Large scale energy storage

CryoHub

Developing Cryogenic Energy Storage at Refrigerated Warehouses as an Interactive Hub to Integrate Renewable Energy in Industrial Food Refrigeration and to Enhance Power Grid Sustainability

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691761.

Deliverable D3.1

Report on current and future benefits of CryoHub

Deliverable Information
Dissemination : Public
Nature : Report
Contractual Delivery Date : 30.06.2017
Actual Delivery Date : 23.09.2017

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Document Information

Project	: CryoHub
Document	: D3.1
Filename	: D3-1 Report of the potential benefits of CryoHub for grid balancing S1.docx
Last saved on	: 23/09/2017 17:17 by Jacques BERTRAND

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Release Details

Release	Date	Comments
Draft 01	01/12/2016	First draft
Draft 02	14/07/2017	Second draft after assessment by Reviewer(s)
Release 01	22/09/2017	First release for approval by Coordinator
Submitted	23/09/2017	Submitted to the Commission

Distribution List

- On the project Portal
- On the CryoHub Intranet (http://cryohub.psutec.com/)

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Acronyms

CAPEX – Capital expenditure
CES-Cryogenic energy storage
CHP – Combined heat and power
IC – Internal combustion
LA – Liquid air
LAES – Liquid air energy storage
NPV – Net present value
OPEX – Operational expenditure
PRU – Power recovery unit
PV – Photovoltaics
RTE – Round trip efficiency

1. Executive Summary

Work package 3 (WP3) was designed to assess the potential benefits of an innovative technology solution, a CryoHub, for grid balancing. Cryohub technology embraces Cryogenic Energy Storage (CES), intermittent renewable energy and unlike few CES systems, previously built around the world and focusing on power generation, CryoHub relies on utilising the released cryogenic cold to facilitate the operation of food storage warehouses. The potential for grid balancing, including the assessment of barriers and drivers to technology adoption, was enabled by data from industrialists. Six companies were selected from representative European countries: United Kingdom (UK), Belgium, Spain, France, Hungary, and Bulgaria. Each company is a refrigerated warehouse or food factory consuming substantial electrical power (average of 500kW) for refrigeration purposes. Cross-company comparisons were carried out to identify similarities and differences. The findings in this report suggest that the business case for grid balancing using Cryohub technology are highly dependent on energy tariffs. The results suggest that trade associations and lobbying groups, representing refrigerated warehouses, should collaborate with policy makers to develop a long term roadmap embracing CES technology. The roadmap should be aimed to maximise the economic and environmental viability of the technology. In addition, the roadmap should capture national, local and international prerequisites of CES in Europe.

2. Context

2.1. CryoHub overview

The CryoHub innovation project investigates the potential of promising technology- cryogenic energy storage (CES) to solve the problem of how to store excess renewable energy. With more and more of our energy coming from renewable energy sources, such as wind, tidal or solar power, there is heightened risk of fluctuations in our future electricity supply, due to the unpredictability of weather patterns. Applications that store excess energy from periods of high production, for release during periods of low production or high energy demand, is currently very limited (Luo *et al.* 2015[1]), but would be of great significance to the energy industry. Cryogenic energy storage has great potential to improve electric power grids and to enable growth in renewable electricity generation.

Cryogenic energy storage (CES) uses cheap, off-peak electricity to convert air into a liquid, which can then be stored over a long period of time in a storage vessel. CryoHub hopes to improve CES efficiency by aligning it with pre-existing cooling and heating facilities found in industrial refrigeration warehouses and food processing plants. It is hoped that clever design and integration of existing equipment for cooling and heating processes will enable sufficient efficiency gains to be made to make the technology market-viable in the near future. CES is not yet efficient enough to be rolled out on any scale, as the system currently has relatively low ‘round-trip’ efficiency when the energy going in is compared to the energy coming out.

2.2. Overview of work package (WP3)

Industrial cold storage facilities can become a more active player within the grid by either selling excessive on-site generated electricity or by improving the power grid balance through smart temperature control, involvement of thermal energy storage (TES) and energy management, thereby providing substantial economic benefits to the cold store operator (Fikiin, 2012[2]; Fikiin and Stankov, 2015[3]). Thus WP3 assessed the potential benefits of CryoHub adoption for grid balancing. To demonstrate the breadth of solutions, this work package examined six refrigerated warehouses or food factories in Europe: United Kingdom, France, Spain, Hungary, Belgium and Bulgaria. The aim was to look in detail at two of the cases which had most potential for current grid balancing, also considering data collected on renewable energy generation sources identified in WP2; and then to undertake a cross-case comparison.

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[1] Luo, X., Wang, J., Dooner, M. and Clarke, J. (2015). Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied Energy, 137, pp. 511-536.

[2] Fikiin, K.A. (2012a). Integration of renewable energy in the cold storage sector. Info Pack 11 of the EU Project ‘Improving the Cold Storage Equipment in Europe (ICE-E)’. Available from: http://www.khlim-inet.be/drupalice/case-studies#infopacks.

[3] Fikiin K.A. and Stankov B.N. (2015). Integration of renewable energy in refrigerated warehouses. Chapter 22, In *Handbook of Research on Advances and Applications in Refrigeration Systems and Technologies.* Eds: Gaspar P.D. and da Silva P.D., 1st edition, Engineering Books, IGI Global, Pennsylvania, USA, pp. 803-853.

Work Package 3 (WP3) *"Current and Future Benefits of CryoHub"* has one main objective: To identify the potential benefits of CryoHub for grid balancing at up to 6 diverse (size, country and weather) refrigerated warehouses or food factories.

2.3. Purpose of deliverable (D3.1)

The six refrigerated warehouses or food factories were used to examine the variability of potential benefits of CryoHub for grid balancing. Other benefits of CES technology such as operational resilience, security, meeting carbon targets were also determined. The case studies were also used to identify barriers to implementation, including policy barriers and national differences of the six countries relating to adoption of CES.

3. Methodology

3.1. Overview

Given the socio-technical nature of WP3, a multi-method approach embracing both qualitative and quantitative data was applied to: data collection and analysis.

3.2. Types of data collection

Companies were identified in four of the six country blocs identified in WP2:

- Belgium (Benelux)
- Hungary and Bulgaria (Central and Eastern Europe)
- France and Spain (Mediterranean countries)
- United Kingdom (UK and Ireland)

There were no companies in the Nordic and Baltic countries nor in Germany and Austria, due to a combination of factors including: larger shares of renewables in the electricity grids of these countries (there is less motivation for these governments to subsidise or promote increased distributed renewables), sparse distribution of local renewable energy (which could be used by refrigeration companies if they don't have their own renewable energy generation), and lack of country representation on the project. The 6 companies provided the diversity intended for the study: size, country and weather.

Three methods of data collection were employed: interviews, questionnaires, empirical data collection.

3.2.1. Interviews and questionnaires

Engaging via interview with senior managers and/or owners of refrigerated warehouses or food factories facilitated the collection of data regarding the potential benefits of CryoHub for grid balancing and perceived barriers to CES technology adoption. Questionnaires were in addition used to collect data in a structured format regarding site details, skills, technologies in use,local/national regulations and incentives for energy reduction. Questionnaires were issued prior to interview and completed post interview. Both interview notes and completed questionnaires were returned for verification to the respondents, and corrections were incorporated into WP3 data records.

3.2.2. Empirical data collection

Additional information on: energy consumption (15 minute interval data) and generation (where applicable) was collected via electronic systems, where we were provided with access, or via spreadsheet tables of actually energy. These data invariably spanned more than one year, demonstrating diurnal, weekly and seasonal variations.

3.3. Types of data analysis

Three methods were used for data analysis: single case study, comparative case study and numerical analysis of the business case for investment.

3.3.1. Case studies

Case studies were conducted using empirical, industry and academic sources. Note that the literature review is included in academic article D3.2. Brief case summaries are provided following thematic analysis of interview and questionnaire transcripts, as well as identification of benefits and barriers.

3.3.2. Case studies using numerical analysis

Numerical analyses were conducted for two of the case companies. These sites had the greatest potential to demonstrate the practical applicability of the CryoHub system, due to their spatial location, access to renewables, and strategic intent of the firms (such as self-sufficiency aims, energy saving targets, or environmental good agendas).

The first, a cold store warehouse in Spain (*Case B*), was located close to a solar installation. As we did not have real generation data for the solar installation near the cold store, software was used to predict the solar generation at this site for 2016. Data from the “NASA surface meteorology and Solar Energy” was used. The import tariff was determined by using tariffs from 6.1 to 6.5 (>450 kW). The different tariffs depend on the voltage level of the connection. In this tariff set, there are 6 tariff periods. We did not have information about export tariffs for the customer as they did not have any renewable energy. It is likely to be based on the market price. The import tariff was also determined from the wholesale price. The export tariff was considered as the import tariff minus the service costs. The import tariff was calculated as 32 per cent higher than the export tariff. This was based on the average service costs during the period of March 2016.

A second cold store warehouse, in Belgium (*Case C*) with renewable energy generation on site was chosen. The energy generation of the solar PV installation every 15 minutes during 2016 was obtained. The import tariff and export tariff was provided by the cold store warehouse. In addition *Case C* has been used to illustrate potential benefits of the CryoHub technology for grid balancing. Case C, which is intended as a demonstrator site, was further analysed using numerical techniques by considering alternative scenarios.

3.3.3. Comparative case analysis

Cases were compared to identify similarities and differences, particularly relating to potential benefits and barriers to CES adoption for grid balancing.

4. Results and discussion

4.1. Overview

This section presents the results of investigations into the potential for grid balancing at six companies across Europe. First, an overview is provided of each case study, noting that the identity of the company has been anonymised. Next, a numerical analysis of two of the cases (companies in Belgium and Spain) are presented. Then, a cross-case comparison is presented identifying future benefits and barriers. The section ends with a discussion of the results.

