A COLD STORE UPGRADE PROJECT TO MEET NET ZERO OBJECTIVES

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ABSTRACT

Over the past 10 years, important and successful steps have been made in reducing energy consumption within the temperature-controlled storage sector in the UK. Recent research suggests further savings of between 30% and 85% are possible for new facilities through diligent building design, choice of construction materials, operator behaviour and modern refrigeration equipment selection. The potential for savings in existing facilities is typically less due to the building condition but possible, nonetheless. This paper details a project carried out at a 50-year-old temperature-controlled facility in Scotland. It demonstrates improvements in energy and safety through the installation of modular low-charge ammonia refrigeration systems. It details how the changeover was achieved in an operational facility and how ongoing energy performance is monitored through the refrigeration plants control system in real-time. It also describes how this data is used to predict annual consumption to help ensure efficient operation in the future.

Keywords: Refrigeration, Ammonia, Energy Efficiency, Low Charge, Retrofit, Low Charge

1. ENERGY SAVINGS IN TEMPERATURE-CONTROLLED STORAGE

The cold chain is a significant consumer of energy worldwide, accounting for an estimated 1% of all CO_2 emissions (James and James, 2010). Temperature-controlled storage is a crucial part of the cold chain and data compiled by the Cold Chain Federation (2022) from 425 facilities across the UK estimated they consumed 3.5 TWh of primary energy in 2018, with 96% of this being electricity. There are believed to be nearly 700 stores in total in the UK, so the total energy consumed by this sector is likely to be nearer 5 TWh.

The sector has made good progress with reducing energy consumption as part of its commitment to the Climate Change Agreement (CCA). Figure 1 shows that since 2013, there has been a 16% improvement in energy efficiency when compared to the 2008 baseline against a government target of 12%. This is a starting point but there is plenty of room for improvement. For example, only 56% of facilities achieved their energy improvement targets between 2017 and 2018, indicating that 44% failed to do so. A new benchmark for energy consumption proposed by Pearson (2019) also suggests larger savings of between 30% and 85% are possible for new facilities. This compared data for recent installations with previous best practice figures from ETSU (1994) and average energy consumption data obtained by Evans (2013) as part of a European-wide study of temperature-controlled storage facilities.

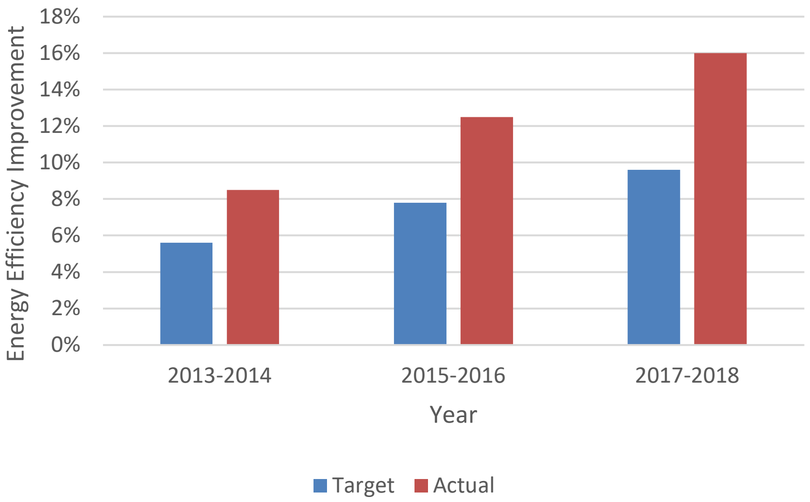

Figure 1. Energy Efficiency Improvement Performance Versus Targets Under The CCA

Adoption of modern design principles, operational improvement, energy-reducing technology and new construction materials are key drivers to achieving savings in new facilities. Savings in existing facilities is more challenging as the infrastructure and operation are already in place and can often be 30 to 40 years old. Nevertheless, improvements are still possible and can make a significant contribution to the move to net zero through the adoption of modern refrigeration technology and software.

