**6.4**	7.3	9.4	kWh/kg

Table 6: Power consumption of IDEALHY cycle at different levels of utilisation

The first row shows the values which were established in the investigation of the "model liquefier" with a capacity of 50 tpd. The values in the second row for a 40 tpd plant were obtained by multiplying the values of the first row with a factor 0.8. It has been assumed that the development work within the test stands has resulted in faster running turbo machines with efficiency equal to that of the larger, slower units for the 50 tpd plant. The third and fourth row show the part load operation of the 40 tpd plant in 50% and 25% part load operation.

Little is known about the part load operation of mixed refrigerant cycles. It is difficult to design flow distributors for two-phase flow for varying flow rates. Probably the mode of operation will be always to run the MR cycle at full load, which will in part-load operation result in a lower separation temperature between the MR and Brayton cycle, i.e. 130 K at full load, 120 K at 50% load and 110 K at 25% load. This will make the task of the Brayton cycle easier.

The specific power consumption of 9.4 kWh/kg for the 10 tpd operation is still much better than the design values for a nominal 10 tpd plant with conventional technology.

4.2.2 Footprint of the commercial 40 tpd demonstration plant

A proposed layout for the site of a 40 tpd demonstration plant is illustrated below, including a side elevation.

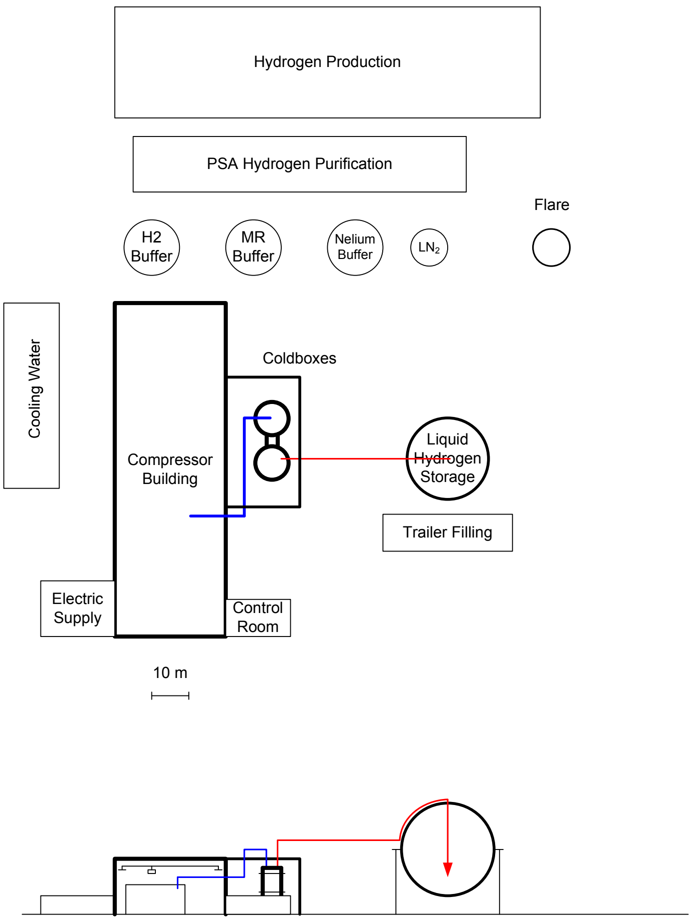

Figure 12: Suggested footprint / elevation for the 40 tpd demonstration plant

5 Options for location of a demonstration plant

When considering possible sites for building a 40-50 tpd hydrogen liquefaction plant, there is a number of factors which must be taken into consideration. This chapter describes the reasoning used to narrow down the possibilities for a plant location, and concludes with two potential sites which are examined in more detail.

To begin with, the plant size itself is a compromise. A minimum size is required in order effectively to test all novel technical aspects (as discussed in section 3 above), while an upper limit to the plant capacity is imposed by the need to develop an infrastructure and market for the liquid hydrogen produced. While the plant size initially chosen was a capacity of 50 tpd, capable of being efficiently operated down to 25% or 30% of capacity (12.5 – 15 tpd) in the early years while the market is building up, the final conclusion drawn in section 4.2 above was that the required efficiency can also be achieved in a 40 tpd plant running at 25% of capacity (10 tpd).

