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 D11-3

Testing and optimisation report

Deliverable Information

Dissemination	: Public
Nature	: Report
Contractual Delivery Date	: 31.03.2021
Actual Delivery Date	: 31.05.2021

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Document Information

Project	: CryoHub
Document	: D11-3 Testing and optimisation report
Filename	: D11-03 Testing and optimisation report S1.docx
Last saved on	: 31/05/2021 08:01 by Jacques Bertrand/Judith Evans

Authorship and Review

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Written by	Alan FOSTER (LSBU)	27/05/2021
For review by	Judith EVANS (LSBU)	30/05/2021

Release Details

Release	Date	Comments
Draft 01	27/05/2021	First draft
Release 01	30/05/2021	Reviewed by Judith EVANS
Submitted	31/05/2021	Submitted

Distribution List

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

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1. Executive summary

CRYOHUB is a European collaborative project that aims to develop cryogenic energy storage using renewable energy to refrigerate food storage warehouses and to enhance power grid sustainability.

In its entirety, the CryoHub concept would contain the following subsystems:

Air liquefaction for storage of excess renewable energy or when demand is low

LA (liquid air) storage in a pressurized cryogenic vessel

Discharge of the LA for warehouse refrigeration and energy recovery when demand is high.

The CryoHub project includes design, build and testing of a demonstrator system which excludes the expensive and proven technology related to liquefaction, but which includes thermal storage, warehouse cooling and power generation from the discharged cryogen.

This deliverable details extended testing of the demonstrator over a range of testing profiles. The models developed in WP4 are used to extend the experimental results to a more realistic complete system.

2. Extended testing

2.1. Test schedule

To test the demonstrator's ability to run as in real life a schedule of tests was set up (Figure 1).

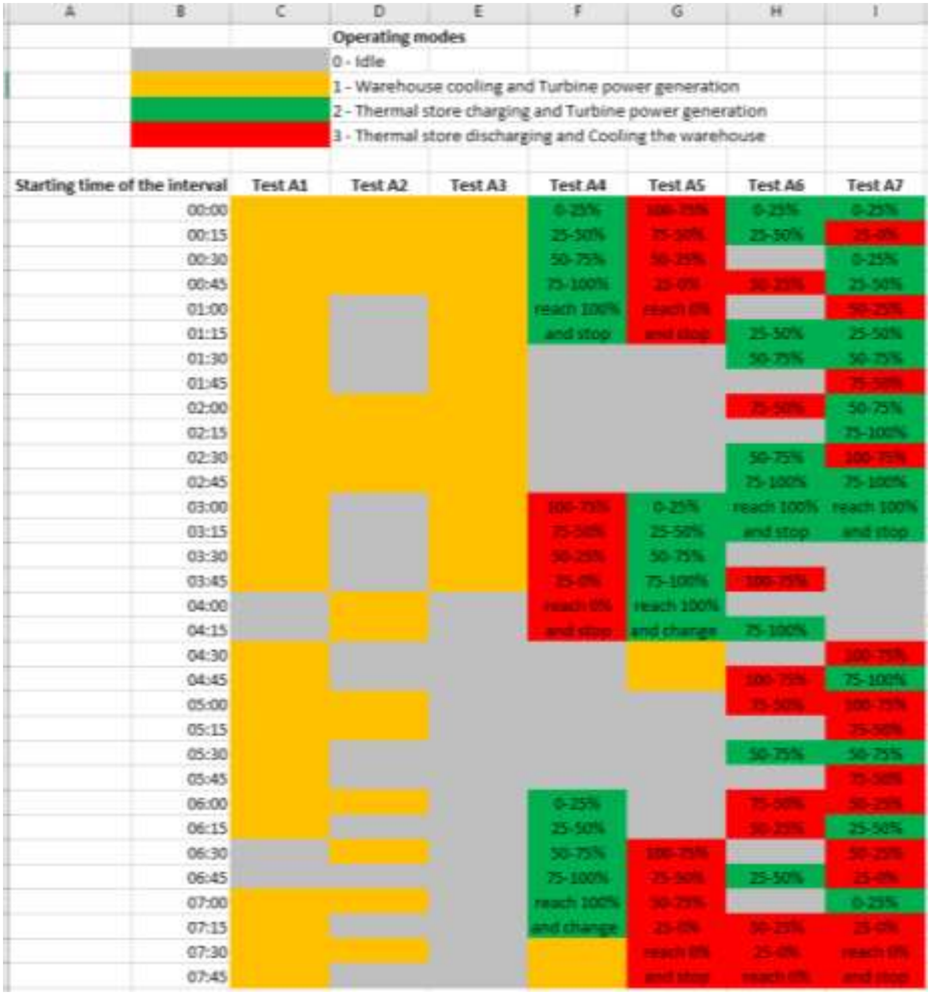

Figure 1. Test schedule

Due to the inability to discharge the thermal store because of the damaged fan, it was not possible to run test A4 to A7. Therefore, Tests A1 to A3 were run along with a test where the mode 1 was cycled every 15 minutes, called A15 and another where mode 1 was cycled every 30 minutes called A30. As it was possible to charge the store, another test was run (Test A1_2) where the system was cycled between mode 1 and mode 2 (coiling warehouse and charging store, both with power generation).

Test A1 and Test A2 and Test A1_2 are also shown in Figure 2.