2. RETROFIT OF EXISTING FACILITY

The Lineage Logistics facility in Bellshill, Scotland, is over 50 years old. Built in 1971, the current facility comprises three cold store chambers operating at -22^{o}C, a +2^{o}C chill chamber and an ambient loading bay. The refrigeration plant dated back to the original installation and was an ammonia-pumped recirculation system located in a machinery room at the front of the building. It comprised four reciprocating compressors, one screw compressor (a recent replacement for a previous fifth reciprocating compressor), an intercooler and a low-temperature surge drum with four liquid pumps. Two evaporative condensers were located on the plant room roof directly above. Ammonia was pumped to eight evaporators, each with manual hot gas defrost and a number of other evaporators which had been out of service for 20+ years. Figure 2 shows a plan of the building including locations for evaporators still in operation (blue blocks) and the plant room. The pipework is visible on the building roof and two valve station 'hubs' are shown in yellow.

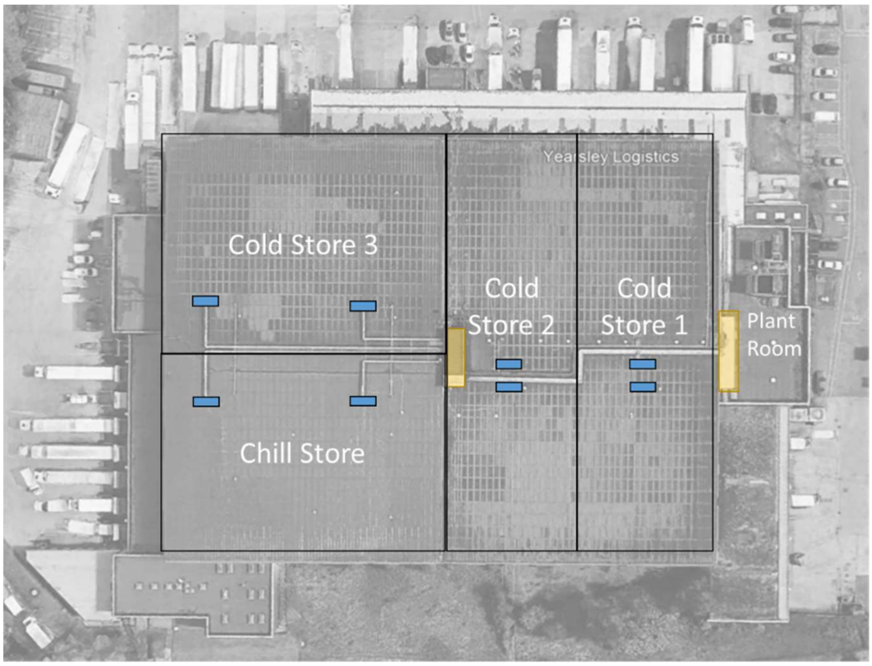

Figure 2. Existing Site Layout

2.1 Replacing the Existing Ammonia Refrigeration System

The refrigeration plant's age meant that it was becoming increasingly difficult to maintain. Challenges with sourcing beyond end-of-life spare parts meant that two of the five reciprocating compressors were out of operation and in recent years there had been a greater frequency of breakdowns and refrigerant leaks. This was affecting reliability and raised concerns over safety - a particular challenge due to the system's three tonnes of ammonia charge and proximity to neighbouring businesses. There was also an inherent inefficiency in plant operation as the chill chamber had originally been designed for low-temperature operation and operated off the same surge drum as the cold store. Energy data from the site suggested a Specific Energy Consumption of between 30 to 35 kWh m^{-3} yr^{-1}, which was higher than the rest of the Lineage UK estate.