4.2. Case studies

4.2.1. Case A – United Kingdom

This company is a large dairy product manufacturer, widely regarded as environmentally responsible, and having environmental and carbon reduction targets. The company's strategic direction encourages the use of renewables and innovation technologies. There is also a robust distribution network for feed-in purposes. Product quality and safety is key, so chill stores require continuous refrigeration. Operational patterns are very consistent with regular daily work patterns (6am to 8pm), reflecting consistent year-round demand for their products. Present production capacity is limited and an increased in chill storage warehousing is anticipated.

4.2.2. Case B – Spain

This company is concerned with growing, processing and storing locally grown vegetables, which are sold to customers who then brand and also export to international buyers. The local community is 'green' oriented. The facility is approximately 6 years old and is an energy efficient facility. The company is open to generating from renewables in principle, for their own use only, although they are not actively pursuing this. National best practice guides exist in Spain for technologies used in this plant which give ranges for usual consumption of electricity, water and wastewater. A fixed part of the electricity (40%) is purchased through the distributor. For the variable part, there is a fluctuating national price and electricity can be bought or sold in advance. An attractive, no longer available, government feed in tariff has resulted in difficulties selling energy to the grid.

4.2.3. Case C – Belgium

This privately owned company is located adjacent to a French fries processor. Waste from the potato peelings are used in a bio-generator partially owned by the owners of the case C cold store. The owners of case C are working on creating a smart grid for the site (cold store and French fries processor) that incorporates PV, bio-generation and CHP. The owners also wish to install a wind turbine in the near future. The facility is not yet running at full capacity so it is able to support an increase in demand.

4.2.4. Case D – France

This large family owned group operates industrial sites across the world, involving frozen and canned foods. They collect vegetable waste from local farmers and use it to produce electricity using biomass technology. The related electricity transformer is hosted by the company which allows them to get a discount from the distributor. The company has planned growth around 10%, having both space to accommodate capacity growth and capability to acquire competitors. They have no grants for energy efficiency but they have been collaborating with main energy supplier to create a long-term road map for renewables.

4.2.5. Case E – Hungary

This privately owned company is a refrigerated storage offering local chilled distribution. Turnover is around 1 million Euros and energy costs are second only to labour costs. Getting skilled labour is an issue. The facility operates 2 shifts over a 16 hour day (5am-9pm). Investment in cooling, moving ramps, storage racks, insulation and lighting over the last 2 years have reduced energy costs. Energy cooling reporting is required by the government but there are no government targets to reduce consumption as 40% of grid energy is nuclear. The company is able to offer sophisticated services to customers to control their own inventories.

4.2.6. Case F – Bulgaria

This 2010-built site stores and distributes foodstuffs to over 85 locations nationally. Labour has been cheap but with skills shortages and competition this is more challenging. There is little automation and operations are kept simple to avoid complex maintenance and servicing issues. The site is resilient with diesel generator supply in the event of grid outage, but with a 20kV transformer on site, outages are rare. The facility is at full capacity. Growth will occur at another site. Energy prices are relatively cheap so there is little incentive for own renewables generation. The regulator requires reporting on refrigerant use.

4.2.7. Case tabulation

The cases are tabulated in Table 1. There are two small stores with less than 0.5 MW average power (Hungary and Bulgaria), two medium stores (UK, Belgium) between 0.5 and 1 MW and two large stores (Spain and France) with more than 1 MW of average power. Three of the stores (UK, Belgium and France) have local renewable generation. Tariff data varies widely with some companies have no option for cheap overnight rates. Most companies have a chilled and frozen store (Spain, Belgium, Hungary and Bulgari). One has only a chilled store (UK) and one has only a frozen store (France). Some have freezing tunnels (Spain and Hungary). The numbers of rooms, and capacities varies widely as do methods for refrigerant. Products can vary widely (Hungary, Bulgaria) or be focussed (UK- dairy, Spain, Belgium, France – vegetable). Company targets toward energy technologies varies widely, with Belgium having very strong ambitions to be energy self-sufficient, others perceive opportunities to use cheaper rate energy (Hungary), or to reduce consumption (Spain), some are considering own energy generation (UK, France) whilst others are not motivated to reduce energy (Bulgaria).

Table 1: Operational and site features of the six case studies

Case study	Mean Power of cold store (MW)	Mean Power of renewables (PV) (kW)	Type	Refrigeration system	Products	Targets/aims
Case A United Kingdom	0.8	37	Chilled store 3ºC and 5ºC	R404A	Yoghurts, milk, butter, cream, and rice pudding.	To maximise the use of renewables and innovative technologies.
Case B Spain	2.7	0	Chilled store 3ºC and 5ºC Freezer store -25ºC	unknown	Entirely vegetables – peas, broccoli, carrots, cauliflower, potatoes, etc.	To reduce energy costs by working to an upper limit for consumption of key utilities /Kg of product.
Case C Belgium	0.6	105	Freezer -20ºC and -18ºC	Ammonia	Potato fries, ice-cream	To become a 'virtual power plant' by adding: wind turbine 2.3MWp; gas turbine (gas from grid) 5.2MW. To deliver and optimise energy for themselves and partner site.
Case D France	4.9	0	Freezer -18°C	Ammonia	Peas, broccoli, corn, carrots, cauliflower, beans and onions	To use biomass technology to generate electricity To reduce 3% of energy consumption on a yearly basis
Case E Hungary	0.2	0	Cold store – 4 separate rooms Freezer -20ºC	R404a	Meat, chicken, fish, fruit, dairy, frites, pizzas, ice cream	Plans to buy cheaper energy at night and overcool -22ºC or -23ºC avoiding some power use in the daytime.
Case F Bulgaria	0.3	0	Ambient 11ºC to 19ºC Cold stores 0ºC to +5ºC Freezer -24ºC to -28ºC	CO_2, ammonia and glycol	Fruit, vegetables, dairy, meat and chocolate	No energy reduction targets and national energy relatively inexpensive and clean

4.3. Case specific analysis

This section considers the electrical consumption and generation of two of the cases: Spain and Belgium. This is in order to identify the times of day that liquid air should be generated and consumed in order to have most benefit.

4.3.1. Case B – Spain

Electrical consumption of the cold store did not follow any pattern, e.g. seasonal or daily, and therefore was considered for this analysis as having a constant base load with a large degree of random fluctuation. The solar generation obviously followed both seasonal and daily patterns as it is proportional to the sunlight at any given time. It was assumed for the sake of this analysis that the solar site matched the average consumption of the warehouse on a particular day. The day chosen was 20th March 2016 (spring equinox). This would mean that the solar site would be in deficit in the winter and producing more energy than required in the summer.

The *Figure 1* below illustrates the electrical consumption of the warehouse and the generation from the solar installation. The energy consumption and generation have been normalised to an average of 1. The reduction in energy consumption between 6 and 10 hours is due to the random fluctuation as described earlier and therefore only particular to that day. On average we can assume that the consumption is constant. The solar generation follows the amount of sunlight as expected. From this result we can see a deficit of energy during the early morning and late night where energy will need to be imported and a surplus of energy during the day when energy would be exported. If the export tariff was higher than the import, which you would expect in a wholesale market (as the network needs to cover its costs), then it would be beneficial to store the excess energy during the day and use it in the evening, therefore meaning that no energy was imported.

However, two extra things need to be considered, firstly, the energy storage mechanism is not 100% efficient therefore not all energy stored will be transferred and secondly the price of energy varies during the day. The import and export tariffs during the day have also been presented in *Figure 1*. The wholesale import and export tariff follow each other, as they are only separated by a service cost. The contract tariffs for the warehouse approximately follow the wholesale price. The price of electricity is cheapest during the early morning and is most expensive in the evening for both types of tariff. The most sensible use for CryoHub appears to be to store energy between 08:00 and 15:00 when the tariff is low and to use the stored energy between approximately 19:00 and 21:00 when the tariff is highest.

If we consider the contract tariff and assume that the cost of export is the same as the cost of import, then the ratio in tariffs between the two periods is 1.23. For it to be cost effective would require a storage efficiency (round trip efficiency) of 81%. If we consider the wholesale price the maximum ratio between wholesale import and export is 1.11, requiring a storage efficiency of 90%.

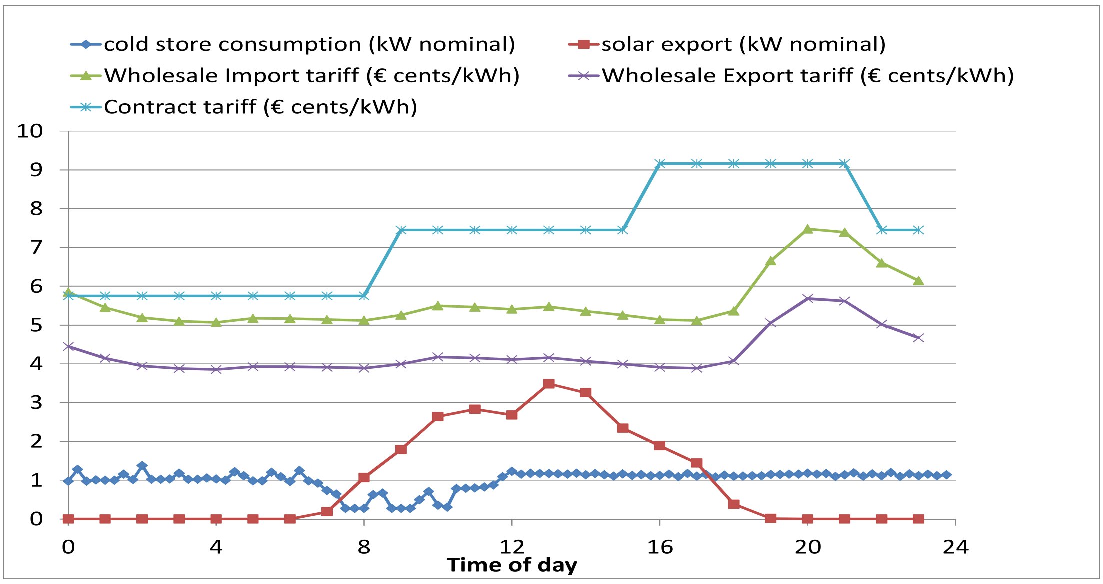


Figure 1: Electrical consumption of case B

The round trip efficiency of the type of CryoHub system planned for the project has been predicted as 46.5%. A best possible efficiency of 79.5% with 800ºC of waste heat has been predicted.