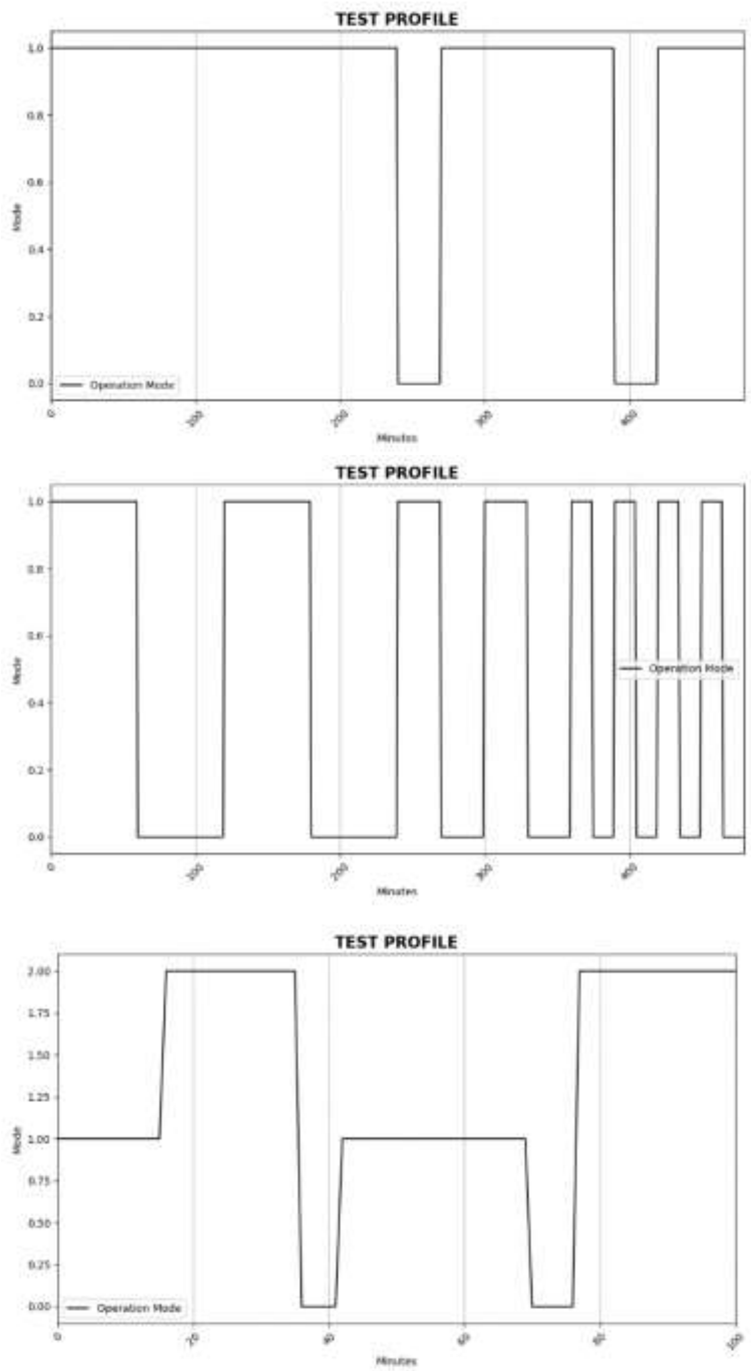

Figure 2. Test A1 (top), Test A2 (middle) and Test A1_2 (bottom).

2.2. Test results

Early in the tests it was found that the liquid nitrogen pump was unable to raise the pressure sufficiently and so the pump was by-passed and the pressure in the liquid nitrogen tank increased to provide sufficient pressure for tests.

Figure 3 shows the generated power from the turbines for Test A1. When the turbines consume power at start up and shutdown, this is shown as a negative value. It can be seen that through the series of tests the generated power decreases steadily from a maximum of 26.9 kW to a minimum of 18.4 kW, a reduction of 31.6%. The reason for the decrease in turbine power was due to a similar decrease in nitrogen flow rate which is also plotted in Figure 3.

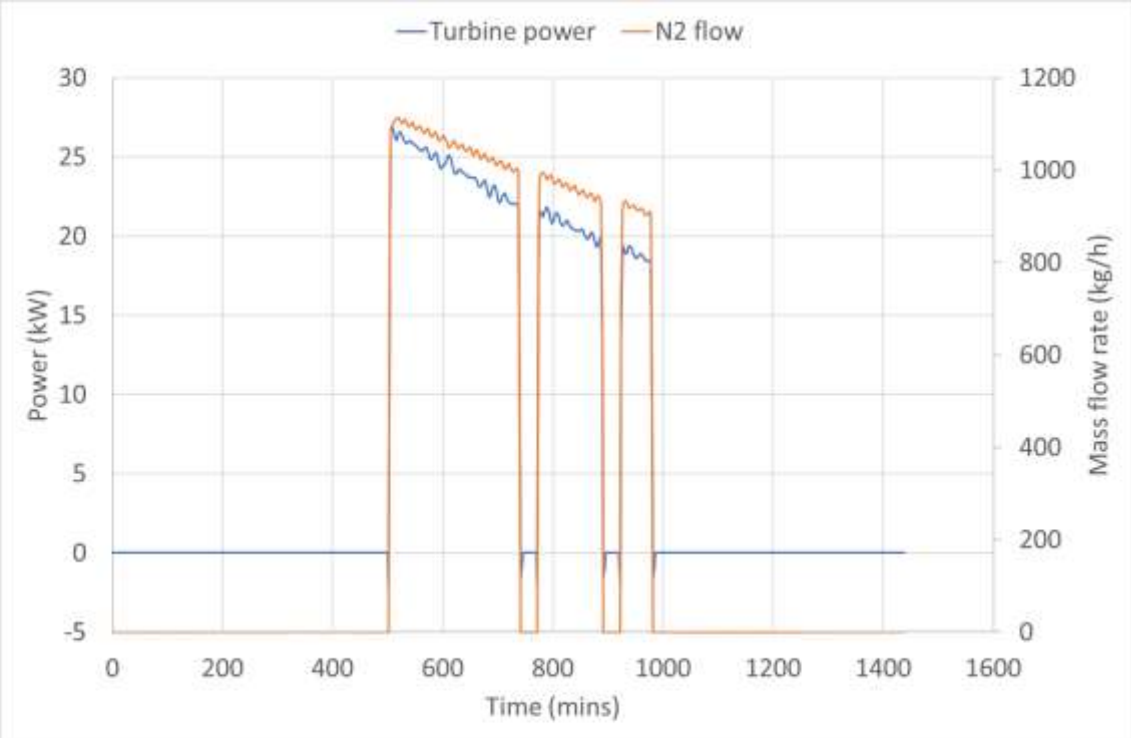

Figure 3. Generated power from the turbines and nitrogen flow rate for test A1.

