Cryogenic Energy Storage for Renewable Refrigeration and Power Supply

CryoHub Briefing Note

Prepared by Dr Suraj Paneru and
Dr Jonathan Radcliffe, University of Birmingham

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Key Messages

- Cryogenic energy storage (CES) has the potential to balance the power grid, increase the take up of renewable energy sources (RES) by storing excess energy generated by RES and provide affordable cooling supply.

- Originally, the CryoHub project aimed to use renewable energy for air liquefaction and storage in case of excess energy or when grid demand is low and/or price is lower. Liquid air (LA) can be pumped and vaporized when needed for warehouse refrigeration and electricity generation. For demonstration purposes, liquid nitrogen (LIN) was used instead of LA, as it was easier to deliver and handle, while possessing similar properties, thermal and rheological behaviour.

- The CryoHub demonstrator has been installed and integrated with the Frigologix cold storage warehouse at Lommel in Belgium. It is being used to test a range of operating scenarios, for which the measured results are compared with the predicted performance modelled during the CryoHub project.

- There are over 1,000 sites in EU 27 and the UK suitable for installing CES, in particular liquid air energy storage (LAES) integrated synergistically with RES and large cold-storage warehouses.

- The financial viability study concluded that employing LAES to avoid exporting energy is currently much more economically viable because the price paid for exported energy appeared to be low. At the moment, choosing the right tariff and installing a large-scale (~200 MW) LAES could provide an acceptable payback.

- Technology cost, technology integration, uncertainty in future value, centralised regulatory framework and rigid energy market structure are the major barriers for the development of new energy storage technologies in the EU 27 and the UK.

- Stakeholders have shown a high level of interest in the CyoHub technology.

- The CryoHub demonstrator at Lommel is now being commissioned and is being used to test a range of operating scenarios through spring 2021, for which the measured results will be compared with the predicted performance modelled in the CryoHub project.

Contents

1. Introduction

The CryoHub project received funding from European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 691761 as an Innovation Action. The project completed in March 2021. This briefing note outlines the key results from the CryoHub project across the technical and non-technical aspects. Figures, tables, and data in this report are taken from the reports, publications, journal articles and deliverables prepared by the CryoHub partners that can be found at: **https://cryohub.info/en-gb/**

The project objectives were to:

- **Balance the power grid mismatch between power demand and energy generation from renewables.**
- **Store energy generated by renewables before supplying it back to the electrical grid.**
- **Provide an affordable cooling supply during power generation.**
- **Increase the take up of renewable energy.**
- **Reduce peak power demand and help decarbonise the power grid.**

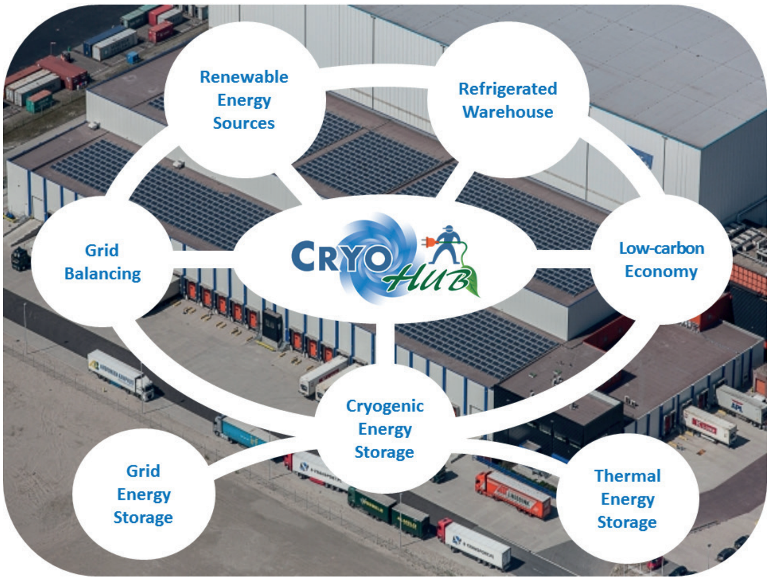


Figure 1: Illustration of CryoHub concept (CryoHub, 2015)

Cryogenic Energy Storage (CES), and specifically Liquid Air Energy Storage (LAES), is an energy storage technology that charges using excess electricity to liquefy air. The cryogenic liquid is stored at ambient pressure and low temperature, then evaporated, superheated and expanded in the discharge unit to generate electricity.