4.3.2. *Case C – Belgium*

Electrical consumption of the cold store did not follow any pattern, e.g. seasonal or daily, and therefore was considered for this analysis as a constant base load with a degree of random fluctuation as for Case B. This is an important consideration in the adaptation of CryoHub, as the cold store load will need to be matched with the renewable energy. The solar generation obviously followed both seasonal and daily patterns as it is proportional to the sunlight at any given time. An analysis was done on the 20th March 2016 (spring equinox). This was chosen as half way between winter and summer.

Figure 2 provides the electrical consumption of the warehouse and the generation from the solar installation. The solar generation follows the amount of sunlight as expected. It appears that the day chosen was under cloud cover for part of the day as the generation rises and falls unexpectedly. For a period of 15 minutes in the middle of the day when the cloud cover lifted there was a surplus of energy from the PV installation and therefore the facility was exporting to the grid. This can be seen where the net import becomes negative at 12:00. If another day which was not cloudy was chosen, there would likely be a surplus of energy (export) for a longer period.

Normally the energy in this period would be sold at the export tariff of €3.195 cents per kWh. However, if the energy was stored using CryoHub technology and released at a later time in peak period it would save importing electricity at the rate of €10.735 cents per kWh. This assumes the CryoHub system is able to absorb the entire capacity of cold energy. However, the energy storage mechanism is not 100% efficient therefore not all energy stored will be transferred. In this scenario (excluding capital costs) as long as the CryoHub storage was more than 30% efficient, then the storage would potentially be financially viable.

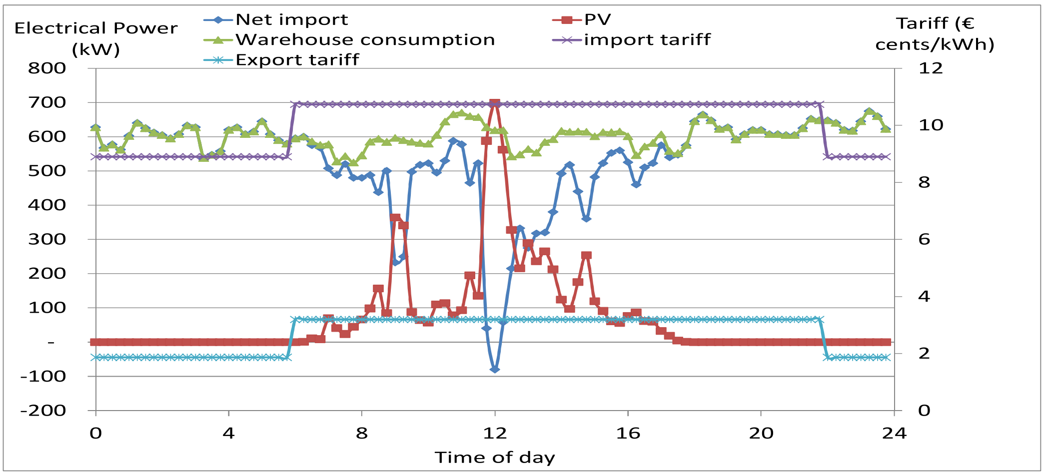


Figure 2: Electrical consumption of case C

The round trip efficiency of the type of CryoHub system planned for the project has been predicted as 46.5%. A best possible efficiency of 79.5% with 800°C of waste heat has been predicted. These efficiencies assume that the cold energy generated in the cryogen evaporation process is usefully used in the cold store warehouse and liquefaction plant.

4.4. Case C – Belgium – deeper numerical analysis

The benefits of the CryoHub technology would most likely be maximal if Company C and its partner site (who process potatoes) were considered as one entity. Therefore, the analysis of the benefits has been carried out considering the whole site. Currently the site has PV, connected to the Company C site and Bio-CHP connected straight into the grid. In the short term a CHP (gas turbine) will be connected to the partner site. A wind turbine is at the early stages of planning, also to be connected to the partner site.

4.4.1. Current energy generation profiles

In 2015 there was an overall deficit in energy to the site. Only very occasionally was there surplus energy. This is shown in *Figure 3*. When the electrical consumption is negative, this means that energy is exported to the grid.

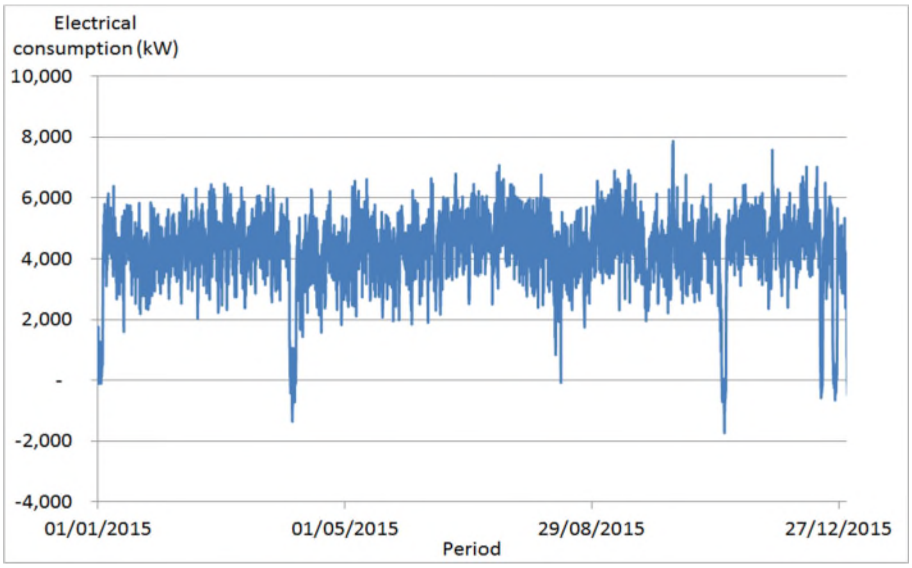
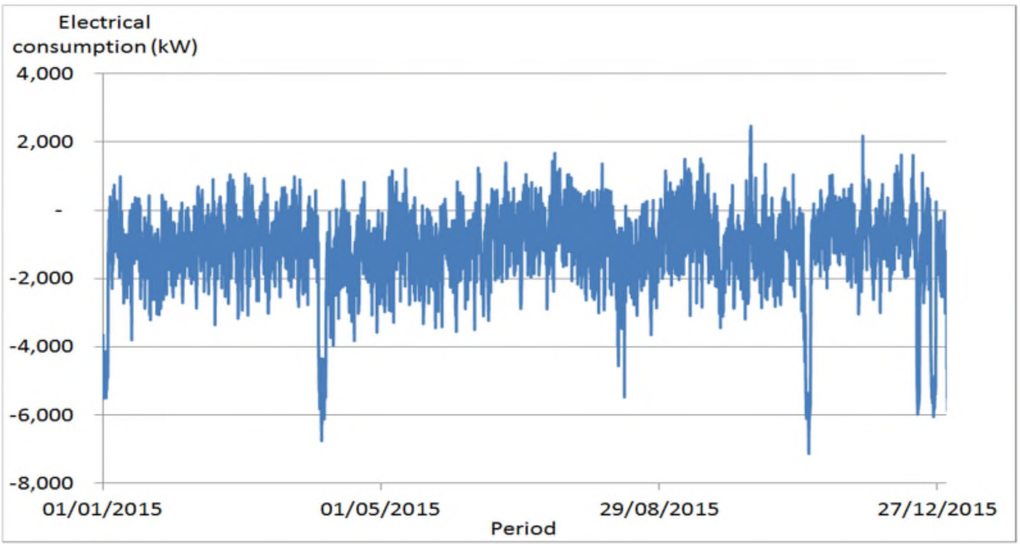


Figure 3: Electrical energy consumption over 2015 for the whole Partner - Company C site

In the future, a 5.4 MW_e CHP system is to be installed. If we assume this system provides exactly 5.4 MW of electrical power all the time, the electrical consumption profile will look as shown in Figure 4. This means that there will be surplus of energy exported to the grid. If applied to 2015 data this fluctuated between 7.1 MW exported to 2.5 MW imported with a mean of 1 MW exported.