The aim is that the liquefaction plant will be self-supporting in operation, although (depending on market developments) it is unlikely to recover the full capital expenditure from construction during its lifetime.

5.1 Hydrogen supply and market

The demonstration liquefaction plant must have both a reliable supply of hydrogen and a ready market. Within the framework of IDEALHY, the supply chains considered for life cycle analysis (LCA) were divided into those *in* the demand country/region and those *distant* from the demand country/region. Given that the most developed market for hydrogen is in Europe, the most logical location for a demonstration plant is *in* this region where transport to market is relatively straightforward.

5.1.1 Hydrogen supply

The supply chains *in* the demand country/region included in the IDEALHY LCA are:

- Electrolysis with surplus wind electricity;
- Reformation of compressed or liquefied natural gas (with and without carbon capture and storage; CCS).

These and any other options which would increase the chances of success for a demonstration plant in the European region will be favoured when making choices for the hydrogen supply. In particular this means taking advantage of any planned (or existing) sources of hydrogen which may fall outside these two categories. Additionally, CCS will be included in any hydrogen supply chains based on natural gas, as hydrogen based on non-carbon-captured fossil fuels fails to give the greenhouse gas advantage required by hydrogen vehicle manufacturers.

There are currently no existing renewable or low-carbon hydrogen plants in Europe of a sufficiently large scale available to supply a 10 tpd liquefier. In Germany there are some plans for new hydrogen plants (e.g. 10MW electrolyser at Brunsbüttel at the mouth of the Elbe) but at present these too are not at the required scale.

When planning the liquefaction demonstration, therefore, a location with a potential hydrogen supply either from natural gas reforming or from water electrolysis must be chosen. It is also of interest to integrate the hydrogen supply with the liquefaction, because of potential efficiency advantages of integrating the two processes.

Obviously the hydrogen for the demonstration plant could be supplied from more than one source. This is of particular relevance to hydrogen supply from renewable electricity, which is by its nature intermittent. It must therefore be combined with a backup supply of hydrogen from a reliable source, because the low temperatures involved in hydrogen liquefaction mean that non-continuous operation brings a large efficiency penalty.

5.1.2 Hydrogen market

5.1.2.1 H2Mobility

In Europe the most rapidly developing market is currently in Germany, where the H2Mobility project plans for a full hydrogen infrastructure to support a growing market in hydrogen vehicles. The UK has a comparable broad-based partnership, UKH2Mobility, and most recently (July 2013) France Mobilité Hydrogène has been launched, but these are at a much earlier stage of development. While there are numerous individual projects related to various aspects of hydrogen technology all over Europe, none approaches these country-wide initiatives in scope and none will have a comparable impact on the market for hydrogen.

Given a successful launch to H2Mobility in Germany and growth as predicted, it is intended that a network of approx. 1,000 hydrogen refuelling stations will be built during the period to 2030, providing hydrogen to a fleet comprising approx. 1.8 million fuel cell electric vehicles (FCEVs) by 2030. This fleet would consume 184,000 tonnes per year of hydrogen. The scenarios envisage that in 2020, existing excess capacity and byproduct H2 will provide 60% of the supply, and that by 2030 this will have fallen to 40%. This means that 110kt per year (ktpa) of hydrogen, or 301 tpd, will be required from other sources in 2030. Water electrolysis is expected to make up the vast majority of this balance.

None of the H2Mobility predictions to 2030 so far includes liquid hydrogen explicitly. Beyond 2030 (or earlier, depending on the progress of other initiatives), however, when refuelling stations scale up and require larger volumes of hydrogen, transporting hydrogen in liquid form will bring efficiency and cost advantages.

5.1.2.2 Hydrogen fuel cell buses

Considerable development of the liquid hydrogen market is required to generate sufficient certainty about the take-off of liquid hydrogen from a 40-50 tpd demonstration plant. Beyond the car fleet envisaged by H2Mobility, bus travel is a growth area for hydrogen vehicles and infrastructure, and could offer an attractive short-to-medium-term market for relatively large quantities of liquid hydrogen, while the fleet of hydrogen cars is building up. Although it is envisaged that buses themselves will carry tanks of compressed hydrogen rather than liquid, the large amounts of hydrogen consumed by a fleet of buses render a liquid hydrogen supply chain potentially more attractive than one based on compressed hydrogen. Furthermore, the decision-making process relating to the drivetrain choice for buses is steered by a different set of interests and priorities from those dictating uptake of fuel cell cars, rendering change in this sphere potentially more rapid than in private cars.