Taking the above into consideration, it was decided to look at options for upgrading and even replacing the refrigeration system. Key to the long-term viability of the site, it would be necessary to have a solution that offered improved reliability but also low energy consumption. An option for overhauling the existing system was considered but it was recognised that this would require the majority of the plant to be changed and there would still be a large ammonia charge at the site. The installation of new systems operating on synthetic refrigerants was also explored but the phase-down of the fluids under the F-gas regulation was a concern for the longer term.

The installation of modular ammonia packages for Lineage in 2019 at their facility at Great Haddon, near Peterborough in England had demonstrated improved efficiency both when compared to other sites in the Lineage estate and also traditional ammonia-pumped recirculation plants installed in the UK. Specific Energy Consumption (SEC) figures of 10 to 11 kWhr m^{-3} yr^{-1} are being achieved with this technology, in line with the recent benchmark proposed for new temperature-controlled facilities. Whilst it was accepted that the age, design, operation, and condition of Bellshill meant that similar SEC performance to Great Haddon was not realistic, known inefficiencies with the existing ammonia system and data collected from other cold store retrofit projects provided evidence that savings could be achieved.

2.2 Modular Ammonia Refrigeration Scheme

To secure long-term reliability and improve energy consumption for the Bellshill facility, a scheme was developed to replace the existing central plant with modular systems similar to Great Haddon for the cold store chambers. The scheme also incorporated the conversion of the chill chamber from direct ammonia to glycol supplied by ammonia chillers.

Figure 3 below shows the proposed scheme. There are three modular, low-charge ammonia packages, one per cold store chamber. Each has two evaporators, with Cold Stores 1 and 2 also having booster fans to support air circulation due to the length of the store and the need to blow through the existing lattice steelwork design (see Figure 4). The chill store has four coolers, connected to a common glycol loop and two ammonia chillers.

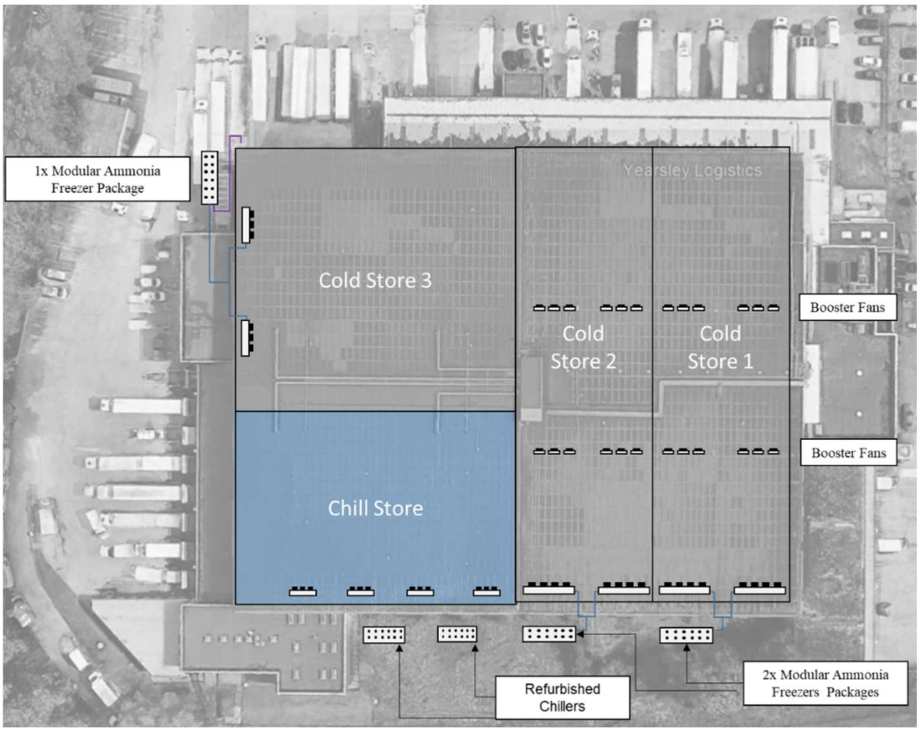

Figure 3. Proposed Modular Plant Layout

Figure 4. Cold Stores 1 and 2 Steelwork Arrangement before and after booster fans were installed

2.3 Determining Cooling Requirement

To determine the cooling requirement for each chamber, new heat load calculations were carried out based on store dimensions, operating temperature, product throughput, materials of construction, personnel numbers, and equipment. Table 1 is a summary of the heat load calculations. These are based on an 18-hour run time for all chambers.