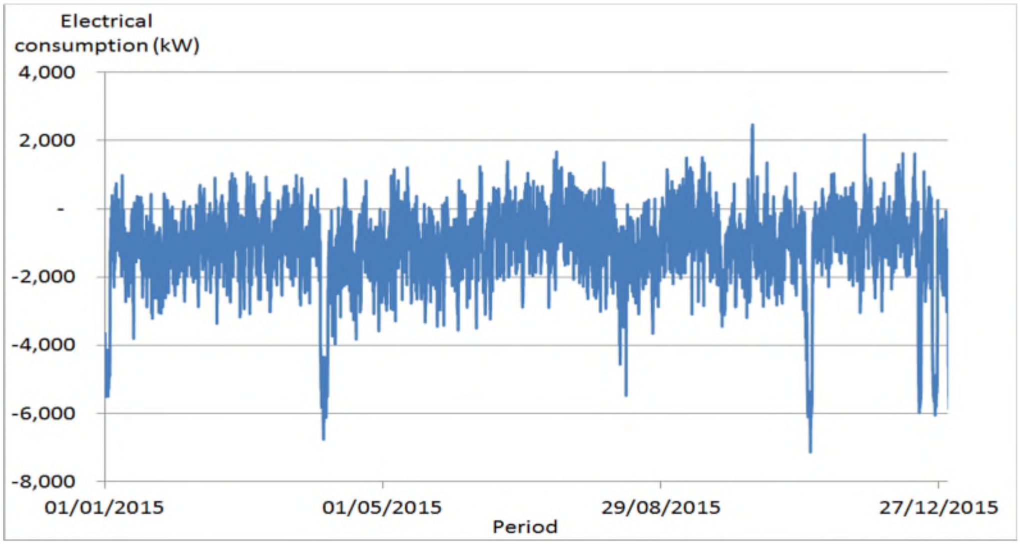


Figure 4: Electrical energy consumption based on 2015 figures for the whole Partner - Company C site with the CHP system included

4.4.2. Future energy generation profiles

There are several potential scenarios for the use of arbitrage by the inclusion of CES, specifically the use of liquid air energy storage (LAES) and siting LA generation:

- Arbitrage based on storing energy off-peak and generating at peak *(scenario 1)*
- Arbitrage based on storing PV energy with balanced (no net import and export) generation and demand *(scenario 2)*

- Arbitrage based on storing wind energy with balanced (no net import and export) generation and demand *(scenario 3)*
- Arbitrage based on the wholesale market price *(scenario 4)*
- Generating LA in a centralised location *(scenario 5)*
- Electricity generation from supplied LA + (Waste Heat Recovery) system *(scenario 6)*
- *Creating a Cryohub (scenario 7)*

These are discussed below. Regarding the first two scenarios, arbitrage involves simultaneous buying and selling of energy in different markets or in derivative forms in order to take advantage of differing prices for the same asset.

4.4.2.1. Scenario 1 – Arbitrage based on storing energy off-peak and generating at peak

In the situation where the PV, bio-CHP and CHP systems are included the whole site exports on average 1.0 MW of power, **Error! Reference source not found.**5 shows the mean daily electrical consumption (green points) for the Company C site. The fluctuation of energy during the day caused by the PV panels can be seen as a dip in the electrical consumption (or increase in export) during the middle of the day.

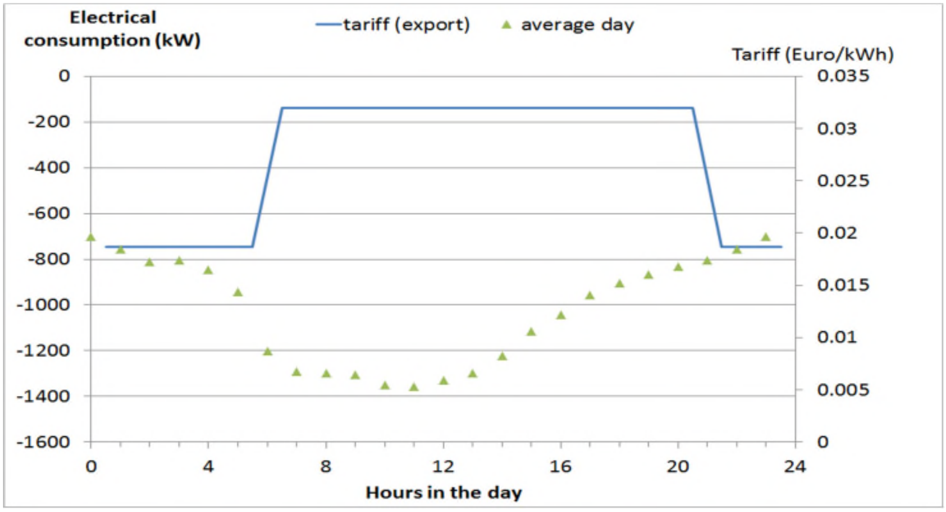


Figure 5: Electrical energy consumption based on an average day in 2015 for the whole Partner - Company C site with the CHP system included (green) and with the CHP output reduced (blue)

It can be seen that the consumption is always negative which means that on an average day there is always a surplus of energy generation. Based on this fact, on average over the course of a day there is no need to store energy for the site itself as the site is always exporting energy. However, there is a difference in the export price between peak and off-peak times (blue line). Due to this there could be an economic case for storing the energy during off-peak time (7.5 MWh) and exporting during peak times. Currently the 24.5 MWh per day of energy is sold for 683 Euro, if the off-peak energy (7.5 MWh) were sold at peak times the revenue would be increased to 783 Euro, a profit of 100 Euro per day or 36,500 Euro per year. It is assumed that all surplus energy is stored and usefully used with a 100% Round Trip Efficiency (RTE).

Based purely on shifting tariffs there is a benefit of storing energy at the low tariff and selling at the high tariff. However, the cost of the LA system should also be taken into account when assessing feasibility. To allow the equipment costs to be estimated, the capacity of key components of the above LAES energy arbitrage scenario have been determined. These are shown below.

- Turbines with an electrical power output of 500 kW (this is based on the 7.5 MWh stored being discharged over the 15 hour peak electrical tariff period);
- Liquefaction system with a peak power of 1.2 MW (mean of 0.84 MW), this is the maximum generation in off-peak hours;
- LA storage of 36 tonnes (based on energy density of discharge turbine of 0.207 kWh/kgLA).

4.4.2.2. *Scenario 2 –Arbitrage based on storing PV energy with balanced (no net import and export) generation and demand*

Another scenario is to have an overall balance between generation and demand on the same day where storage would be used to balance demand. To create this ‘perfect balance’ where there is ‘net-zero’ electrical consumption the energy profile can be maintained but shifted upwards (as shown by the blue points in Figure 7). In this case the electrical generation needed is lower than previously deployed (4.4 MW_e instead of 5.4 MW_e). The variation caused by the PV leads to a deficit in generated power in the early and late hours of the day and a surplus of power during the middle of the day. There is now a potential opportunity to store power at peak generation and use it when generation is low (i.e. no net import of energy to the site occurs). The tariff for import and export at peak and off-peak times are also shown in Figure 6.

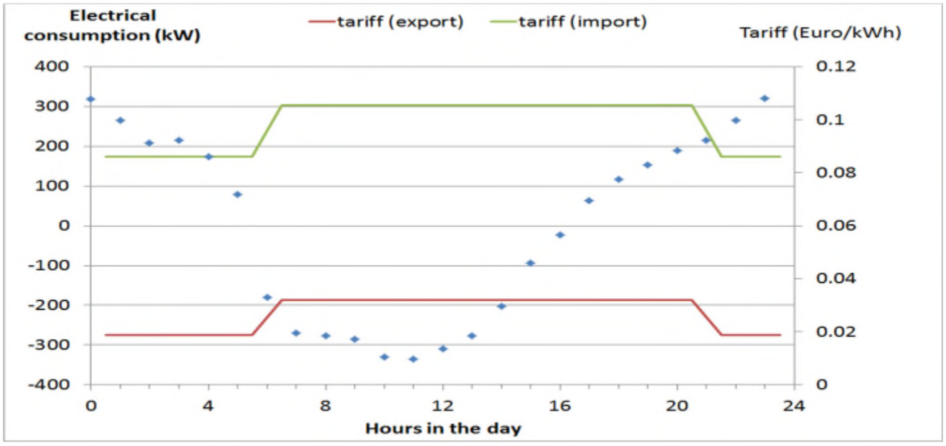


Figure 6: Electrical energy consumption based on an average day in 2015 for the whole Partner - Company C site with the CHP output reduced (blue) and import and export tariffs

The cost (without arbitrage) of the energy in each hour of the day based on the import and export tariff at peak and off-peak times is shown in Figure 7. In this scenario, there is no net export or import and so the average energy consumption is zero. The cost of import during the early morning and late evening is more than the generation price during the day due to the import tariffs being more than the export tariffs. The total cost (without arbitrage) of electricity (import minus export) is calculated as 156 Euro per day or 57,100 Euro per year which is the saving that can be achieved. If the peak capacity component of the electricity bill is also removed (assuming 400 kW peak) this gives a total saving of 59,900 Euro. It is assumed that all surplus energy is stored and usefully used later with a 100% RTE.

The specification of a LA storage system for the above scenario is:

- Turbines with an electrical power output of 320 kW (peak consumption shown in Figure 6);
- Liquefaction system with a peak power of 335 kW (mean of 235 kW), this is the peak generation power;
- LA storage of 12 tonnes (based on energy density of discharge turbine of 0.207 kWh/kgLA).

Scenario 2 generates more revenue with a smaller plant (therefore lower capital cost) than scenario 1 Therefore it is a better scenario in terms of providing a better financial return. This shows that with the current tariff levels that LA works better where there is import and export of energy rather than just export.

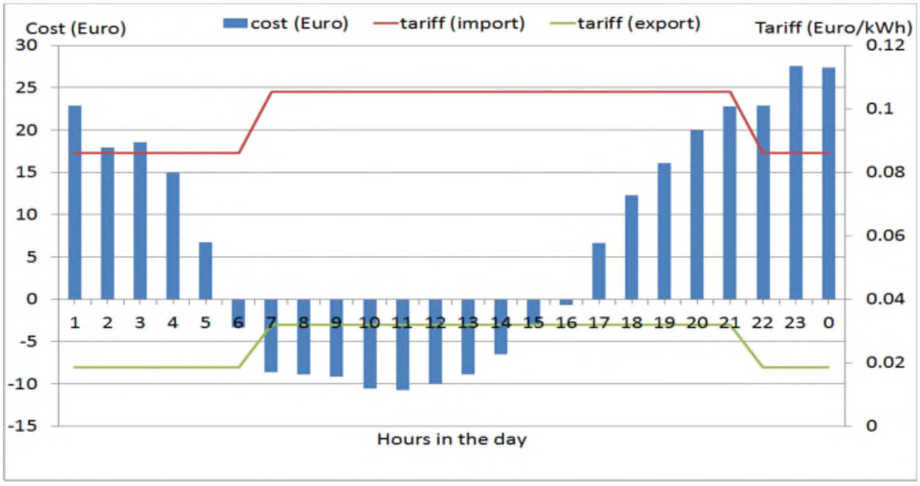


Figure 7: Electrical energy tariffs and income and expenditure based on an average day in 2015 for the whole Partner - Company C site with a reduced output CHP system included

4.4.2.3. Scenario 3 – Arbitrage based on storing wind energy with balanced (no net import and export) generation and demand

A wind turbine is planned to be installed in this scenario future. When this is added the current situation (Scenario 1) it will make the surplus of energy even greater and therefore will make a LA system less attractive. Therefore, the following analysis examines a balanced system (like Scenario 2) with a wind turbine rather than PV. The wind turbine provides a more ‘peaky’ and less consistent energy generation than PV. Data from the wind resource prediction department in CENER was used to produce wind velocity for a 10 m high (hub height) wind turbine at the Company C location for 2010. This wind velocity data was transformed into power generation over the year (*Figure 8)*. The wind turbine is proposed to have a peak of 3.6 MW electrical power. To create a ‘perfect balance’ as described earlier (‘net-zero’ electrical consumption as in scenario 2), a constant electrical load of 0.88 MW (mean power of wind turbines over the year) is required. It is assumed that all surplus energy is stored and usefully used with a 100% RTE. The net benefit in having zero energy imported is 248,000 Euro per year.