The reason for the decrease in mass flow rate is due to a decrease in pressure from the vessel providing the liquid nitrogen shown in Figure 4. The drop in pressure was due to the naturally decrease in pressure as the nitrogen left the vessel. Between tests the pressure increased again due to ambient heating. If the pump had been capable of operation at the design conditions, the pressure would have been maintained during the tests.

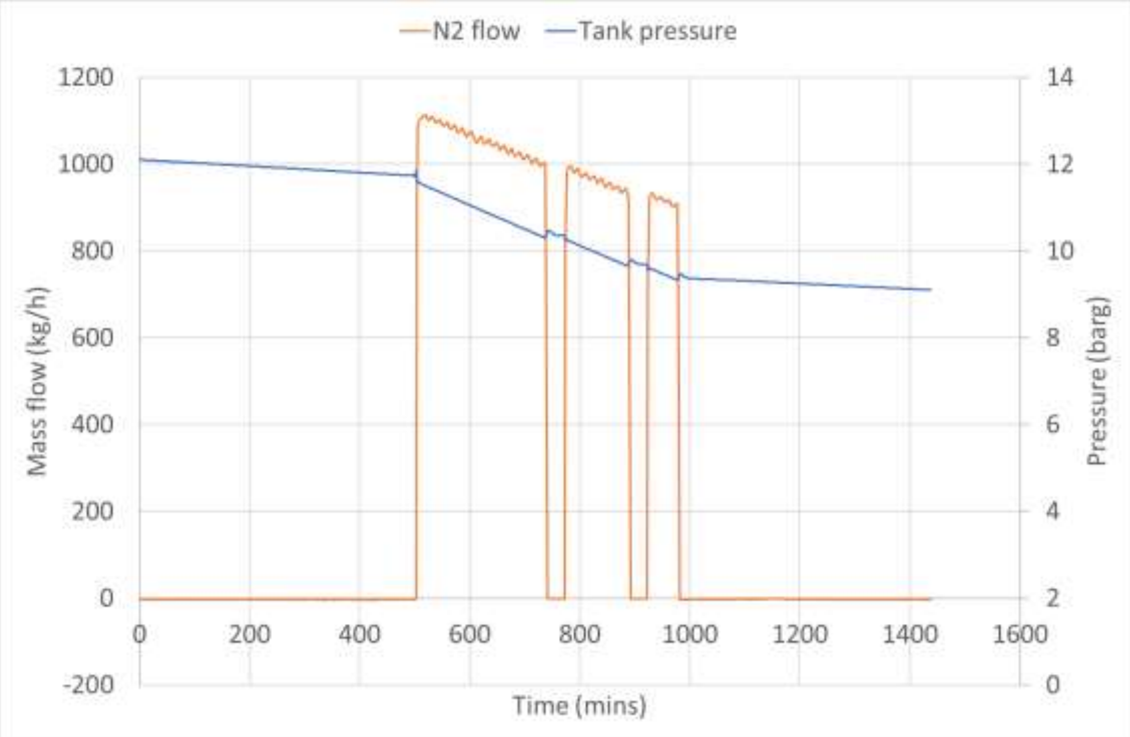

Figure 4. Nitrogen flow rate and pressure from nitrogen tank for test A1.

Figure 5 shows the heat extracted by the warehouse heat exchanger. It can also be seen that this reduced as the nitrogen mass flow rate reduced, from a maximum of 107 kW to a minimum of 82 kW.