Table 1. Summary of Heat Load Calculations

Chamber	Cold Store 1	Cold Store 2	Cold Store 3	Chill Store
Temperature	-22°C	-22°C	-22°C	+2°C
Dimensions l x w x h m	83.6 x 25 x 11.1	83.6 x 26 x 11.1	51.1 x 48.3 x 12.3	51.1 x 35.5 x 12.3
Volume m^{-3}	23,199	24,127	30,358	22,313
Fabric losses kW	56.5	48.9	63.1	27.5
Air Infiltration kW	92.9	93.2	94.0	110.4
Product kW	23.3	19.4	19.4	14.4
Lighting kW	10.5	10.9	12.3	18.1
Occupancy kW	1.7	1.7	1.7	1.7
Equipment kW	5.0	5.0	6.0	11.8
18/24 hours run kW	63.2	59.7	65.5	61.3
Evaporator Fans kW	31.2*	31.2*	15.6	17.6
Total Heat Load kW	284.3	270.0	277.6	262.7
Cooling Density kW m^{-3}	12.3	11.2	9.1	11.8
New Plant Capacity kW	290	290	290	264

* includes evaporator *and* booster fan motors

Three modular, air-cooled, ammonia cold store packages were selected for each of the cold store chambers, with a capacity of 290 kW per store. Two modular, ammonia chillers were selected for the chill chamber. This modular approach allowed for the new equipment to be installed, whilst keeping the existing plant and site operational. It also avoided the need to build a new plant room or create space in the existing ammonia machinery room.

2.4 Chill Plant Installation

The first plant to be replaced was inside the chill store. Two ammonia chillers had been purchased from a site that had been decommissioned the previous year. Originally installed in 2007 as water chillers for a data centre and air conditioning application, each consists of a plate heat exchanger (PHE) evaporator, screw compressor, air-cooled condenser, low-pressure receiver and stainless-steel electrical panel. Before installation at Bellshill, both chillers were refurbished which included an overall of the plate heat exchanger evaporators to enable them to operate on glycol. The screw compressor on both packages was also overhauled and the chiller PLCs were replaced due to the obsolescence of the original hardware. Figure 5 shows the chiller positioned on a new plinth at the side of the store during the installation phase.

Figure 5. Refurbished Ammonia Chillers, Pumpset and Glycol Cooler During Installation

A standalone pump set was manufactured to circulate glycol through both chillers and supply four air coolers inside the chill store. The coolers have a capacity of 66 kW each based on a design air on the temperature of +1°C and glycol flow/return temperatures of -7.5°C/-2°C. The coolers are fitted with electric defrost and have a protective frame to prevent damage during operation. Commissioning was completed in May 2021.

2.4 Freezer Plant Installation

Retrofitting of the three cold store chambers followed and involved the installation of modular low-charge ammonia packages in each store. Two of the packages were purchased from another business which had installed them as part of a new facility in 2020 but then decided not to operate the building as a freezer. After removal from the previous site, both were transported to Bellshill and positioned on new concrete plinths behind Cold Stores 1 and 2 and adjacent to the recently installed ammonia chillers. Each system consists of two economised screw compressors, a low-pressure receiver vessel, an air-cooled condenser, a four-way defrost valve, expansion valves and a stainless-steel electrical panel with a PLC controller. These are mounted on a steel base frame as shown in Figure 7. Liquid and wet return carbon steel pipework with PIR insulation and alu-zinc cladding run from each package to two aluminium tubes and fin air coolers mounted at the underside of the ceiling in each cold store.