The CryoHub concept is also to utilise the stored cold so that when discharging, the liquefied air is pumped and vaporized to produce energy for both warehouse refrigeration and electricity generation, i.e., it operates in a cogeneration mode (CryoHub, 2015, Fikiin et al., 2017)

By coupling with renewable generation, the CryoHub technology has the potential to deliver multiple benefits: low carbon cooling, avoiding high grid electricity prices, and providing ancillary services to the grid. The project aimed to demonstrate the technical feasibility of the concept and assess the costs and benefits from its operation.

2. The potential for using LAES at cold storage warehouses co-located with renewable energy sources

(Fikiin et al., 2019) have mapped the large, refrigerated food warehouses (over 0.5 MW) across the EU27 and the UK in a dedicated study exploring the potential for using LAES at refrigerated warehouses co-located with renewable energy. The survey reported some 1,049 warehouses; among them 503 warehouses were classed as energy intensive as they had a real or an estimated average power consumption exceeding 500 kW. The study also identified 3,200 major (over 1 MW) solar PV installations and 11,700 major onshore wind parks to discover the best areas for RES integration across EU27 and the UK.

The information gathered by the survey ensures a science-based approach to RES integration in refrigerated warehousing. The-first-of-its-kind Europe-wide mapping of the energy expenditure by the refrigerated storage sector, co-located with the RES availability, permits us to identify the EU regions and areas which are most promising for renewable energy projects in the area of industrial food refrigeration.

The study shows that the concentration of large, refrigerated warehouses in Europe depends on the population density and the production capacities for perishable food commodities. The potential for using CES and particularly LAES at refrigerated food facilities depend on the overall technology level and the economic development in a country or region, rather than just on the demand for food storage. Factors, such as population growth, migration and urbanisation processes, dietary habits (e.g., increase use of ready-to-eat and chilled foods), etc., also have a strong impact on economies and sustainability, thereby warranting further investigations. The study of Fikiin et al. (2019) suggests that cryogenic energy storage, integrated synergistically with RES and large refrigerated warehouses, is a promising environmentally friendly technology.

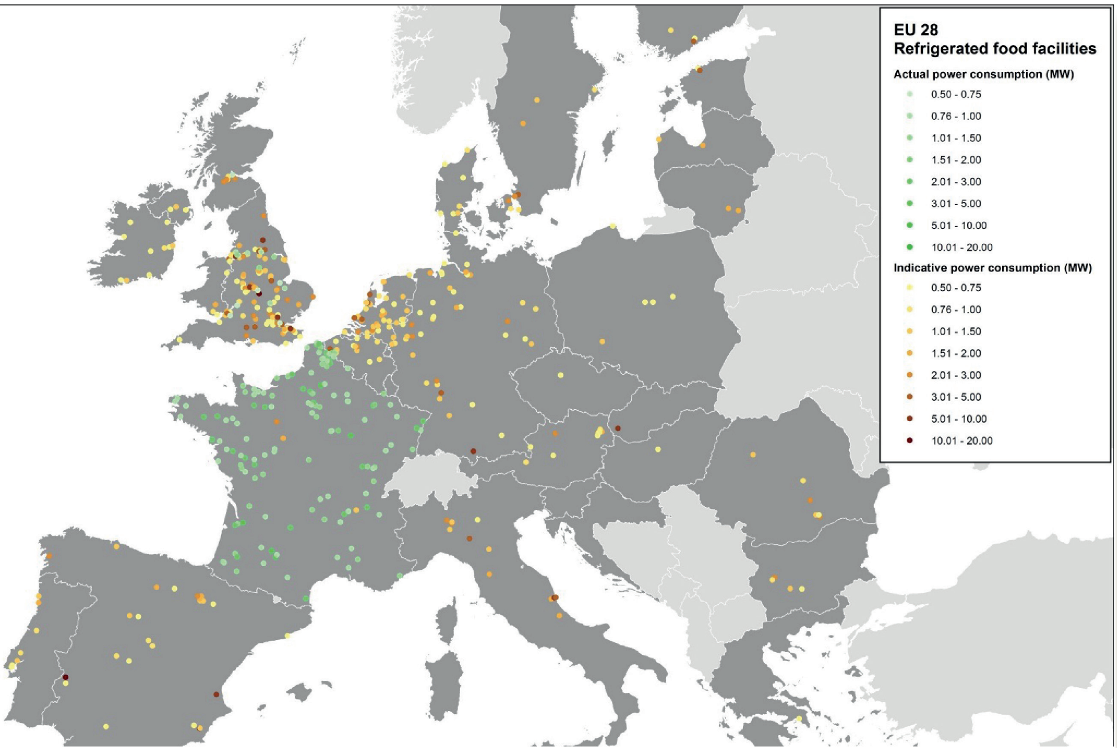


Figure 2: Mapping large, refrigerated food warehouse (over 0.5 MW) across EU27 and the UK (Fikiin et al., 2019)

3. The CryoHub Demonstrator

The CryoHub project included the design, build and testing of a demonstrator system for cold thermal storage, warehouse cooling and power generation from a discharged cryogen.