The specification of a LA storage system for the above scenario is:

- Turbines with an electrical power output of 880 kW (power generation when wind not blowing);

- Liquefaction system with a peak power of 2.7 MW (mean of 2.2 MW), this is the peak generation power required when considering the constant site load (0.9 MW);
- LA storage of 692 tonnes (based on energy density of discharge turbine of 0.207 kWh/kgLA).

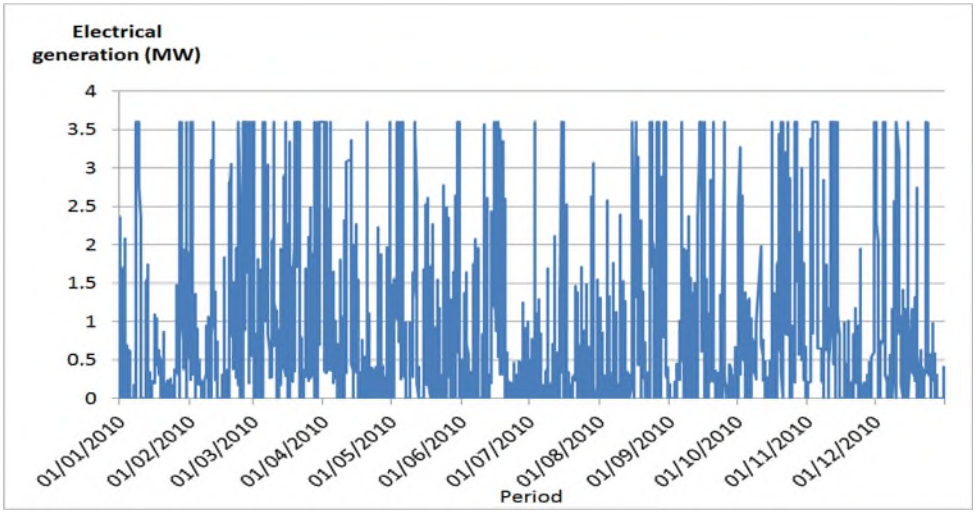


Figure 8: Predicted electrical energy generation of a 10 m high 3.6 MWp wind turbine at Company C site based on 2010 wind data

For these scenarios, the various capital and operational costs, Net Present Value, Revenue, capital cost and payback are considered next.

a) Capital and operational costs of LAES

Capital and operational costs vary depending on scenario. The costs are based on the following components: Turbines, Skid, Heat Exchangers (HE), Liquefaction, Liquid Air (LA) storage, and cold air storage. Liquefaction makes up around half of the costs. The specific cost estimates are shown in *Table 2*.

Turbines have been costed at 400 Euro/kW, based on steam turbines for an industrial food application[4]. A turbine for this application is not 'off the shelf'. Therefore, there would be non-recurring engineering (NRE) costs. Therefore, these costs are based on building and selling in large numbers.

Heat exchangers have been costed at 123 Euro /kW[5]. The Liquefier has been costed at 0.382 * kW input + 2160 thousand Euros from data from 3 different sized plants

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[4] http://www.steamturbo.com/industry-application/sugar-factory-vrbatky-29.html

[5] https://www.brunel.ac.uk/__data/assets/pdf_file/0005/468113/Heat-exchangers-for-industrial-heat-recovery-Sam-Jouhara.pdf

provided by Air Liquide[6]. LA storage has been costed at 700 Euro per tonne (Air Liquide). Cold air storage has been assumed to be the same cost as LA storage. The skid has been estimated as the same value of 300 000 Euro for every scenario. There is large uncertainty about this cost.

Table 2: Cost of equipment for the three different scenarios

	Scenario 1	Scenario 2	Scenario 3
Turbines (€)	200,616	128,113	351,826
Skid (€)	300,000	300,000	300,000
HEs (€)	154,224	98,487	270,466
Liquefaction (€)	2,618,590	2,287,974	3,199,206
LA storage (€)	25,440	8,734	484,593
Cold air storage (€)	25,440	8,734	484,593
Total (€)	3,324,310	2,832,042	5,090,685
Payback time (years)	91.0	47.7	20.5

These calculations assume a RTE of 100%. For a lower RTE, payback period will increase. For an 80% RTE, which is feasible with high temperature waste heat of 800ºC (which should be available from the CHP plant), the payback period would rise by a factor of approximately 25%. This assumes that the waste heat is not used elsewhere, but if it is already usefully used elsewhere the value of this heat should not be taken into account.

It should be noted that energy tariffs are likely to change in the future and that the payback period would be reduced if the difference in price between import and export were increased.

The capital cost of the liquefier is by far the most expensive item. However, its price does not increase much as the system increases in price. This leads to two conclusions. Firstly, the payback improves as the system gets larger. This can be seen with scenario 3. Secondly, it implies that much of the cost of the liquefier is fixed cost which would stay the same if the quantity of liquefiers sold increased. Therefore, the payback period could be reduced with economies of scale. An economic system would be too large for the company C site and therefore needs to be shared with other operators to reduce the capital cost.

b) Net Present Value (NPV)

An NPV assessment has been carried out on scenario 3. A 4% discount rate (provided by Company C) has been used as well as a yearly operation and maintenance cost of 3% of capital value. This makes the payback well over 100 years.

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[6] https://www.airliquide.com/

c) Revenue

It is possible to assess the potential paybacks of the CryoHub system to the other case study sites by considering the income that could be generated by the different tariffs at different times and the capital cost of the CryoHub system.

Table3 shows the tariffs (€ per kWh) at different times for each of the case study sites.

Table 3: Electrical energy consumption tariffs for the different case studies

	A	B	C	E
Import night	0.0741912	0.0575	0.0861	0.074778
Import day	0.1176936	0.0745	0.10545	0.074778
Import evening	n/a	0.0916	n/a	n/a
Export night	0.04332	Not known	0.01865	0.049852
Export day	0.04332	Not known	0.03195	0.049852

From this we can calculate the minimum RTE that could generate revenue (N.B. this excludes capital costs). This value is the ratio of the tariffs used in the arbitrage. We can also calculate the revenue (€ per kWh stored). This revenue assumes an RTE of 0.8. The revenue is directly proportional to the RTE, so the values can easily be recalculated with different RTEs.

Four scenarios have been chosen;

- Always import (store from grid at night to generate during day);
- Always import (store from grid at night to generate during evening);
- Always export (store from RES at night to generate during day). N.B. will not work with PV;
- Net zero import and export (store from RES during day and generate at night). Assume PV.

The minimum RTE required to generate revenue and the revenue at an RTE of 0.8 for the different scenarios and case studies is shown in Table 4.

Table 4: Minimum RTE and potential revenue generated for the different case studies for the different scenarios

	A	B	C	E
Always import (store from grid at night to generate during day)				
Minimum RTE	0.630	0.7718	0.817	1
Revenue RTE (€/kWh)	0.035	0.0136	0.015	0
Always import (store from grid at night to generate during evening)				
Minimum RTE	n/a	0.628	n/a	n/a
Revenue RTE (€/kWh)	n/a	0.02728	n/a	n/a
Always export (store from RES at night to generate during day). N.B. will not work with PV.				

Minimum RTE	1	Not known	0.584	1
Revenue RTE (€/kWh)	0	Not known	0.011	0
Net zero import and export (store from RES during day and generate at night). Assume PV				
Revenue RTE (€/kWh)	0.059	Not known	0.069	0.02

For the final scenario (net zero import and export) there is no minimum RTE, however, the ratio of the energy generated to that stored is the RTE. Therefore if the RTE is 0.8, only 80% of the energy stored will go back to electrical energy generation. From these results it can be seen that by far the best income per kWh stored is for the net zero import and export scenario.

d) *Capital cost and payback*

The above evaluation was based solely on revenue. The following assessment includes capital cost and payback. The following costs were based on the Highview system (Highview, 2012). They assume 4 MW liquefaction, 10 MW power generation and 4 hours of storage. This provides a 40 MW capacity. The unit is assumed to charge in 10 hours and discharge in 4 hours every day. This is a larger system the company C, however, in the same order of magnitude. The cost (CAPEX) of the LAES system in million € for the 10 MW power system (PRU) and larger versions is given in Table5 as well as the cost for 1st of kind (FoK), 10th of kind (OK) and 100th OK. A factor of 0.6 was used to scale the systems (meaning a 20 MW unit would cost $(20/10)^{0.6}$ as much as the 10 MW unit. A learning rate of 17.5% was used, meaning costs reduced by 17.5% each time the number of units was doubled.