Figure 7 Coldstore Package Ammonia Refrigeration Plants

A third plant was manufactured specifically for the project at a nearby production facility in Renfrew and positioned on the opposite site of the building, adjacent to Cold Store 3. This helped to keep the pipework installation short and reduced the ammonia charge for this system.

The plant serving Cold Store 3 was equipped with a fully welded plate and shell heat exchanger partial condenser. The condenser offers free heat recovery to generate warm glycol which is circulated through a break-loop and delivered to the underfloor heater mat glycol flow and return headers serving all four chambers. A shell and tube glycol-to-glycol heat exchanger was used in the break-loop to safeguard the condenser from any potential contaminants which may materialise in the 50-year-old pipework after it was drained down, flushed and charged with new fluid. The shell and tube design means the heat exchanger can be more easily serviced and cleaned in the future compared with other heat exchanger designs.

In addition to the energy reductions offered by the new refrigeration plant, the site elected to install insulated roofing panels on top of the existing ceiling to provide better thermal performance and a reduction in air infiltration – further reducing the heat load and improving the SEC performance of the facility. This step was taken after other energy-saving measures such as LED lighting, door alarms, strip curtains etc. were already deployed showing the site's continued commitment to reducing energy gains at their source and achieving savings in cooling demand and reducing energy and carbon impact.

All five packaged systems were risk-assessed with regards to their refrigerant inventory and associated gas detectors and sounder beacons were installed. The pressure relief pipework was taken to a high level, terminating above the roof line to ensure any release will have minimal local impact taking advantage of the exit velocity and ammonia's buoyancy in air. The gas detection on the units links to a central HMI which can communicate with the manufacturer's remote monitoring and dial-out system alerting on-call engineers and nominated site personnel in the event of a leak or other operational event detected by the PLC.
The plants were commissioned between June and August 2021, starting with Cold Store 1, then 2 and finally Cold

Store 3. They were initially set to run on temporary power due to delays with the delivery and installation of a new transformer at the site in the original timeframe. The switch to mains power took place between August and October 2021 allowing for the decant, decommissioning and partial removal of the historic pumped circulation plant.

3. PERFORMANCE ANALYSIS

Data collected from the site's energy meters enabled a comparison of performance between the original and new plant to be carried out. Figure 8 shows weekly data for the first 23 weeks of 2022 and the equivalent period in 2021. This provides a fair comparison as the 2021 data precedes the installation of new cold store equipment and operating the plant on generators. There is a clear reduction in overall power consumption year-on-year since the transition from a central plant with evaporative condensers to air-cooled, modular systems. The weekly saving varies from 9% to 36% over this period with an average saving of around 20%. These savings are attributed to the use of the low-pressure receiver system design alongside modern equipment with PLC controls including:

- Use of aluminium evaporator tubing and the low overfeed low-pressure receiver system design that results in a 6 K approach between air on and ammonia evaporating temperature without the need for liquid pumps.
- All evaporator and condenser fans are EC type, varying speed and energy based on the cube law in proportion to cooling and heat rejection demand.
- Floating head pressure control which varies both fan speed and condensing temperature based on demand and ambient temperature.
- Fixed speed compressors operating at 100% capacity when called upon to run. This ensures that the efficiency benefit of the economiser is realised at all times and eliminates the 3% losses associated with inverter drives on compressor motors (often used for capacity variation through speed control).
- An integrated PLC software that monitors the main energy-consuming components in the system and optimises performance by controlling the starting, stopping and speed of components based on ambient temperature and cooling demand. Previous research has indicated that this form of control philosophy can save an additional 15% of energy when added to plant with EC fans and variable speed drives (Gillies, 2014).