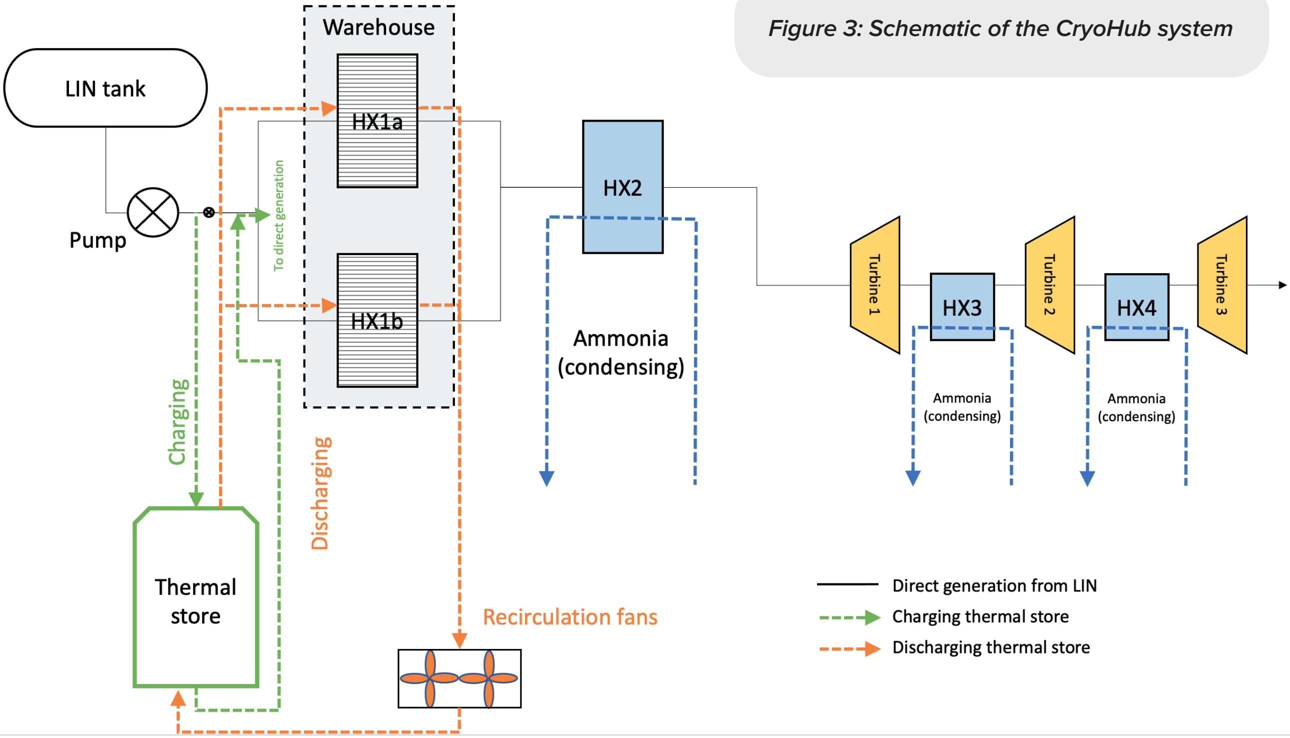
The CryoHub concept contains the following subsystems:

1. Air liquefaction for storage of excess renewable energy or when demand is low.
2. LA (liquid air) storage in a pressurized cryogenic vessel.
3. Discharge of the LA for warehouse refrigeration and energy recovery when demand is high.

The conceptual design of the CryoHub demonstrator evolved during the project for scientific and budgetary reasons. The main budgetary constraint has been related to liquefaction, which is very expensive but at the same time well established technology. Liquefaction on site was therefore excluded from the demonstrator, being replaced by supply of cryogen from a storage tank. To simplify the demonstrator further, the use of liquid nitrogen (LIN) was chosen to replace liquid air (LA). While the latter could be used in system for cryogenic energy storage, liquid nitrogen is a standard cryogen routinely supplied by partner Air Liquide and has far fewer safety requirements and technical challenges.