Table 5: CAPEX for different size and number of systems

PRU (MW)	FoK (M€)	10th OK (M€)	100th OK (M€)
10	25.4	13.4	7.1
50	70.7	37.3	19.7
200	174.4	92.1	48.6

The revenue (in million €) for these system's for the best scenario (Net zero import and export, Company C) is shown in the *Table 6*. It is based on an RTE of 0.8.

Table 6: Revenue (in millions €) for the systems

PRU (MW)	FoK (M€)	10th OK (M€)
10	1.01	1.01
50	5.07	5.07
200	20.28	20.28

A simple payback period (in years) has been calculated by dividing the CAPEX by the yearly revenue in the table 7.

Table 7: An illustration of a simple payback

PRU (MW)	FoK (years)	10th OK (years)	100th OK (M€)
10	25.1	13.2	7.0
50	13.9	7.4	3.9
200	8.6	4.5	2.4

If we consider an NPV assessment on a 10th OK system at 10 MW PRU, assuming there are no operational and maintenance costs and a 4% discount rate, we arrive at a payback period of 19 years and for 100th OK of 9 years. Therefore the economic justification at the smaller (10MW PRU) system is challenging, unless the numbers of units are very large. Whereas a FoK system at the large scale (200 MW) would payback in only 11 years. This indicates that the system is more suited to a large grid scale system rather than a small scale cold store warehouse based system, unless the numbers of very high.

4.4.2.4.Scenario 4 – Arbitrage based on the wholesale market price

The energy tariffs used by Company C are not very volatile. There are only two periods, off and on peak and the difference in price between the two periods is quite small, reducing the amount of revenue that can be generated by arbitrage. It was therefore considered to look at prices on the UK wholesale market. These are the prices that energy was traded each hour in 2016, when bought one day ahead. They varied between a minimum of £7.05 per MWh to £999 per MWh with a mean of £40.44 per MWh. Based on this there appears a much larger potential for arbitrage compared to the Company C tariffs. If it was possible to arbitrage on every unit of energy over the year (2016), so that energy was purchased each hour below the modal energy (£35.00 per MWh) and sold when above, the profit would be £111,000 per MW traded. This is based on a total energy consumption of just buying the energy of £355,000 per MW. To do this requires always being able to store the energy when below the modal price. Figure 9 shows that the system would continue to store LA from February to May, storing a total of almost 1800 MWh and then would discharge until the end of the year.

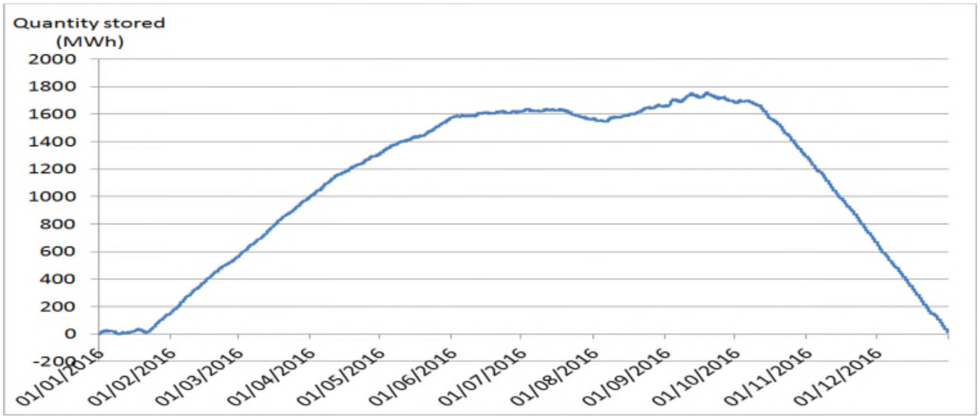

Figure 9: Quantity of energy stored during the year, if the LA system had no limit to its storage capability

It is not practical to have a LA system which will store over such a long period. Therefore, it has been assumed that no more than 12 hours (12 MWh) energy can be stored. For this scenario (*Figure10*) the difference in buying and selling price is now £39,845 per MW traded. The reduced value is because not all of the energy can be stored. This can be seen in February to May when the storage is mostly at its maximum. There will also be times, particularly in November and December when the discharge is needed but the storage is empty. The capital expenditure calculated for a 1 MW turbine, 1 MW liquefaction and 12 MWh storage is €3.6 million. Based on this yearly revenue the payback period is 78 years, not including the cost of investment or running costs. This is worse than scenario 2 because although the revenue is higher, the capital costs are even greater. For this scenario, the average buying price was £29.84 and selling price was £45.39 per MWh. For Scenario 2 energy is bought for £95 per MWh and sold for £29 per MWh. Therefore, there is a larger difference in the tariffs for the Company C scenario 2 than for the wholesale price scenario, which is why the payback is better.

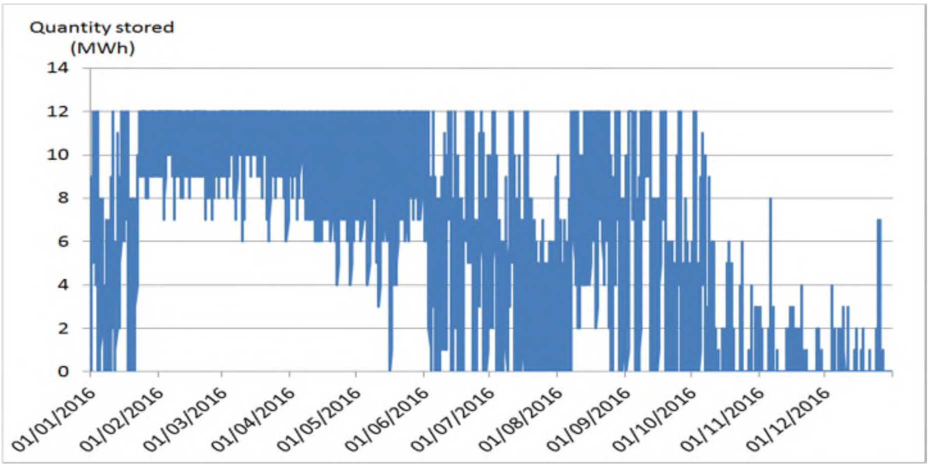

Figure 10: Quantity of energy stored during the year, if the LA system had a 12 hour (12 MWh) storage capability

4.4.2.5.Scenario 5 – Generating LA in a centralised location

The previous scenarios assumed that LA were generated on site using a liquefaction system. The cost of the liquefaction system was the major factor causing the business case to look unattractive. Therefore the following scenario was investigated to examine the LAES without a liquefaction system. For this case, LA is supplied rather than created on site (based on a LA tank mixing LO2 and LN2). According to reasonably achievable LA discharge calculations (60:1, 4 stages expander running at 87.5% efficiency and recovering heat at 800ºC), 0.233 kWh of electrical energy could be generated per kg LA, or, conversely, 4.29 kg LA would be required per kWh of electricity generated. For the system to be economically viable the cost of energy used to produce LA needs to be less than or equal to the energy tariff multiplied by the cost of energy generation as shown in Equation 1.

$$
\begin{aligned}
&LAIR\ production\ cost_{per\ kg} \\
&\leq LAIR\ Energy\ Tariff * LAIR\ Energy\ generation_{per\ kg}
\end{aligned}
$$

Equation 1: Production cost viability

The economic benefit depends on the tariff difference between LA production and discharge. The data provided by Company C gives us the following thresholds for economic viability (using the highest buying tariff of 10.7353 c€/kWhe for Company C) as shown in Equation 2.

$$LA\ production\ cost_{per\ kg} \leq 10.7353\ \frac{c€}{\mathrm{kWhe}} * \ 0.233\frac{\mathrm{kWhe}}{\mathrm{kg\ LA}} = \ 2.505\frac{c€}{\mathrm{kg\ LA}}$$

Equation 2: Threshold for economic viability

It is now possible to compare the LA production costs against this threshold and find out if having a simplified LAES could be economically beneficial. This gives the energy cost of producing LA and assumes there are no extra costs e.g. CAPEX. The capital costs of the liquefactor are estimated using preliminary costs of small-to-large scale LA production plants provided in *Figure 11*.

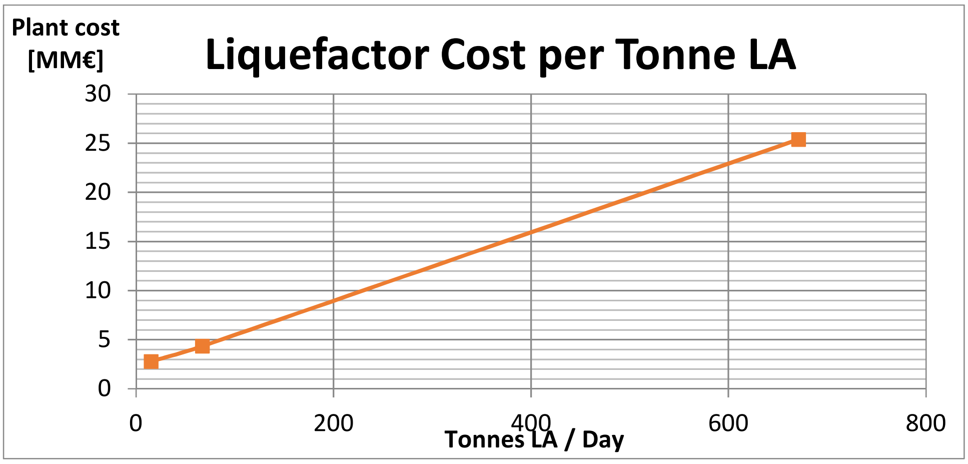

Figure 11: Liquefactor cost trend with tonnes LA / day

Assuming the capital investment comes at a cost of 4.5% interest rate, 5% maintenance cost (increasing at 4.5% inflation YoY), and personnel cost being twice the maintenance cost, one can estimate the total investment needed to produce LA. Since the plant would be operated during night time to reduce OPEX, one can assume the total LA production being a fraction of the nominal maximum production if the plant was operated continuously. This leads to the following costs calculated in *Table 8* and plotted in *Figure 12*. The trend tends to be exponential and converging towards 3.3 [c€/l LA].