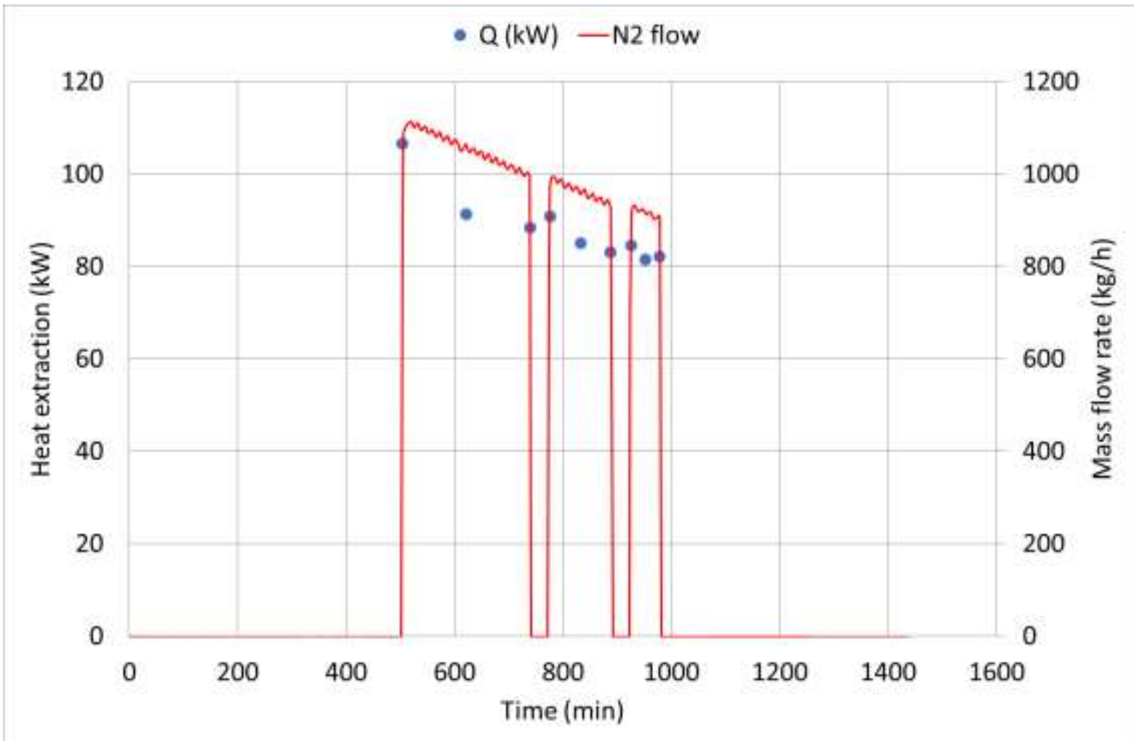

Figure 5. Heat extraction from warehouse heat exchanger and mass flow rate for test A1.

Test A15 was designed to test the performance of the system when cycling rapidly (15 mins on followed by 15 mins off, repeated 4 times). Figure 6 shows that the demonstrator was able to reliably generate power for this test scenario. Compared to Test A1 the generated power was higher at 30 kW, due to the higher mass flow rate, caused by higher nitrogen vessel pressure.

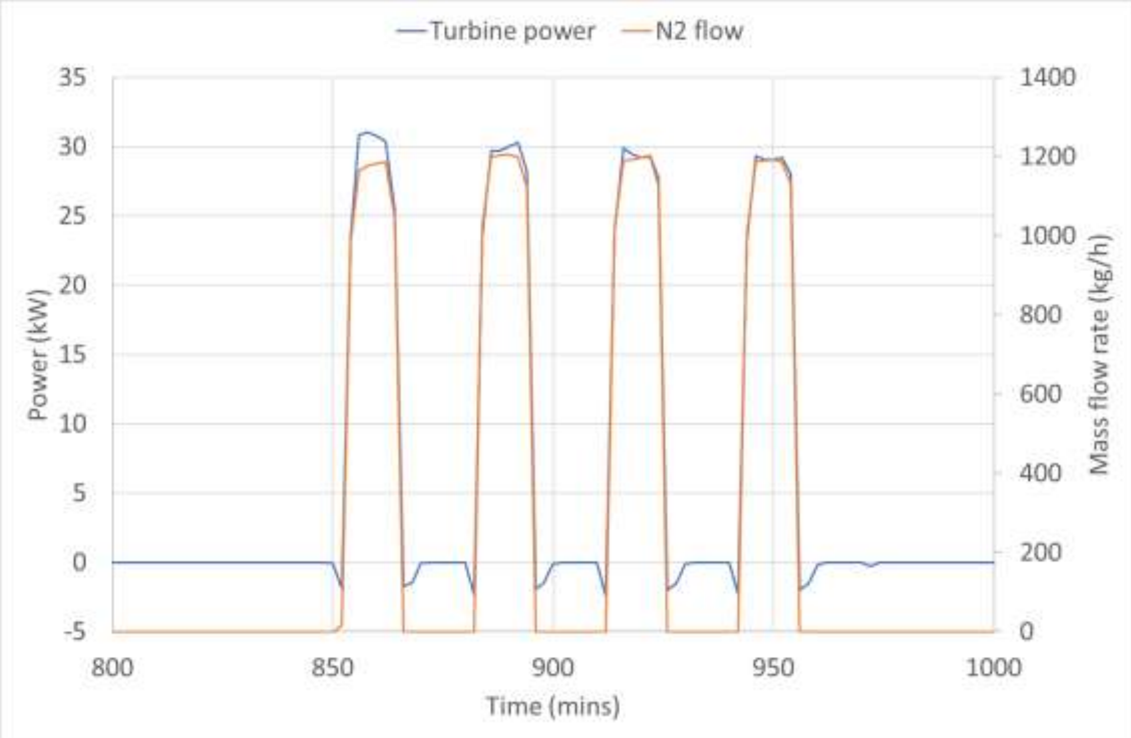

Figure 6. Generated power from the turbines and nitrogen flow rate for test A15.

Test A1_2 was designed to test the function of the system when running between modes 1 and 2. As can be seen from Figure 7, the generated power was similar (approximately 40 kW) whether cooling the warehouse or charging the thermal store. Apart from a drop in power at approximately 700 minutes during mode 2, the system was able to switch between modes and supply consistent power to the turbines. The drop in power at approximately 700 minutes was caused by a drop in nitrogen flow rate, caused by a drop in pressure from 14 to 9 bar to the turbine. It should be noted that even with this drop in pressure, the turbine continued to generate power and the pressure recovered.