The CryoHub project was designed to integrate cryogenic energy storage with a refrigerated warehouse facility. The industrial scale demonstrator has been installed at a frozen storage warehouse operated by Frigologix at Lommel in Belgium. The warehouse has capacity to process 40,000 pallets of frozen and 5,000 pallets of fresh food at a time and consumes approximately 5,000 MWh/y electricity, of which 1,000 MWh is supplied from solar PV. The demonstrator has been assembled and integrated with the warehouse and the electrical grid.

Figure 3: Schematic of the CryoHub system



The output from the demonstrator system was found to be:

- 129 kW cooling to warehouse (equiv. 51 kW electrical)
- 45 kW electrical power (turbines)

From an input of:

- 0.42 kg/s LIN (2.13 MW)
- 6 kW fan power

Giving a round-trip efficiency (RTE) of 4.5%, assuming COP of ammonia refrigeration (-30°C) =2.5, and the energy cost of LIN production is 1.4 kWh/kg.

This includes electricity generated, cooling to warehouse, warehouse fan power; but doesn't include defrosts, start-up and shutdown losses, Interstage cooling from turbines (-30 to -40°C).

The RTE is low in the demonstrator system because the energy cost of liquefaction is much higher than the energy production from turbines and value of cooling to cold store warehouse. The liquefaction cost would come down for a demonstrator system connected to the liquefaction system via a thermal store. The heat from liquefaction system could then be recycled via thermal store and high temperature process waste heat could be utilised to obtain higher pressures and more efficient turbines and pumps.

Figure 4 shows the skid positioned on site at Frigologix, with the heat exchanger block now connected on the top layer, prior to delivery of the thermal store. Figure 5 shows the skid alongside the warehouse wall, with the thermal store now in position and the vacuum insulated pipes leading to the warehouse heat exchangers.

Figure 4: The skid and heat exchanger block connected and installed at Frigologix: (Dohmeyer & Frigologix).

Figure 5: Side view of the demonstrator skid with thermal store (Dohmeyer & Frigologix).

4. Financial viability of LAES applied to the cold storage warehouses

The financial viability study of LAES carried out by (Foster et al., 2018) showed that load shift between peak and off-peak electricity tariffs was not economically viable because the ratio between off-peak and peak tariffs was higher than round trip efficiency (RTE). To assess the potential benefits of CryoHub, broader electricity tariff plans were reviewed (Table 1) which suggested that choosing the right tariff can help reduce the cost of off-peak energy and maximise the benefits of load shifting.

The study concluded that employing LAES to avoid exporting energy is currently much more economically viable. This is because in the study carried out, the price paid for exported energy was low. A large-scale (~200 MW) LAES could provide an acceptable payback. The lack of a competitive market for small scale liquefaction systems was identified as the reason for the higher cost of small scale LAES. In the future, the increased volatility in the electricity market, driving a larger difference in energy prices, could improve the financial viability of LAES. Furthermore, government incentives for energy storage could help bring down the cost of LAES, making it viable in the future.

ELECTRICITY TARIFF PLAN TYPE	SPECIFICATIONS
Single rate	With single rate tariff plan (also known as flat and standard rate) there are no peak or off-peak periods. This means that the same rate applies at any time when energy is used. The rate is usually lower than the peak rates from a time of use tariff. This means a single rate plan could be a good choice if daily load change is not significant.
Time of use (ToU)	A time of use tariff means that electricity tariffs differ at peak and off-peak times of the day. Peak rates usually apply in the evening; off-peak rates usually apply overnight. This means a ToU plan could be a good choice if daily load can vary significantly.
Controlled load	For some electricity consuming equipment, like heating systems, the electricity provider charges a rate just for that appliance/equipment and the energy it uses. Often that appliance has its own meter. It is usually only for equipment that runs overnight or in off-peak times so controlled load rates are usually lower.
Demand	Plans with demand charges will have regular usage and supply charges but will have added demand charges on top. Demand (kW) is a measure of how intensely electricity is used at a point in time instead of usage over time. Therefore, demand will be high when many appliances are on at the same time. Different retailers have different ways of applying demand charges including: highest demand in a period of time; average of peak demand over a period of time; different demand rates in different seasons.