Table 8: Cost Items for varying liquefactor sizes

Tonnes/day	MM€	Capital cost [MM€]	Maintenance Cost [MM€]	Personnel Cost [MM€]	Total Cost [MM€]	Investment Cost per liter LA [c€]
1	2.389796	3.373708504	1.321484102	2.642968204	9.727956	213.22
4	2.477443	3.497441227	1.369950301	2.739900601	10.08473	55.26
16	2.829416	3.994325694	1.564580312	3.129160623	11.51748	15.78
64	4.259447	6.013120776	2.35534383	4.71068766	17.33859	5.94
128	6.221262	8.782643286	3.440167834	6.880335668	25.32440	4.34
256	10.33383	14.58841654	5.714293486	11.42858697	42.06512	3.60
512	19.31473	27.26687596	10.68045537	21.36091073	78.62297	3.37

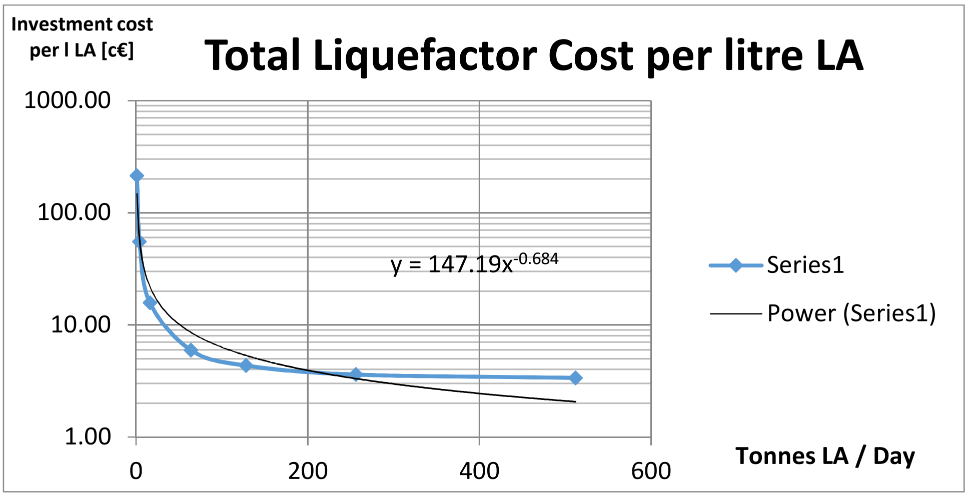

Figure 12 Total liquefactor costs varying with liquefactor size

4.4.2.6.Electricity generation from supplied LA + (Waste Heat Recovery) (Scenario 6)

The energy intensity of LA production is in the range of $0.460 \text{ (current technology ASU) } \frac{kWhe}{kgLAIR}$ (data produced by modelling a "standard" air separation unit (ASU) with variable design parameters and no cold-energy-recycle). We can calculate the cost of LA productions using the lowest export tariff of 1.865 c€/kWhe (Company C) as shown in Equation 3.

- $LA\ production\ cost_{per\ kg} = [0.46]\frac{kWhe}{kgLAIR} * 1.865\ \frac{c€}{\text{kWhe}} = [0.858]\ \frac{c€}{\text{kg LA}}$

Equation 3: LA production cost

It is assumed that the LA is produced using surplus electrical energy generated on the remote site from renewables, which would normally be sold to the grid. With these numbers, it seems reasonable to conclude the system might be feasible. Adding the distribution costs of LA for 100 km (using Spiritus Consulting estimates of £1.5-1.75 /22 tonne/km = [0.008522 ; 0.009943] c€/km/kg); brings the cost per kgLAIR to the range [1.7010; 1.8523] euro cents as shown in Equation 4.

$$Delivered\ LA\ cost_{per\ kg} = [0.858]\frac{c€}{\text{kg LA}} + 100\ km * [0.008522\ ;\ 0.009943]\ c€/km/kg$$
$$= [1.710\ ;\ \ 1.8523]\frac{c€}{kgLAIR}$$

Equation 4: LA production cost including distribution costs

These figures would give a net benefit to the user per kgLAIR to the range [0.795; 0.6527] euro cents as shown in Equation 5.

$$2.505\frac{c€}{\text{kg LA}} - [1.710\,;\ 1.8523]\frac{c€}{kgLAIR} = [0.795\,;0.6527]\frac{c€}{kgLAIR\ used}$$

Equation 5: Net benefits

Which, translates into a profit per kgLAIR to the range [3.412; 2.801] euro cents as shown in Equation 6.

$$[0.795\,;0.6527]\frac{c€}{kgLAIR\ used}\Big/0.233\frac{\text{kWhe}}{\text{kg LA}} = [3.412\,;2.801]\frac{c€}{kWhe\ Produced}$$

Equation 6: Profits

For a 1 MWh system on a daily discharge cycle this converts into a benefit of **34.12 to 28.01 €/year.** Assuming daily energy price fluctuations occur only Monday to Friday, one gets 260 working days a year, meaning a net **return on investment (ROI) of 8,871 €/year**.

Typical turbomachinery equipment runs at around 400 €/kW installed (see earlier). A realistic cost of engineering works and liquid air storage tanks can be considered as two times that of the discharge turbine (800 €/kW). A total LAES system installed cost of 1200 €/kW. Considering the case where the Company C plant wanted to be grid independent, it would need 2582 kWh stored and a peak discharge power of 320 kW. Therefore, a €384,000 investment, with a ROI given by the 2,582 kWh discharge (€22,912) would give a **payback time of 16.8 years**.

This result, doesn't consider the benefit of having the cooling capacity created by the LA evaporation. Therefore, the investment may be more attractive if coupled with a refrigerated warehouse facility or with RES incentives or compulsory energy storage electrical grid requirements, as happens in some parts of the EU already.

4.4.2.7.Scenario 6 – Creating a Cryohub

Due to the high capital cost of a liquefaction system, it may be financially beneficial to share the CAPEX by using the LA generated by the liquefaction system for other purposes. The price of cryogenics, much like other items, is related to the quantity you purchase, therefore there is a potential cost reduction in utilising more cryogenics on site. Some other uses of LA for the cold store warehouse include: LA application in fast freezing, LA application in refrigerated transportation, the Dearman refrigerated truck, air application in effluent treatment, and integration with refrigeration system. These are discussed below.

a) Liquefied air application in fast freezing

Cryogenic food freezing processes use either liquid nitrogen or liquid carbon dioxide for food freezing. These inert air fluids offer a valuable alternative to traditional mechanical chilling and refrigeration systems that generally use artificial refrigerants. There are significant advantages for food manufacturers in using cryogenic freezing and chilling solutions as compared to traditional mechanical systems:

- Compact equipment and less floor space needed thanks to extremely rapid freezing;
- Flexibility and speed of freezing, which increases the efficiency of the production chain;
- Freezing of delicate and perishable foods without affecting their taste or texture;
- Lower dehydration and higher product quality than with slow freezing systems.

Liquefied air is a cryogen that roughly has the same thermal properties than liquid nitrogen and which can therefore be used alternatively for food freezing.

b) Liquefied air application in refrigerated transportation

LA could potentially be used in food transport vehicles. Air Liquide have developed an innovative solution for cold storage truck transport known as Blueeze™ based on the use of liquid nitrogen. The air that circulates inside the refrigerated container is cooled through the circulation of liquid nitrogen cooled to -196°C in one or more hermetically sealed exchangers before the nitrogen is released as a gas into the atmosphere. This fully operational solution that is now deployed includes a supply station for the liquid nitrogen, the on board cold generator, and related services. It offers a more reliable way to ensure that the cold chain is not broken while also bringing exceptional environmental benefits to business and local government customers:

- Fast and highly controlled drop in temperature;
- Silent system, ideal for overnight deliveries and driver comfort;

- Zero polluting emissions during operation since the only by-product is nitrogen, the principal component of air;
- Sustainable: the carbon footprint is reduced by around 85% (France);
- Less need for maintenance and maximum availability, as well as consistent cold quality regardless of the age of the cold generator since the technology has no internal combustion motor.

The liquefied air that will be generated by the CryoHub system can replace the liquid nitrogen of the Blueeze solution, provided LOX cleaning of the circuit. Indeed, the temperatures and pressures levels of both cryogens are similar and the Blueeze designed heat exchanger can perfectly work with liquefied air. Even better, we can envisage a direct injection of liquefied air inside the refrigerated truck container without using a heat exchanger since this cryogen is breathable. Indeed, the heat transfer will be improved.

c) The Dearman refrigerated truck

The small footprint provided by LA storage and its intrinsic energy density make it possible to add it as a propulsion system for refrigerated trucks. This is the concept behind the Dearman engine. Heat from the refrigerated compartment is transferred to the engine expansion chamber via a heat transfer fluid. This heat makes the LA evaporate and increase in pressure, providing mechanical work to drive the engine. Refrigerated transport runs on cooling based on vapour compression cycles driven directly or indirectly by IC engines with an electrical or mechanical power offtake. The typical thermal efficiency of an IC engine is around 30-40%, while a refrigeration cycle would approach a coefficient of performance (COP) of 1.5 on a refrigerated truck. This means that the combined chemical energy (from diesel) to cooling power efficiency is around 45-60% (or in turn an effective COP of 0.45-0.6). LA production has a typical COP of 0.20, although this is lower than that for the IC system described earlier, the cost of electricity per kWh is much lower than the cost of diesel per kWh. This combination of power generation and cooling capacity makes for a clean form of refrigerated transport with no “on site” CO_2 production. When coupling LA production with RES, the entire refrigerated transport process could achieve 0 CO_2 emissions.

d) Air application in effluent treatment

Air is used in the aerobic biological wastewater treatment. It is injected in the form of fine bubbles by means of a compressor. It might be possible to replace this compressor by the air produced by the CryoHub system. Once again, this air can be recovered as a by-product from previous onsite cooling applications.

e) Integration with refrigeration system

If the LA storage system contained a liquefaction system as proposed above, then all of the cold generated during the energy generation would be more usefully employed in the liquefaction system. This would provide a better benefit than using it in the cold store, where the generation of cold by the existing conventional refrigeration plant is much more cost effective. If, however, the LA was delivered from an outside source, recovering the cold using heat exchangers placed within the cold store would be required to increase efficiency of the system.