During the same 23-week period, temperature compliance was maintained across all four chambers and previous issues relating to plant reliability and refrigerant leakage were eliminated. In addition to energy savings, the annual maintenance spend has been reduced by 60% due to a reduction in the number of engineer visits and replacement parts required. The air-cooled design has removed the need for water and associated water treatment chemicals previously required for the evaporative condensers which worked using a remote sump. In terms of a health and safety benefit, the refrigerant charge was reduced from 3,000 kg (in the central system) to 612 kg spread across the five systems. Each freezer system has 180 kg and there is 36 kg in each chiller.

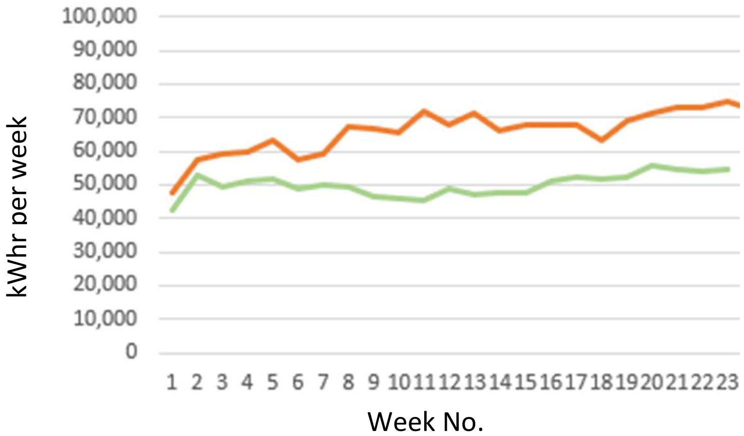

Figure 8. Comparison of Site Energy Data for Weeks 1 to 23 of 2022 vs 2021

4. MONITORING OF ONGOING PLANT PERFORMANCE

It is both commercially and environmentally important that the improvement in performance is maintained into the future. Refrigeration systems are typically commissioned in line with the operating criteria set by the designer at the outset, but there is often no ongoing monitoring to ensure this is maintained throughout the plant's operational life.

4.1 Performance Optimisation Software

The new installation at Bellshill has been equipped with performance management software which extracts data from the refrigeration plant control software and exports it offsite through an internet connection into a cloud-based model. The software monitors energy and key plant performance indicators (e.g. pressures, temperatures) and the data is analysed to identify movement away from design conditions. A 'digital twin' of the refrigeration system is modelled inside the software to enable a comparison of actual data from the site with the theoretical operation for known ambient and load conditions. The model maps the energy performance of key components based on supplier data and from this, it is possible to report differences that could result in increased energy usage. Deviations can be translated into projections of future consumption and operating costs to help the owner understand why action is necessary to return the equipment back to its optimum efficiency. Remedial work can then be planned into ongoing maintenance and service activity. Once complete, the effect of any change can then be monitored, and the saving demonstrated.

Plant component health is also measured and displayed to help find any suboptimal component's performance. A component health report for one of the freezer plants at Bellshill is shown in Figure 9. Green represents healthy components and there is a colour scale through amber to red as health deteriorates. This provides a quick visual overview of a plant's condition to further support maintenance and service works.

Figure 9. Refrigeration Plant Equipment Health Report

4.2 Specific Energy Consumption (SEC) Forecasting

Since the completion of the installation at Bellshill, the new ammonia chill and cold store packaged system PLC software has been enhanced to provide a real-time prediction of SEC. It uses the approach described by Pearson (2021) and takes 'kWhr yesterday' data from the plant to produce an annual SEC figure where 365 days of previous data is available. It also provides short, medium, and long-range predictions based on smaller data sets. The short-range forecast estimates the SEC in 95 days' time based on 270 days of 'kWhr yesterday' data and has an accuracy of +/-5%. A medium-range prediction is based on 90 days of data and forecasts the SEC in 275 days' time with an accuracy of +/-20%. The long-range prediction uses only 10 days of data to predict the SEC 355 days into the future with an accuracy of +/-30%. The benefit of predictions based on smaller data sets of 10 and 90 days is that they provide a swift indication of recent changes in energy performance caused by alterations to plant operation (e.g., setpoint changes), a deterioration in component performance (e.g., compressor wear) or changes to site operating practices (e.g., poor door management).