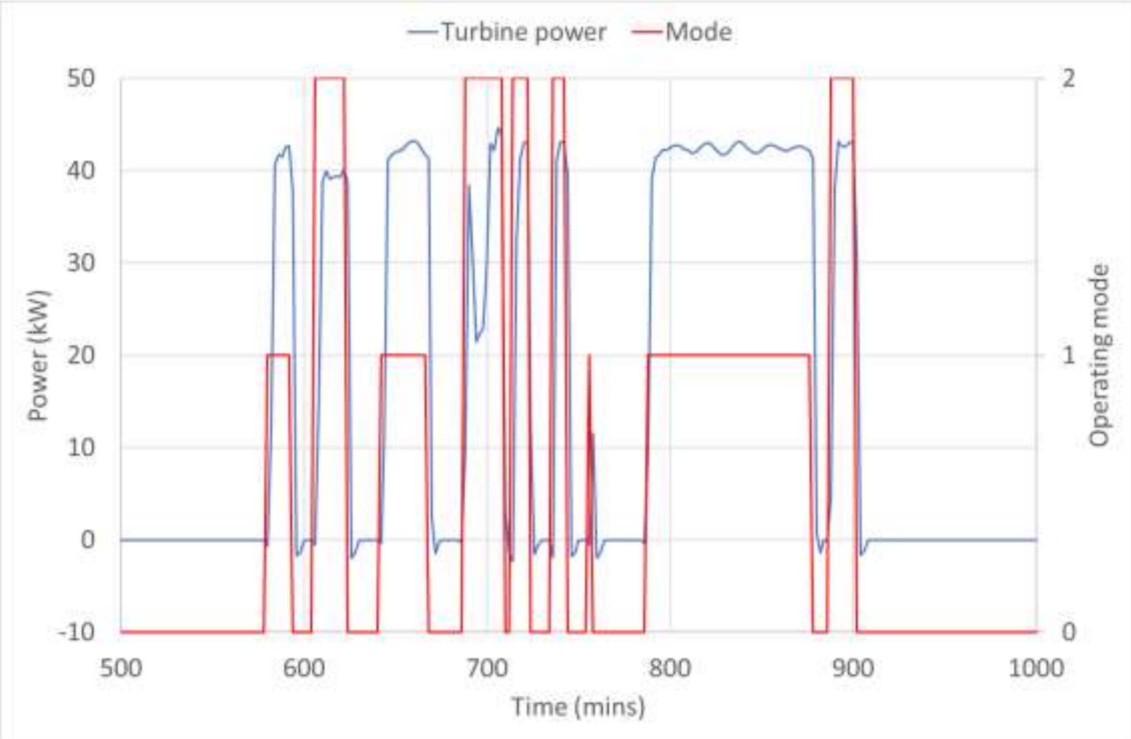

Figure 7. Generated power from the turbines for different modes in Test A1_2.

Figure 8 shows that during both modes of operation liquid nitrogen at -155°C entered either the warehouse heat exchanger or the thermal store. After a pulldown period nitrogen at -20°C exited the warehouse heat exchanger.

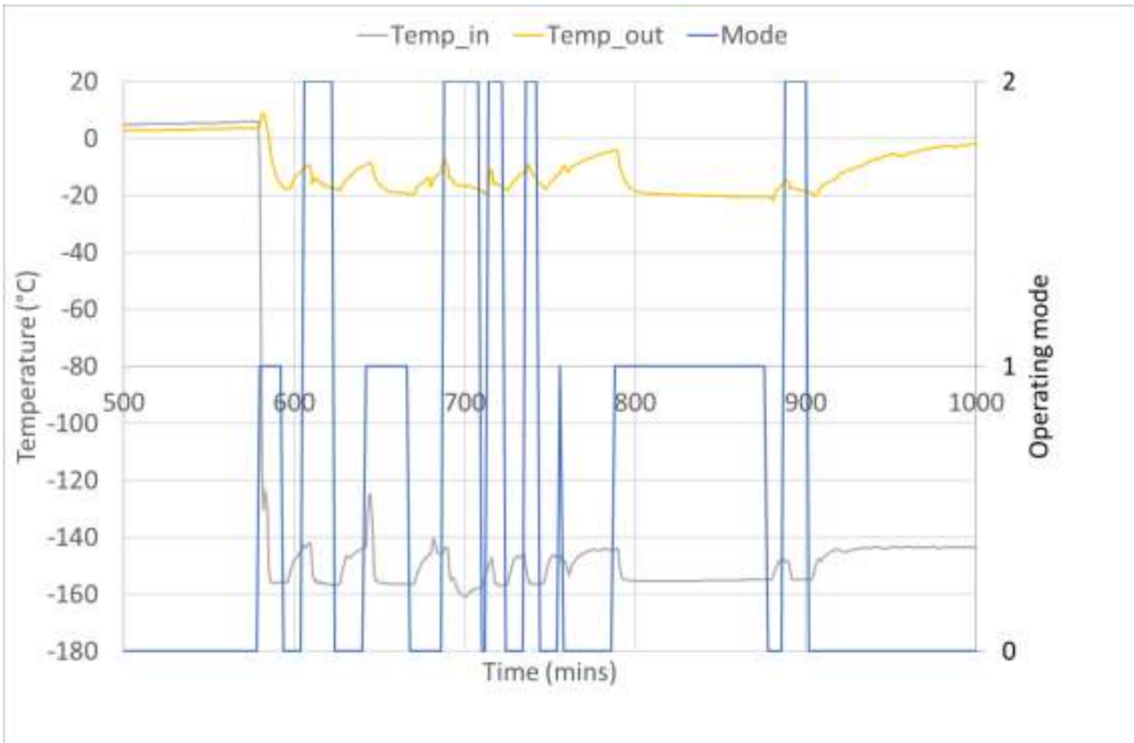

Figure 8. Temperature of nitrogen into and out of the warehouse heat exchanger in mode 1 and into the thermal store and out of the warehouse heat exchanger in mode 2 for Test A1_2.

It is clear from the results presented that the pressure provided to the turbines affects both mass flow rate and turbine power. Figure 9 shows the relationship between these variables during tests conducted. There was a very good straight line relationship showing that the turbine power was very well correlated to the pressure of the nitrogen entering the turbines.