5. Energy policy drivers that have implication for the success of CryoHub technology

Energy policy is a driver of technological development with implications for the developmental success of CryoHub technology. The key policies in the EU, identified as a part of a study carried out by Carbon Data Resources (CDR) with input from Association of European Renewable Energy Research Centres (EUREC), were:

- The drive for energy security and independence from energy imports boosting domestic development of renewable energy schemes
- The EU wide clean energy package - focussing on delivering the stable legislative framework needed to facilitate the clean energy transition and on achieving the Paris Agreement commitments
- Existing, legally binding member state targets for RES (20% by 2020) and greenhouse gas (GHG) emission reduction working in concert, and the potential of future 'stretch' targets for RES of 32% by 2030
- Renewable energy trends anticipating ongoing growth in variable RES
- Planned investment in energy infrastructure to allow for the integration of more RES into the power system
- The development and integration of energy storage as a key element of both the recast Renewable Energy Directive (REDII) and the Market Design Initiative (MDI)

An analysis of energy storage policies specifically was carried out as a part of the study by the University of Birmingham, covering Germany, UK, USA, Australia, Japan and South Korea (Radcliffe et al., 2020). The study concluded that the growth of energy storage technologies and market development are highly dependent on a favourable policy environment and investment in R&D from the government though the policies themselves are varied. **Examples of key policy approaches enabling energy storage are:**

- Consumer-led deployment of energy storage in Japan and California
- Demand-side management in New York
- Integrated renewable and energy storage and ease of starting a new business in Australia
- Private sector investment in R&D of energy storage in South Korea
- Prosumerism (consumers who also actively produce electricity, i.e., from the rooftop solar PV) in Germany, the UK and Hawaii
- Target-setting and sending a positive signal to the market in Japan

6. Stakeholder surveys

A survey of policy and market barriers for the development of new energy storage technologies in the EU was carried out through questionnaires and interviews with stakeholders from both the energy and refrigeration sectors (Radcliffe et al., 2020). The following key policy and market barriers are identified:

- **Capital expenditure/ Technology cost:**
  New technologies are likely to be expensive which discourages stakeholders to install such technologies. The stakeholders were cautious about the financial performance of new technology. It was suggested that the new technology should be able to demonstrate tangible evidence that it can provide a return on investment (ROI) within 3-5 years of installation.

- **Technology integration:**
  If the new technology cannot be integrated with the existing system/ process, this can discourage the businesses to install it.

- **Uncertainty in future value:**
  Energy storage technologies are still expensive and new more effective future technologies can affect the investments in existing new technologies.

- **Regulatory framework:**
  Existing regulatory framework was designed for a centralized energy system, which can become a barrier for the new, distributed energy systems. Therefore, regulatory reforms to remove barriers and create a more level playing field for niche systems such as Cryogenic Energy Storage is necessary. Some countries have double taxation of storage while others have bureaucratic processes that can take too long to get permission for the installation of new technology.

- **Market structure:**
  Current electricity market and the heating market is too rigid and there is not enough freedom for new business models. Energy storage technologies such as batteries have market dependency outside Europe which can also be a barrier to the development of new technologies inside the EU.

The stakeholders suggested the following technology-related issues that need to be addressed in order to facilitate the development of new energy storage technology:

- Decrease the cost
- Improve cycle efficiency of an energy storage system
- Decrease the energy storage system size
- Clear labelling or demonstrating the environmental efficacy of the technology to allow front-runner businesses to promote their 'green branding'.
- More R&D should be carried out for system integration, demonstration and good programming for materials and component research

The study by (Radcliffe et al., 2020) concludes that the industry stakeholders such as operators of large food storage warehouses have to deal with natural uncertainty such as the variable quantity of harvest, variable timing of harvest and ever-changing market demand, therefore new technology should be designed to cope with such changes and minimize uncertainties. On the policy side, the governments should provide (further) explicit support for the development and/or deployment of storage, including LAES technology, over the next 5+ years as it does for a range of low carbon technologies. The government should also provide additional support for R&D, demonstration and deployment support.

At the final stakeholder webinar, a survey of attendees (65% of whom were from the private sector) found:

- **92%**

  recognised that benefits could come from energy storage

- **65%**

  were 'enthusiastic' when asked their attitude to testing or demonstrating new technology in their business

- **64%**

  identified 'a viable business case' would be the most important factor when considering whether to invest in the CryoHub technology

- **80%**

  were slightly interested, very interested or extremely interested in investing in CryoHub technology.

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