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

Fuel Cells and Hydrogen Joint Undertaking (FCH JU)

Grant Agreement Number 278177

Title:	Assessment of Complete Plan
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Deliverable Number:	5.23
Date:	22 November 2013
Report Classification:	Public

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

In work packages 1 and 2 of the IDEALHY project, existing and proposed processes for hydrogen liquefaction at large scale (>50 tonnes per day) were benchmarked and the most most promising concept developed further. The process was optimised for the lowest energy consumption while working to the minimum possible investment cost, and discussions were held with equipment manufacturers with regard to component availability.

The IDEALHY liquefaction process uses two successive Brayton cycles with a common compressor train. The refrigerant is a helium/neon mixture (‘Nelium’) selected for optimum compressibility and refrigeration efficiency. The pre-cooling to 130K uses a mixed refrigerant (MR), and this MR cycle provides the 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.

Plans have been made (see Deliverable D5.22) for a 40 tonne per day liquefaction plant at a location in Europe. The plant design is such that it is capable of efficient operation well below its full capacity, in order to adapt to anticipated growth in the market for hydrogen.

This document takes a step back from the detailed technical discussions found in other reports to assess the IDEALHY liquefaction process and project as a whole. It challenges the original premises which formed the basis of the project and analyses the outcome. The aim of this exercise is to highlight areas for discussion in the process design and in the approach as a whole, in order to generate a more robust plan for the future.

Key Words

Hydrogen liquefaction

Vehicle fuel

Hydrogen distribution

Feed compression

MR precooling

Nelium

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1 Introduction

The IDEALHY project is an enabling project, aiming to show the potential of liquid hydrogen as an energy carrier by demonstrating that the liquefaction itself need not be as energy-intensive as has hitherto been the case.

An liquefaction process has been designed for plants between 40 and 200 tonnes per day (tpd), taking into account safety and risk management at all stages of the liquid hydrogen value chain and while keeping investment cost at a minimum. The process design reduces the liquefaction energy requirement by half, thus reducing liquefaction cost to competitive levels and rendering greenhouse gas emissions comparable with those from compressed hydrogen. Finally, a strategic plan was made for construction of a demonstration plant, including options for the plant location, development of hydrogen supply / market and possible strategic partners. These are described in Deliverable 5.22.

This report analyses the outcomes of the IDEALHY project. It attempts to identify debatable areas in the conclusions drawn and on this basis to justify decisions taken during the project.

2 Suitability of Hydrogen as Vehicle Fuel

2.1 Premise / Result: Hydrogen will play an important role as a vehicle fuel

In order for car manufacturers to meet stringent future EU standards for vehicle tailpipe emissions, a significant proportion of car fleets will need to be zero emission vehicles (ZEVs). Hydrogen is an ideal fuel for a significant proportion of these ZEVs because of the potential speed and relative simplicity of refuelling (in contrast to electric vehicles) and the much greater range of operation than that of battery cars.

2.2 Counterargument: Role of natural gas and electric vehicles

Compressed natural gas (CNG) has already been demonstrated as a reliable automotive fuel in the USA and liquefied natural gas (LNG) is increasing its market share for freight vehicles. The adaptations needed to vehicle technology and infrastructure are much less great (and consequently less costly) than for hydrogen while an appreciable reduction in emissions is achieved.

2.3 Assessment: Valid premise

CNG and LNG vehicles still use an internal combustion engine whose efficiency cannot equal that of a fuel cell. While their emissions are lower than those from petrol cars, therefore, they can never be zero, unlike hydrogen or electric vehicles. Hydrogen-fuelled vehicles have the potential to combine zero emissions (if the hydrogen is produced from renewable sources) with a range comparable to that of gasoline fuelled vehicles.

3 Advantages of Liquid versus Gaseous Hydrogen

3.1 Premise / Result: Liquid hydrogen is necessary

Liquid hydrogen (rather than gaseous) will be needed for storage and distribution in the future as the market for hydrogen grows, both for mobility and for other uses.

3.2 Counterargument: Gaseous hydrogen is better

Hydrogen is produced and distributed more efficiently in gaseous form, as is currently the situation. Liquefaction is energy-intensive and the storage / transport of liquid hydrogen is not yet mature enough to serve a bulk market.

3.3 Assessment: Valid premise

The IDEALHY project has developed a liquefaction process which uses half as much energy as the most efficient plant currently operating. This increase in efficiency in a key part of the liquid hydrogen supply chain has shown that (in the absence of a pipeline network) liquid hydrogen can be the most economical way of distributing large quantities of hydrogen to the end user. Advantages include:

- Fewer trucks on the road owing to 4x greater capacity than hydrogen compressed at 500 bar
  - this capacity is 10x greater than the 200 bar trucks currently used;
  - high throughput of large refuelling stations render supply from gaseous hydrogen logistically unfeasible;
- Lower greenhouse gas emissions from transport owing to fewer trucks (beyond distribution distances of approx. 400km);
- Possibilities for longer-distance transport by sea using isocontainers or purpose-built liquid hydrogen vessels;
- Storage at the hydrogen refuelling station (HRS) is cheaper and more compact for liquid hydrogen;
- Equipment for compression to 700 bar (for refuelling) is cheaper for a liquid-supplied HRS.