A study of urban buses by McKinsey *('Urban buses: alternative powertrains for Europe'*, McKinsey, December 2012) has confirmed that fuel cell buses can be a valid and cost-effective option for reducing city emissions. The low-carbon city transport initiatives (often arising from aspirations at a local governance level (rather than at national level) to reduce transport emissions) already using hydrogen fuel cell buses go some way towards bearing out this supposition. Figure 13 illustrates European fuel cell bus projects ongoing as at October 2012, and at the time of writing there is a large number of comparable initiatives in Europe under discussion.

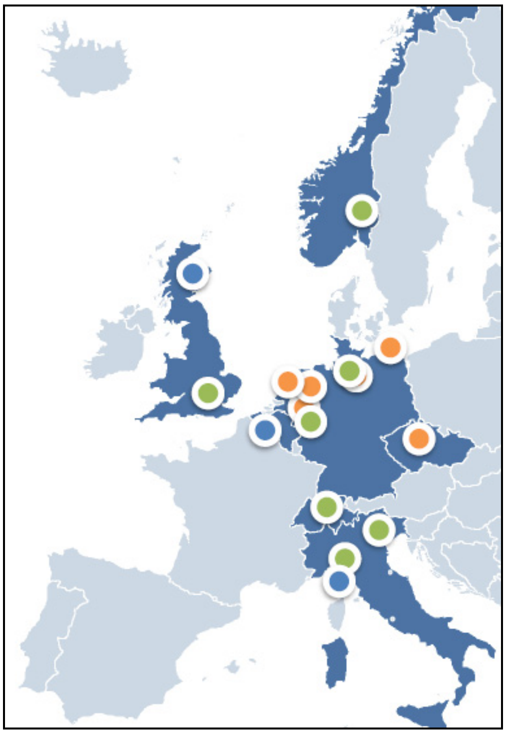

Figure 13: Bus initiatives in Europe (courtesy of Element Energy Ltd.)
Green circles: CHIC (Clean Hydrogen in Cities) projects; Blue circles: cities participating in High V.Lo-City initiatives; Orange circles: independent projects.

Preliminary calculations as to the numbers of cars and buses which could potentially be supplied from a 40 tpd hydrogen liquefaction plant running at 25% capacity (10 tpd output) are given in Table 7 below. Assumptions made about the ratio of local to remote consumption of the hydrogen produced are listed, and two alternatives are given for the distribution of hydrogen between buses and cars. It illustrates that the output of such a plant is at a scale compatible with anticipated developments in the European hydrogen market.

The numbers in the FCEV car fleet envisaged in the H2Mobility scenarios for Germany are given for comparison, showing how a demonstration liquefaction plant at this scale has a good fit with the anticipated growth of the Europe-wide hydrogen distribution infrastructure. Close collaboration with bus manufacturers and with related low-carbon initiatives will be crucial to the success of a functional commercial hydrogen liquefaction plant.

	90% / 10% bus / car	80% / 20% bus / car
Local cars	341	683
Local buses	63	56
Remote cars	2,991	5,982
Remote buses	551	490
H2Mobility fleet envisaged 2020	156,000	
H2Mobility fleet envisaged 2030	1,773,000	

Table 7: Potential distribution of hydrogen from a 40 tpd liquefaction plant working at 25% of capacity. Local = road transport to nearby stations, consuming 10% of plant output, remote = sea transport to more distant stations for remaining 90%. [IDEALHY calculations]

5.2 Transport of hydrogen to market

In addition to being (relatively) close to a (future) market for hydrogen, the demonstration plant must be at a location from where hydrogen can readily be transported by road or by ship. In the IDEALHY scenarios, only transport methods already in existence are considered for the demonstration plant, namely using isocontainers transported either by lorry (land) or ship (sea or inland waterways). A coastal location would also be advantageous given that both pipeline natural gas and large amounts of renewable power are available in Europe primarily in offshore (and often remote) locations. This renders sea transport of the hydrogen to market crucial.