This means that preventative measures can be quickly enacted to benefit the annual energy performance.

These corrective changes can also be monitored and reviewed using the smaller data sets when the work is complete to ensure the desired outcome. Suggestions for improved performance can also be trialled using the SEC prediction tool and quickly assessed in terms of their success.

The software has been installed at another site within the Lineage group and an example of the output can be seen in Figure 10. The long-range forecast shows the quick change in SEC prediction when changes were made in February and then in March.

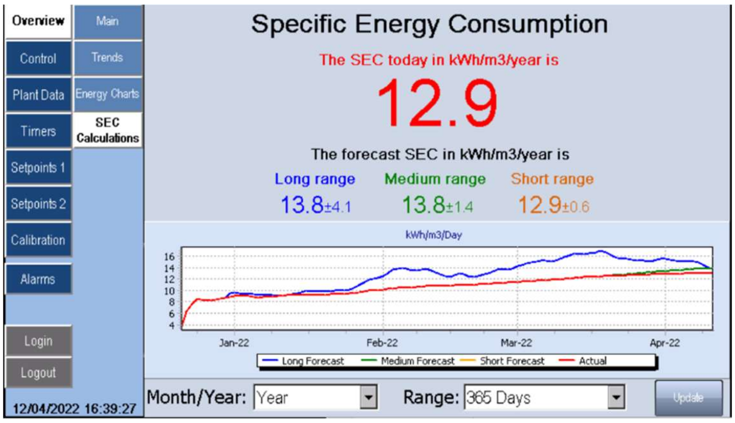

Figure 10. Screenshot of an SEC Prediction

Applying the algorithm to energy data collected since commissioning the new plant at Bellshill in the latter part of 2021 results in a prediction for annual SEC of between 20 and 22 kWh m^{-3} $yr^{-1,}$ which represents an annual saving of 30% when compared to the previous central plant. Further improvement could also be possible through repair and replacement of the building fabric to reduce heat gains.

5. CONCLUSIONS

The environmental benefit of this project cannot be understated. Lineage has managed to fully refurnish a historic facility with a modern, efficient refrigeration plant whilst reducing cooling demand through heat reduction measures to improve the energy use of the facility. These steps have delivered long-term peace of mind for the security of the site with regard to operational risk and costs. The use of factory-refurbished and overhauled refrigeration equipment has avoided the need for more than 80 Tonnes of fresh raw material and prevented valuable components from entering the recycling and waste streams before they are end-of-life. This project is an example of good circular economy practice and demonstrates that this way of working can work well for business, people, and the environment.

The project demonstrates that improvements can be made in the energy performance of existing temperature-controlled warehouses through the use of modern, modular, low-charge ammonia packaged systems. An initial energy assessment based on 23 weeks of data has indicated savings of around 20% have been achieved in the first part of 2022. An algorithm used to predict annual consumption based on a data set of less than a year indicates this could be as high as 30%. Further operating cost savings have been realised through a reduction in ongoing maintenance spend and the elimination of water and treatment chemicals for evaporative condensers.

The considerable reduction in total ammonia charge from 3,000kg to 612kg split across 5 circuits has offered improved peace of mind for the site manager both in terms of health and safety and redundancy. Both factors are particularly important when operating a facility with tenanted space to ensure client safety and temperature control compliance as well as plant uptime – all of which are key to a reliable and scalable operation.

The use of an algorithm to predict annual energy performance has demonstrated a high level of accuracy based on short-range predictions using 275 days of data. Smaller data sets of 90 days and 10 days have proved to be useful in providing early signs of performance drift that can then be addressed quickly, to help reduce running costs and emissions. The aim now is to update the software at Bellshill to incorporate this function and use this as part of ongoing maintenance planning. By doing so, it is hoped that the recently installed systems will maintain their performance long into the future and contribute towards the UK net zero targets.

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