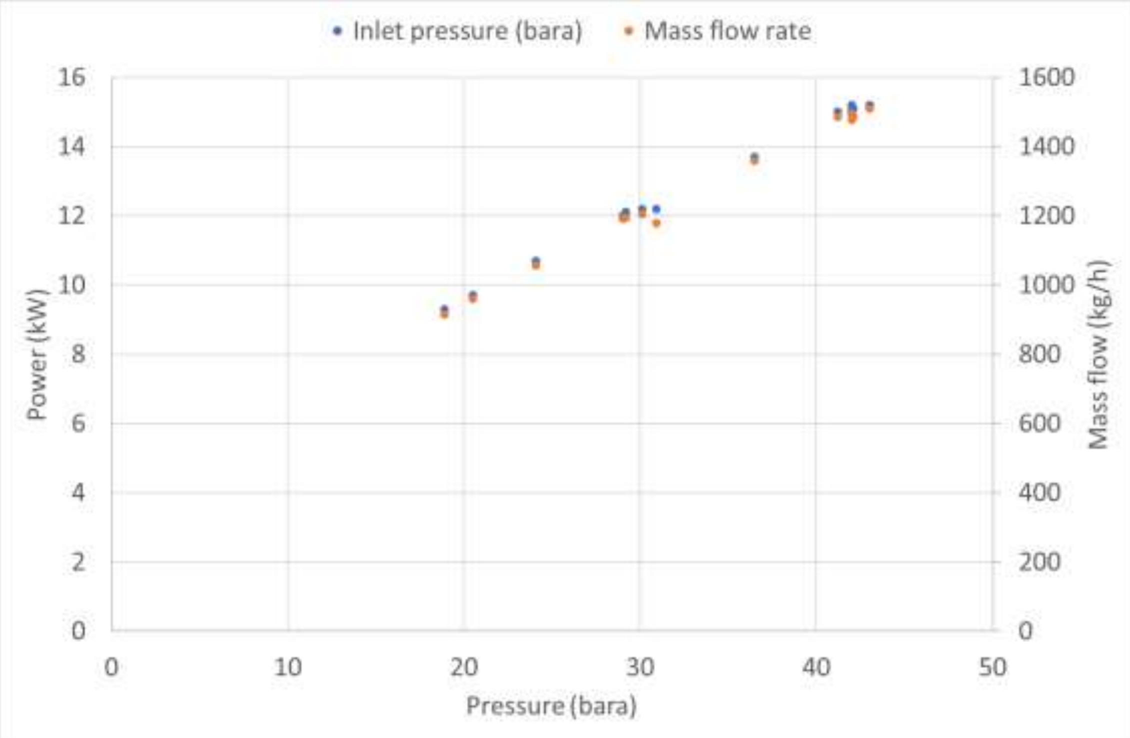

Figure 9. Turbine power and mass flow rate of nitrogen for different turbine inlet pressures.

The turbines were designed to operate at -7.5°C inlet temperature. This was because it was initially planned to use the cooled nitrogen exiting the turbines to cool the chilled warehouse. Since this was not the case in the final demonstrator, turbines temperature were controlled to 0°C by the ammonia heat exchangers. Figure 10 shows the inlet and outlet temperature of the first turbine along with the total power generated. As the turbines start to generate power the temperature into the first turbine decreases as liquid nitrogen is evaporated in the warehouse heat exchanger. Once this gets just below 0°C, the ammonia valve starts to open and the ammonia heat exchanger heats the nitrogen. Once the nitrogen rises above 0°C, the ammonia valve starts to close. This causes an oscillation in the turbine inlet temperature around the 0°C set point. This fluctuation caused by the control can also be seen in the temperature at the outlet of the turbine. Oscillations in generated power can also be seen caused by this temperature fluctuation, as higher temperature nitrogen causes more power to be generated. This fluctuation is on top of the gradual reduction in power caused by reduced mass flow due to reduce pressure.

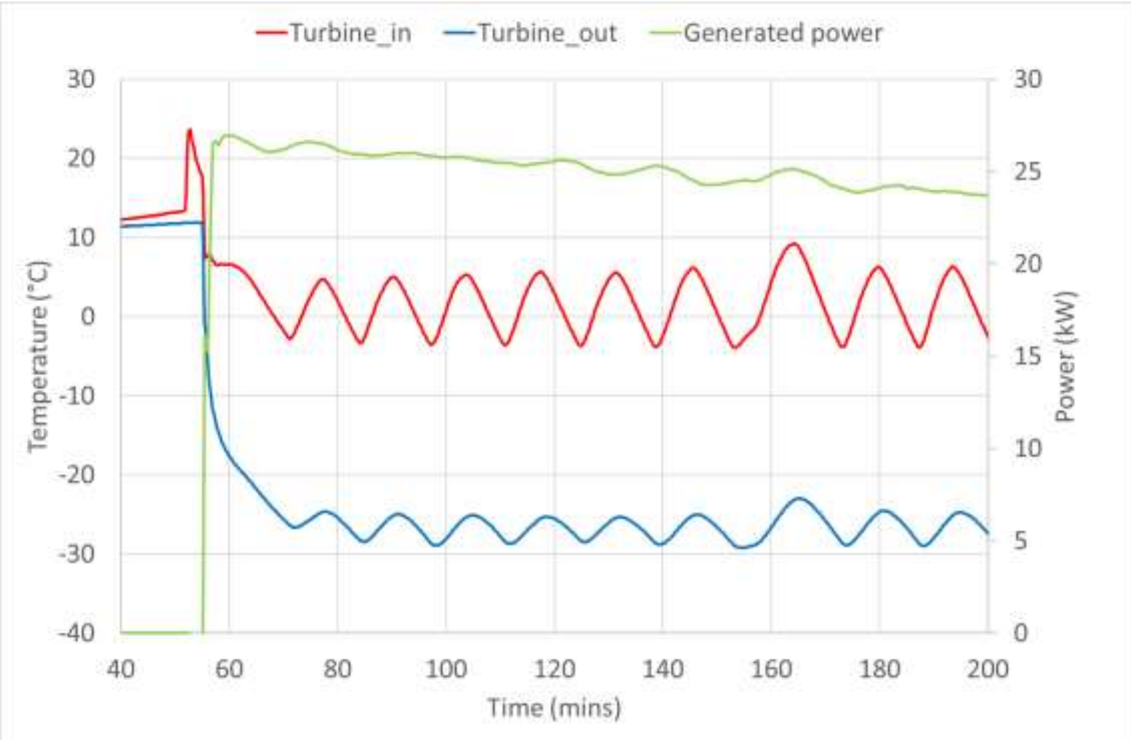

Figure 10. Generated power along with inlet and outlet temperature of the first turbine.