Despite the long-distance potential of ocean transport in principle, in practice the boil-off losses from isocontainers during loading, shipping and offloading place a limit on the advisable shipping distance if losses are to be kept at an acceptable (under 1%) level. Preliminary assessments of anticipated losses indicate that a transit threshold of 750km by sea could be appropriate as a realistic cut-off in assessment of potential locations. Longer distances may also be feasible but would require more detailed study.

5.3 Potential for carbon capture and storage

As mentioned in 5.1.1 above, for a clean hydrogen supply to the demonstration plant, CCS is essential if the hydrogen source is of fossil origin. CCS projects in Europe, however, generally struggle with a planning and permitting environment which is not (yet) particularly supportive of CCS, and onshore projects in particular frequently face considerable opposition. There is also appreciable technical, market and first mover risk associated with CCS projects at present.

In choosing a location, therefore, the local appetite for CCS could prove the deciding factor.

5.4 Other location issues

A hydrogen liquefaction plant (including hydrogen supply) forms a large industrial facility and as such has requirements common to other such plants. These are listed below, together with other factors which would favour a location.

- sufficient space
- appropriate permits to operate, including readiness of (local) government to cooperate
- proximity to other industry and/or to an existing hydrogen source
- proximity to related technical facilities
- presence of (related) hydrogen initiatives
- appetite of country/region for hydrogen technology / initiatives in general

5.5 Justification of a commercial test plant

As reasoned earlier, a non-commercial alternative exists to a commercial demonstration plant. Despite the business risk entailed in building a commercial demonstration plant, however, it is the opinion of the IDEALHY consortium that this approach is more advisable than the non-commercial option, provided that a test stand stage is included as described in section 3.4.

A non-commercial demonstration plant (no net output) would require a comparable financial investment to a commercial plant without the potential for income from commercial operation, or from future expansion to operation at full capacity once a market is developed.

5.6 Countries under consideration

Considering European locations in the light of the factors outlined above, two principal options spring to mind.

5.6.1 Germany

Germany is an obvious candidate because of its leading position (through H2Mobility) in the development of a hydrogen infrastructure and market. It does not, however, have clear options for supply of large amounts of hydrogen, as it lacks major fossil resources, and although it has high proportions of renewable power, this alone (as discussed in 5.1.1 above) is not sufficient for reliable hydrogen supply on a large scale.

5.6.2 Norway

In Norway, a large number of aspects favourable to a demonstration hydrogen liquefaction plant combine, namely:

- Sufficiently abundant (offshore) natural gas (NG) reserves
- NG pipeline infrastructure to a number of onshore terminals
- Experience with operation of (offshore) CCS and reasonably open attitude to new CCS installations
- Innovative attitude with respect to new developments in the field of energy (e.g. LNG ferries)
- Other hydrogen initiatives already under way (also see section 6_Ref362254696 \r \h |6})
- Proximity to largest future H2 market (Germany)
    - accessible for UK as/when UKH2Mobility project begins and market grows
    - major ports e.g. Rotterdam (NL) also accessible

6 Norway

6.1 Market context

Norway is a country with a forward-looking energy outlook perhaps surprising given its position as one of the world's larger oil and gas exporters. In 2004 a governmental hydrogen programme was set up with the following overarching goals:

- Production of hydrogen from natural gas with carbon capture, at a cost that is competitive with petrol or diesel, for use in Europe;
- Early introduction of hydrogen vehicles in Norway;
- Development of internationally-leading competence in hydrogen storage, with competitive products and services;
- Development of a 'hydrogen technology industry', comprising: participation of Norwegian companies in international supply chains for hydrogen technology; the supply of hydrogen refuelling stations using electrolysis; competence in the use of fuel cells on ships; and R&D of an international standard in fields related to hydrogen.

Beyond hydrogen alone, the Norwegian government is extremely interested in clean energy provision. The Energi21 strategy (led by the Ministry of Petroleum and Energy) defined an R&D framework relating to stationary energy production/consumption and CCS, and it identified six technology areas as priorities in 2008. These are:

- Solar cells (industrial development in the supply chain for the export market);
- Offshore wind power (industrial development and use of domestic resources);
- Use of domestic resources to provide grid balancing services to the European market;
- CCS technology to safeguard the future economic value of Norwegian gas resources;
- Flexible energy systems: smart grid operation and the integration of renewable sources;
- Technology for the use of waste heat and conversion of low-grade heat to electricity.