4 Centralised versus Decentralised Production

4.1 Premise / Result: Hydrogen should be produced and liquefied on a large scale at few locations

The most efficient infrastructure for hydrogen for mobility is centralised production (maximising benefits of scale) and transport over (relatively) long distances, which favours the use of liquid over gaseous hydrogen.

4.2 Counterargument: Renewable and distributed hydrogen will be the main source

Difficulties with carbon capture and sequestration (CCS) mean that centralised (fossil) production of hydrogen will never be truly green. For deep decarbonisation, hydrogen should be produced at a smaller scale, meaning that smaller liquefaction plants would be needed (if at all). Furthermore, distributed production of hydrogen means shorter distribution distances, so that gaseous hydrogen would make more economic sense.

4.3 Assessment: Valid premise

It currently seems likely that hydrogen for mobility will be produced by a range of methods including both centralised and distributed production. Local conditions (infrastructure, resources, market distribution) will dictate the most advantageous option and although there will undoubtedly be cases in which decentralised production from renewables is the logical choice (e.g. when there is the option of producing balancing power), there will be a significant role for large-scale centralised production and liquefaction. In resource-poor locations (Japan is a case in point), decentralised production may be all but impossible.

5 Plant Location

5.1 Premise / Result: Norway seems a promising option for location

Norway is a country with large reserves of fossil fuel, principally gas, and of renewable (hydro- and wind) power. The population is generally highly educated and levels of awareness of hydrogen and alternative fuels is high both at an individual and at a governmental level. There is already an excellent infrastructure for natural gas and many sites with good connections to hydrogen supply and to a potential distribution infrastructure at which a liquefaction plant could be built. Liquid hydrogen could be distributed from the Norwegian coast to European markets via isocontainer shipping.

Carbon emissions from Sleipner, one of Norway's major gas fields, are already captured and sequestered, meaning that there is actual experience with carbon capture and sequestration (CCS) in the country. There are various ongoing initiatives relating to the introduction of ZEVs, both electric and hydrogen-powered, and in the Oslo / Akershus conurbation, takeup of electric vehicles is reaching levels higher than anywhere else in the world.

5.2 Counterargument: Other European countries present more advantages

Norway's main state oil/gas company, Norsk Hydro, does not currently include hydrogen in its focus areas for future development. Furthermore, while CCS has been practised at Sleipner for some time, that installation is far offshore, and although work has been carried out relating to trials of onshore CCS at Mongstad, there is some way to go before the technology will be available at the scale envisaged for IDEALHY.

Although the market for hydrogen in Norway is growing, at most the country's population can support only a small demand. If a large-scale liquefaction plant is to be built, the European mainland is a more logical location, given the current development in the area of hydrogen fuelled buses.

5.3 Assessment: More work needed

The arguments cited above are all true to a certain extent and the rationale behind Norway as an ideal location is not clear-cut. An additional factor which could render Norway more attractive would be the possibility of liquid hydrogen supply to Japan via shipping over an Arctic route, but on the other hand if public transport initiatives for hydrogen in mainland Europe are successful, the market for hydrogen will show significant growth sooner in this location.

It is recommended that more research be carried out in this area, in particular with regard to ongoing developments in hydrogen bus initiatives.

6 Feed Compression

6.1 Premise / Result: Feed compression to 80 bar is required

Compression of the feed to 80 bar has allowed development of the most efficient liquefaction process, so a plant should be designed which can operate at this high pressure.

6.2 Counterargument: Such high pressure brings more disadvantages

The feed gas compressor is expensive, has large leaks to the outside. The high pressure reduces the choice of usable fins in the heat exchangers and the possible block size of such heat exchangers. The compression makes only sense, if an efficient expansion at the cold end is available, which is not yet the case.

6.3 Assessment: compression

The OPEX are reduced by the feed compression for all capacities.

The compressor needed to compress the feed hydrogen from a pressure of 2 MPa to the optimum liquefaction pressure of about 8 MPa is a standard industrial product, which can be purchased from several different suppliers. Its cost has to be recovered by savings in the equipment for the Brayton cycle, which cools the hydrogen from about 100 to 27 K. This Brayton section is by far the most voluminous and expensive part of the total plant. Therefore above a certain plant capacity savings in the Brayton section will overcompensate the cost of the feed compressor. The plant capacity, above which the introduction of a feed compressor reduces the overall CAPEX is probably between 10 and 20 tpd.