2.3. Start up and shutdown losses

The start-up and shutdown time of the turbines and the energy consumption during this time needs to be taken into account to ascertain the maximum rate of switching of the power generation.

It takes a finite time from the moment it is decided that generation needs to occur to the time at which generation can occur. This is because the turbines need to undergo internal checks and need to spin up to the required speed.

Figure 11 below shows the power to the turbine to spin it up, from the time that the control software initiates to the start sequence (0 min) to the time the turbine starts to generate power (power becomes negative). It took 2 minutes to start the turbine and in this time, it consumed 0.055 kWh of energy.

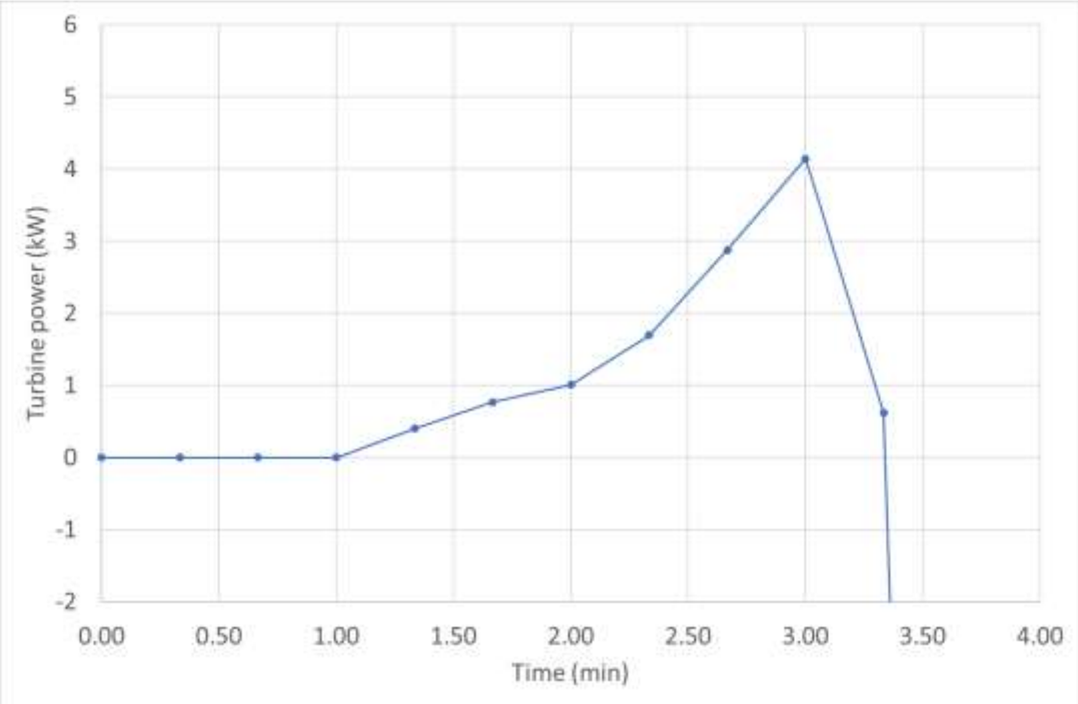

Figure 11. Power consumed by turbines during start up.

The turbine can also not be stopped instantly, and when the stop sequence is applied, power is required to ramp down the speed of the turbine.

Figure 12 shows the power to ramp down the turbine speed. It took 4 minutes to stop the turbine and in this time, it consumed 0.097 kWh of energy.

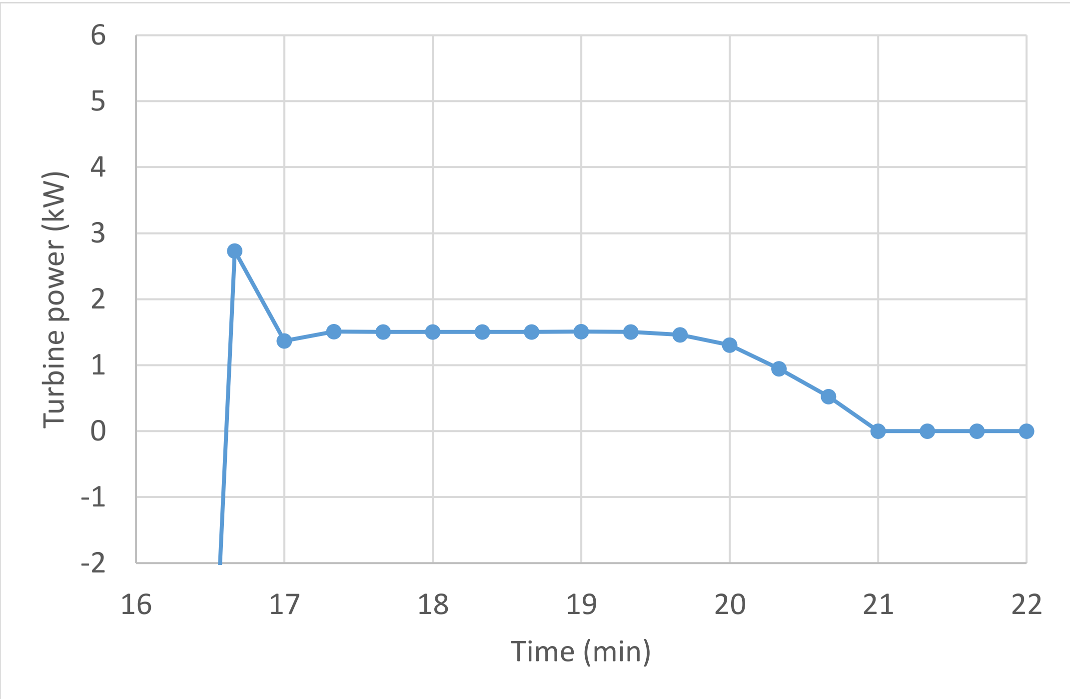

Figure 12. Power consumed by turbines during shutdown.