The nation made further ambitious CO_2 pledges in 2009, aiming to cut emissions by 30% (from 1990 levels) in 2020 and to be carbon neutral by 2050. Although a third of these reductions may be made via Norwegian investments in low-carbon projects elsewhere, the majority will be in domestic emissions.

Since Norway already relies on renewable resources (principally hydropower) for over 97% of its electricity[1], the bulk of the CO_2 reduction must be met by the transport sector. Furthermore, emphasis is placed on long-term sustainable (low-carbon) utilisation of the country's gas resources, with considerable emphasis on CCS development and implementation.

The government's ambition is to have 50,000 zero emission vehicles on the road by 2018. The population distribution and driving patterns in Norway mean that there are practical

[1] Note however that Norway 'sells' a considerable proportion of its clean power in the form of certificates with guarantees of origin, and consumes an equivalent amount of (non-clean) power from the European energy mix.

constraints on the number of cars in the fleet which could be powered by grid electricity, and biofuels also have limited availability[2]. The strong implication is that hydrogen will play a key role in Norway's future transport infrastructure, not only on the road but also in ferries and ships.

Together with city bus initiatives planned, this means that there is an appreciable future domestic market for bulk (liquid) hydrogen.

6.2 Possible sites in Norway – details

Along the coast of Norway there are various natural gas pipeline terminals, at most of which there are gas processing plants of some kind. This section lists coastal sites initially identified as possible sites for a demonstration hydrogen liquefaction plant.

Note that a site's inclusion in this list does not presuppose plans on the part of the owner or operator to build such a hydrogen liquefaction plant.

6.2.1 Kårstø and Risavika

- At Kårstø: Gas processing plant operated by Statoil; 420MW gas-fired power plant commissioned in 2007 with plans for full-scale CCS (1.2Mt annually) never completed
- At Risavika: Site operated by Skangass: 0.3Mtpa LNG plant processing gas by pipeline from Kårstø; further gas testing infrastructure still present

6.2.2 Kollsnes

- Gas processing plant site operated by Statoil
- LNG and CNG plant operated by Gasnor (now owned by Shell)

6.2.3 Nyhamna

Gas processing plant operated by Shell, treating gas from the Ormen Lange field before transfer by subsea pipeline to Easington in the UK.

6.2.4 Tjeldbergodden

- Gas receiving terminal operated by Statoil
- Also methanol production (900Mtpa) and air separation units

6.2.5 Grenland/Porsgrunn/Hærøya area

- Large industrial park owned by Statoil with wide variety of company premises
- Statoil R&D/technology centre at Porsgrunn
- By-product industrial pipeline hydrogen supplying HRS, now being upgraded to 700bar
- Small-scale sustainable H2 production (NEL alkaline electrolyser combined with renewable power

[2] Maximum estimated 10% of transportation needs from biomass, NorWays report, 2009.

6.2.6 Mongstad

- Gas receiving site operated by Statoil, using pipeline gas from Kollsnes
    - Combined heat and power plant under construction; 280MWe / 350MWth
- CO_2 technology centre, a joint venture (JV) between the Norwegian government, Shell, Sasol and Statoil
    - Extraction and capture of post-combustion CO_2 from natural gas

6.2.7 Sleipner

- Offshore field operated by Statoil (gas processed at Kollsnes)
    - Captures 1Mt CO_2/year in offshore CCS

6.2.8 Hammerfest / Snøhvit

- 4.2Mtpa LNG production site operated by Statoil
    - Operational problems dogging LNG production
    - Very remote site (north of Arctic Circle), so distribution cumbersome and expensive

6.3 Shortlist of sites selected

The two sites initially selected for further investigation are the Mongstad CO_2 research centre and the technology centre at Porsgrunn. In the final months of the IDEALHY project the options at these two locations will be further explored, together with options for collaboration.

7 References

Fuel Cells and Hydrogen in Norway, Fuel Cell Today report (2012)

8 Acknowledgements

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