4.5. Perceived benefits of CES

Perceived benefits from the case studies are summarised in *Table 9*. As demonstrated below, there were perceived benefits identified in United Kingdom, Spain, France and Belgium; but not in Hungary.

Table 9: Perceived benefits of cryogenic energy storage

Case A	**Case B**
▪ Good environmental kudos. ▪ Reduced electricity consumption. ▪ Will allow us to meet our environmental objectives. ▪ Satisfy our customer environmental objectives.	▪ One of the means for us to reach 100% renewable energy consumption.
Case C	**Case D**
▪ To provide targeted power to freezer tunnels especially during daytime use. ▪ To enable energy generated by PV during the day to be used during the night to help to lower storeroom temperatures to -25°C. ▪ The absence of feed-in-tariffs	▪ Can be used to shift consumption of electricity from expensive periods of high demand to periods of lower cost electricity during low demand.
Case E	**Case F**
▪ Use of a levy for grid connection would encourage local investment in alternative technologies	▪ By improving the overall efficiency of the power grid, we can use the storage to accelerate the broader adoption of renewable energy.

Companies A and B highlighted the benefit of environmental kudos to their companies, and that more generally the prevalence of environmental targets were shifting companies to increase their use of renewable technologies for energy use. Companies C and D noted that CES might help them increase usability of their renewable energies. The adoption of a CryoHub system could provide a way of storing power when available from renewable sources, particularly from intermittent sources such as wind and solar, to better match the supply of electricity to demand.

Company C also observed that should the government introduce a policy to discourage grid feed-in, such as through a reduction in feed-in-tariff rates, then it would make the Cryohub concept more attractive by reducing the pay-back period.

All companies, except Company E which perceived no benefit of on-site renewable technologies, noted the perceived ability to reduce energy costs through CES. Company F noted the potential to improve grid conditions whilst Company D noted the ability to shift demand to use the grid at times of cheaper tariffs. This ability to shift loads was also noted by Company C.

Company E (Hungary) noted that grid connection is currently free of charge. One of the distribution network operators is lobbying to levy a fee for the use of their network. This change in policy would benefit Cryohub technology adoption.

4.6. Perceived barriers of CES

Table 10 illustrates the key perceived company specific and policy barriers identified from the six countries.

Table 10: Barriers to cryogenic energy storage implementation

Case	Company barriers	Policy barriers
A	▪ Capital cost of installation ▪ Rate of return on investment ▪ Technical difficulties of operation and maintenance ▪ Not a desired core competence	▪ Don't know any barriers to CES.
B	▪ Don't know any barriers to CES	▪ Over-installation of renewable technologies limits grid feed-in potential
C	▪ Unfamiliarity with the technology ▪ Can't distribute electricity around site because of regulatory restrictions on moving electricity under public roads (around 3 sides of the site).	▪ Encouragement of large-scale renewable energy would discourage local energy production
D	▪ Safety ▪ Cost ▪ Payback ▪ Easy to use or not	▪ Lack of policy incentives
E	▪ Operational costs ▪ Better locations for renewable generation	▪ Potential for grid feed-in levy
F	▪ Operational costs ▪ Risk management ▪ Flexibility of action	▪ Not aware of any policy barriers

As shown in *Table 10*, from a company viewpoint, they were concerned with cost (Companies A, D, E and F). Specifically, Company A was concerned with capital cost whilst Companies E and F with operational costs. Companies A and D perceived the rate of return/payback a potential barrier. The same companies mentioned perceived barriers in the technical skills needed to make use of the technology. Company A mentioned they did not desire the use of CES whilst companies B and C were not familiar enough with the technology to comment.

Company C noted a practical barrier was the restriction of distributing electricity under/over public roads. In order to make use of electricity across a site it is possible that the CES location and renewable energy generation locations are not in the same place as refrigeration and electrical power needs. If a public highway may need crossing, then the siting of CES and renewable energy will need careful planning.

Company D raised a perceived barrier of safety. Some of the companies mentioned that using intermittent renewals as a feed for CES could act as an indirect barrier to CES adoption, namely, that should any subsidy for renewable energy be removed, it would make the business case for CES less attractive. It was suggested that trade associations or lobbying groups might help with keeping renewable subsidies in place. Company E noted that their spatial location in the country was not as favourable as those of other companies in respect of renewables effectiveness. Company E mentioned there was no source of renewable energy nor bio-waste available on their site.

Company F noted the need for risk management of technologies. Whilst technologies and innovations can give companies competitive advantage, if the technologies are poorly understood or not simple to operate, then they will result in costly mistakes. The adoption of Cryohub technology within the sector suggests that refrigerated warehouses or food factories will have to examine the technological risks meticulously and mitigate them effectively. It will be vital for the sector to fully develop their in-house capabilities. Company F was a subsidiary of a large group and did not have the flexibility or motivation to innovate other than in ways directed by headquarters.

From a policy viewpoint, Company B (Spain) noted that in 2007 the feed in tariff was established. All the capacity in Spain was installed in a 2-year period after which the Government cut the tariffs. The Government expected 500MW to be installed and they got 4,000 MW and so the cost to them of the feed in tariff was much inflated. The problem became such that the Government have actively put barriers in the way of people connecting to the grid. So now selling energy to the grid is a problem. A Government licence is required and they are not interested if the power production is not at large scale. There is also not a cost-benefit from the cold store point of view as there is now no feed in tariff and the company can achieve only a variable low rate. As a result, individual plants tend to install what they can consume only.

Company C (Belgium) observed that if the government is pro-active in raising the proportion of large-scale renewable technologies providing energy to the grid, then this would act as a deterrant for local renewable energy production. This was affirmed by Company F (Bulgaria) who noted that national energy production had a high proportion of renewables and so acted as a barrier to local/distributed innovation.

Company D (France) observed that the government supports small PV installations producing up to 50kWp (peak power) maximum which is aimed at the domestic market. There is no support for larger systems for companies. Also, there are no national grants for energy efficiency projects; grants are for buying equipment only. Otherwise, there were no perceived government or local regulatory barriers to cryogenic storage adoption, but there was also no visibility of CES technology, suggesting that trade bodies and lobbying groups need to collaborate with the food refrigeration industry to raise the profile of the technology and its particularly strong role in maximising economic and environmental viability for growing food refrigeration needs.

5. Conclusions and recommendations

5.1 Conclusions

Work Package 3 identified the potential benefits of CryoHub for grid balancing at up to six diverse refrigerated warehouses or food factories. The location of these refrigerated factories and their proximity to renewable energy sources or own renewables generation has a large bearing on their potential for technology adoption, as does the company technology appetite. Two of the six case studies had the potential for grid balancing and so numerical analysis were conducted for these.

Results for Company B suggest that there is no economic benefit in using the CryoHub system, even with a supply of high quality waste heat. This was due to their being no feed in tariff data for this company. If a feed in tariff was provided it may be low enough for the Cryohub technology to become viable.

For Company C, there is a potential economic benefit in using the CryoHub system, even without a supply of high quality waste heat. This result show that the difference in tariffs between import and export provide a potentially economically viable reason for storing renewable energy. The quantity of energy stored, frequency of operation and therefore money saved in a period (e.g. a whole year) has been considered and compared to the capital expenditure for the CryoHub storage system to investigate payback period. The benefits of CryoHub to store energy from a number of scenarios have been explored.

The perceived benefits of CES and Cryohub technology across all cases include reduced environmental impact and improved operational efficiency. It was also noted that the local grid would benefit from both reduced and time-shifted demand, improving the utility operator’s ability to meet their other demand. Barriers include capital cost and the need for technical capability. Political uncertainties relating to the government’s (changing) support (or not) for renewables was also a clear barrier as policies and subsidies could help to improve the business case for CES adoption.

5.2 Recommendations

There are emerging themes in the case studies analysed: motivation to act, flexibility to act, regulatory/policy influences, uncertainty. Each of these could developed:

- Some case companies are **motivated** towards the use of renewable technologies, including self-generation, and it is these who are most likely to understand the challenges of intermittency and recognize the value of site or plant level storage. Working more deeply with these companies to monitor changes in tariffs, technology costs, own demand changes, etc. will begin to identify the nearness of Cryohub technology when considered in parallel with business models for a variety of services, not just for capacity markets, but also for flexibility services.
- Some case companies have less **flexibility** to act. This is a result of various causes: recent investments in their facilities which have tied up their available funds; 'green' loans or subsidies not being very attractive; they are controlled by larger groups and cannot make local investment decisions. There is still opportunity to work with these organisations on medium or longer term horizons for investment or influence.
- Regulatory/policy influences and changing political preferences toward renewables are extremely difficult to predict and can change very rapidly. Whilst it clearly benefits the local grid if energy demand is reduced by refrigerated food companies, there is no monetary recognition. There is an opportunity to work with case companies who operate in distribution grids where capacity limits are regularly reached, in order to incentivise companies to self-generate.
- There is clearly uncertainty about Cryohub technology, its operational and safety needs, the potential for storage and the skills needed to arbitrage on energy markets. These uncertainties can be reduced through workshops, articles in food magazines, blogs, and other industrial and academic outlets, perhaps illustrating some basic implementation alternatives to make the technology solution more accessible. There is nevertheless an element of customisation for Cryohub as benefits are greatest when cross-site integration is achieved to reduce overall grid energy needs.

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