3. Extending operational data using modelling

At a mass flow rate of liquid nitrogen from the liquid nitrogen tank of 0.42 kg/s and a power consumption of 6 kW for the warehouse heat exchanger fans, 129 kW of cooling was generated in the cold store warehouse and 45 kW of electrical power was generated by the turbines.

Using a COP of 2.5 for the warehouse refrigeration system, the cooling to the warehouse offset 51 kW of electrical power from the grid. The total net grid offset power was therefore 96 kW.

Using an energy consumption of liquid nitrogen production of 1.4 kWh/kg, the liquid nitrogen flow rate would have cost 2.13 MW of power.

This leads to a round trip efficiency of 4.5%. This ignores, start up and shutdown losses, available cooling between stages, venting of liquid nitrogen due to heat gain and transport of the liquid nitrogen.

The original concept was to recover cold energy between turbines (turbine reheat) using a heat transfer fluid to a chilled warehouse. During the project it was found that heat transfer fluids would be in laminar flow, which caused the effectiveness of the heat exchangers to be very low. This meant that they would be prohibitively large and expensive. Therefore, it was decided to provide reheat to the turbines using condensing ammonia from the warehouse refrigeration system. This allowed the heat exchangers to be much smaller and cheaper.

Although this solution allowed adequate reheat of the turbines it consequently meant that the cooling effect of the turbines was wasted. If had been possible to recover this cooling it would have provided 30 kW to the chilled warehouse. At a COP of 4 for the chiller refrigeration system, this would have reduced the grid power by a further 7.5 kW increasing the RTE to 4.9%.

The pressures at different stages were very similar in reality to that modelled (Table 1).

Table 1. Design and actual pressure at different stages.

Pressure (bara)	Design	Actual
After pump	15.4	16.3
Before Turbine 1	14.8	15.4
Before Turbine 2	6.4	6.7
Before Turbine 3	2.5	2.7

Turbine efficiencies were lower in reality to those modelled (Table 2).

Table 2. Design and actual turbine efficiencies.

Turbine efficiency (%)	Design	Actual
Turbine 1	79	53
Turbine 2	81	61
Turbine 3	74	64

If the turbine efficiencies were higher, the main benefit would have been increased electrical power generated by the turbines, with a small benefit from increased inter stage cooling. This would have increased the RTE to 5.5%.

To keep capital expenditure low, the system was run at a relatively low pressure of 15 bar. Table 3 shows the benefit of increasing this pressure using a pump with a 25% efficiency.

Table 3. Round trip efficiency for different pump pressures.

Pump pressure (bara)	RTE (%)
15	5.5
30	6.0
60	6.3
75	5.7

The main capital expenditure which was outside of the project costs was a liquefaction system. If we had a liquefaction system, as originally anticipated at the beginning of the project we would have had the ability to recycle cold from the evaporation of the nitrogen and recycle back to the liquefaction system improving its efficiency. As the liquefier would not operate at the same turbines as the expansion, a thermal store is required. Assuming a cold storage efficiency of 91% and assuming there is no use of the waste heat from the liquefaction compressors, the RTE is increased to 14%.

Table 4 shows the benefit of waste heat to increasing the RTE. By using waste heat from the liquefier the RTE can be increased. By using waste heat at 750ºC the RTE can be increased to 61%.

Table 4. Round trip efficiency for different pump pressures.

	RTE (%)
Heat recycle from liquefier @ 230°C	31
+ waste heat @ 350°C	38
+ waste heat @ 550°C	49
+ waste heat @ 650°C	55
+ waste heat @ 750°C	61

4. Potential improvements

There was little opportunity to adapt the installed components.

Results indicated that the rotational speed of the turbine was not “matched” to the specific speed needed for an efficient expansion. This was not optimised on each stage. Therefore there could be scope to change the RPMs (from 20K rpm to 22K rpm) on each stage and establish whether the specific speed increase improves the isentropic efficiencies, or if the windage losses offset any gain and thus provide optimum turbine speeds. However, this was not possible using the installed turbines.

There would be scope to increase the turbine inlet temperature to 50°C with little detriment to the cooling system. This will increase power output all else being equal, but it might decrease the isentropic efficiency if the turbine efficiency characteristic moves further away from design point.

5. Conclusion

1. The liquefaction system was 2/3 of the cost of the entire system. Therefore, it needs to be optimally utilised to pay back the CAPEX. LAES would only use the liquefaction for a small part of the day. Therefore, the liquefaction system either needs to be producing cryogenic gases for other services the rest of the time, or the LAES needs to be incorporated into a liquefaction system that already exists.
2. The energy required to liquefy nitrogen is considerable. Therefore, waste heat needs to be recovered, stored and used to boost turbine power, also waste cold needs to be recovered from evaporation, stored and used to precool the air in the liquefier.
3. Evaporating liquid nitrogen in the cold store is relatively simple, but not a sensible approach, as the value of the offset of this cold to the ammonia refrigeration is small compared to the benefit of precooling the air in the liquefier.
4. It is probably not economically viable to recover the cold between heat turbines.
5. The thermal store is key to making the system efficient with a liquefier, this is probably the area that requires further research.
6. LAES needs to find a niche area to compete with hydrogen as an energy store for long periods, beyond where batteries are economical.