7 Precooling

7.1 Premise / Result: Mixed refrigerant precooling is the best option

Mixed refrigerant (MR) precooling is the most efficient and cost-effective choice for the first stage of cooling (to approx. 130K).

7.2 Counterargument: MR is complex, expensive and unproven

MR refrigeration is complicated and difficult to control. Efficient operation at part-load operation is not known. The use of liquid nitrogen reduces CAPEX and is much more flexible.

7.3 Assessment: Valid premise

MR refrigeration at comparable conditions and capacity is already installed in a considerable number of peak-shaving plants for liquefaction of natural gas in US and elsewhere, and should thus be considered as proven technology.

Part load operation may be implemented by variable guide vanes in the compressor and/or variable speed. Further flexibility for a pilot plant, for which part load is most relevant, may be given by using parallel compressors and/or manipulation of the refrigerant charge and composition. Thus part load down to e.g. 25% should not be an issue.

Use of nitrogen as refrigerant could be an option, but in a plant producing hydrogen for energy purposes the energy efficiency and operating cost aspects will be very important. Liquid nitrogen will have a lower energy efficiency and a considerably higher operating cost (OPEX), which will outweigh the argument of a low CAPEX. Further it is also a question if liquid nitrogen will have a low CAPEX in this setting, since it probably needs to be produced in a separate plant, or you need a closed nitrogen cycle.

Given the argumentation above, it is also questionable whether a liquid nitrogen plant will be more flexible than a MR plant.

8 Refrigerant for Cryogenic Cooling

8.1 Premise / Result: Nelium is the best option

Nelium allows the use of turbo compressors and the efficient recovery of turbine power, which results in a big boost of efficiency gain and cheap compressors

8.2 Counterargument: Cheaper options would be better

Neon is expensive and requires totally hermetic compressors and expanders.

8.3 Assessment:

In the Brayton cycle the refrigerant neon is everywhere in the gaseous state. Therefore the quantity of gas needed is about 2000 Nm3, of which 25 % are Neon. So the cost of this refrigerant is negligible compared to the cost of the rest of the plant. On the other hand all components in the cycle have to be tight both in operation and in standstill. This is a drawback in comparison with the alternative refrigerant hydrogen, for which a certain amount of continuous loss can be tolerated.

But the required tight components (turbo-compressor, expander) are on the market for reasonable prices.

The use of Nelium allows to use turbo compressors and expanders with work recovery for the Brayton cycle. This potential is responsible for more than 20 % reduction in the OPEX for large plants.

And for large systems the turbo compressors for Nelium have a lower investment cost than the required huge piston compressors needed for the compression of the alternative refrigerant hydrogen.

9 Turbines for Final Expansion

9.1 Premise / Result: Use of gas bearing turbines or piston expanders

The final expansion of the precooled feed in gas bearing turbines or piston expanders is feasible.

9.2 Counterargument

These components do not yet exist. The result of development is uncertain. Gas bearing turbines at this location have a poor part-load efficiency.

9.3 Assessment:

For the final expansion of the hydrogen in the supercritical region one has the choice between gas bearing turbines and piston expanders. Similar machines exist for somewhat different process conditions, so the development risk is small. This kind of machines will be needed in any case for all processes for the large scale liquefaction of hydrogen.

10 Flash Gas Handling

10.1 Premise / Result: Flash gas can be re-liquefied

The re-liquefaction of the flash gas in a para-hydrogen cycle is feasible, efficient and cheap.

10.2 Counterargument: Issue of reconversion to *ortho*-hydrogen

It is not known, whether a reconversion from para- to ortho-hydrogen will occur e.g. during the ambient temperature compression. This would be detrimental to the para-content of the product.

10.3 Assessment:

The para-hydrogen cycle for the re-condensation of the flash gas is indeed a feature, which has not been used or tested before. If the assumption turn out to be too optimistic there exists as alternative a closed Joule-Thomson cycle with normal hydrogen as refrigerant. It has the only disadvantage that its evaporation temperature would have to be about 0.3 K lower than the storage temperature of the para hydrogen. So the volumetric flow rate and the power consumption of the recycle compressor would have to be 5 % larger. This would have a 0.5 % effect on the total plant power consumption.

11 Conclusions and Next Steps

This assessment exercise has raised a large number of valid questions and objections to the results and conclusions drawn during IDEALHY. Counterarguments have been presented here, and the overall conclusion is that the initial premises and the results of the IDEALHY project have in general held their own.

The area which has seen least discussion in the project and in which the most work remains to be done is in the trade-off needed between capital expenditure, operating expenses and efficiency advantages. For future work leading to an actual plant design, it will be crucial to carry out detailed cost engineering on the proposed design and to ensure that the process ultimately selected is economically feasible.