Field Experience of PX G1300® Pressure Exchanger in Commercial CO_2 Refrigeration Systems: Performance Measurement & Validation

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SECTION 1: SCOPE

This paper gives an overview of how Energy Recovery's PX G1300® pressure exchanger (PX G) improves the energy efficiency and cooling capacity of commercial CO_2 refrigeration systems. The PX G recovers high-pressure energy from the exit of the gas cooler and utilizes it to reduce work done by the main compressor rack. Pressure exchanger technology can be integrated into new or existing systems and is adaptable to diverse system designs. This paper demonstrates how the PX G has been integrated within a variety of existing rack designs to drive energy savings**.** Data was obtained from multiple field installations across North America and Europe. Methodical measurement & validation (M&V) campaigns were conducted with customer agreement at multiple sites. Energy Recovery and several refrigeration rack manufacturers conducted data analyses to assess the performance improvements resulting from integration of a PX G, with selected findings independently reviewed by third-party M&V provider DC Engineering. The PX G1300 has accumulated more than 25,000 operational hours and demonstrated a Coefficient of Performance (COP) peak increase of up to 30%, with projected annual energy savings of up to 15% or more. Operational data from multiple sites demonstrates evidence of flash gas flow reduction, leading to a capacity increase that can help safeguard against heat waves and avoid system downtime leading to food spoilage. Furthermore, field data demonstrating the effect of the PX G in reducing system pressure fluctuations is also presented. Additional whitepapers demonstrating PX G performance will be released as more data becomes available in 2025 and beyond.

SECTION 2: INTRODUCTION

The Energy Recovery PX® Pressure Exchanger® (PX) is recognized around the world as a trusted, reliable, high-performing energy efficiency device for seawater reverse osmosis (SWRO) desalination. The PX reduces energy use by as much as 60% within a SWRO system -- a critical leap forward in technology that made SWRO cost-effective, reduced carbon emissions, and made it possible for the industry to adopt SWRO technology over emissions-intensive thermal desalination processes. In the three decades since it was first introduced, the PX has expanded to accommodate a wide range of pressure and flow levels, making it suitable for a large variety of water treatment processes including industrial wastewater treatment, brackish water treatment, and water reuse.

Recently Energy Recovery showed that the PX G can also perform gas compression, in CO2 transcritical compression and can simultaneously act as a compressor and an expander [1-3]. Energy Recovery further demonstrated that the PX can help improve the efficiency of CO2 refrigeration systems significantly [3-6, 8-14, 16]. Higher discharge pressures observed in CO2 refrigeration systems provide an opportunity for the PX to recover that high differential pressure energy and use it to save the compression work required by the system.

Energy Recovery has applied its core pressure exchanger technology to the PX G1300, which can handle liquid, gas, supercritical fluids, and the two-phase liquid gas mixtures and deliver the energy savings and the emissions reductions for the CO2 refrigeration systems. The PX G1300 is designed to efficiently capture and transfer pressure energy, making commercial processes more efficient and environmentally sustainable, leading to lower costs, reduced energy consumption, and reduced carbon emissions.

2.1 What problem does the PX G1300 solve?

CO_2 has recently emerged as an attractive option as a low global warming, non-ozone depleting, non-toxic, non-flammable refrigerant. However, in warmer climates, the energy efficiency of transcritical CO_2 (TC-CO_2) refrigeration systems quickly deteriorates. The reasons for this loss of efficiency are as follows:

1. Significantly higher saturation pressure (hence condensing pressure) of CO_2 compared to other common refrigerants.
2. Large exergy destruction during the expansion across a high-pressure valve.
3. Large amounts of flash gas produced at higher ambient temperatures, especially when the condenser/gas cooler pressure is limited to below 100 bar.

To remedy these challenges, Energy Recovery commercialized a new type of device called a rotary gas pressure exchanger (PX G) that can recover the expansion work--that would have otherwise been wasted during expansion across a high-pressure valve--and use it for compressing the CO_2 vapor without consuming external mechanical or electrical energy. In other words, the PX G achieves expansion work recovery and uses it to compress a portion of the CO_2 vapor for "free". Unlike ejectors which typically provide 4-6 bar of pressure lift, the PX G can provide up to 70 bar of free differential pressure lift, all the way from receiver pressure to the condenser/gas cooler pressure. Due to this "free" compression, the PX G can save a significant amount of compression work required by the refrigeration system. The PX G acts as a compressor and as an expansion device, providing an all-in-one compact and high-speed rotary machine. Unlike traditional compressors, the compression of low-pressure CO_2 vapor in the PX G is accomplished not through a reciprocating piston or a scroll, but rather through acoustic waves generated during direct contact fluid-to-fluid pressure exchange between a high-pressure supercritical fluid stream and a low-pressure vapor stream inside a rotating duct.

Due to this large differential pressure, in which "free compression" is facilitated by the PX G, a Coefficient of Performance (COP) increase (efficiency improvement) of up to 30% can be accomplished by a PX G-integrated TC-CO_2 system. Various system architecture inventions using the PX G have been successfully implemented [4, 6, 8-14, 16] to achieve this COP improvement. Some of these utilize the PX G to compress the flash gas from the receiver all the way to the gas cooler inlet (similar to a parallel compressor, but with minimum power input), while others utilize the PX G as a mechanical subcooling compressor (also with minimum power input), thus reducing the total system mass flow per unit heat absorbed in the evaporator.

2.2 Independent validation of PX G1300 physics and its value proposition in CO_2 refrigeration

Since the first introduction of pressure exchanger (PX) technology by Energy Recovery during the prestigious Gustav Lorentzen Conference on Natural Refrigerants in 2022 [3], various national labs (Oak Ridge National Lab in the U.S., SINTEF in Norway) and universities around the world (MIT in the U.S., NTNU in Norway, BITS Pilani in India, EPFL in Switzerland) have studied the fundamental thermodynamics of the PX analytically and experimentally. Upon confirmation of its sound working physics, they have published their results in peer-reviewed conferences and prestigious international journals [3-6,10,12,14,15]. The stringent peer-review process for these prominent journals carried out by international subject matter experts has further validated the scientific and commercial merit of the PX technology as it applies to CO_2 refrigeration. Rigorous lab testing of the PX G has demonstrated its transcritical compression-expansion ability at high differential pressure and the subsequent energy savings. Based on these results, major refrigeration OEMs are evaluating the benefits of PX G1300 within new types TC-CO2 systems which include; efficiency improvement, capacity increase, heat wave adaptability and to reduce overall operating costs in commercial refrigeration applications. Data from several PX G1300 installations in grocery stores across Europe and the U.S. is presented in section 5 of this paper.

SECTION 3: PX G1300 PRESSURE EXCHANGER -- OPERATING PRINCIPLE

3.1 Working principle of the PX G1300

A schematic of the PX G is shown in Figure 1. It consists of a high-speed rotor with axial ducts. The rotor spins inside a sleeve and is contained axially between two end caps. The rotor floats axially between these two end caps due to hydrodynamic/hydrostatic pressure created by the thin gas film (a few microns thick) between rotor and end caps. This allows the rotor to spin freely at high speed without a mechanical thrust bearing. The thin film also acts as a hydrodynamic gas seal, thus alleviating the need for a separate mechanical seal between high-pressure and low-pressure sides. The rotor is also supported radially with a thin gas film (a few microns thick) between the rotor and sleeve. This eliminates the need for a radial bearing. The viscous friction loss associated with the thin gas bearing film in axial and radial clearances of the PX G is typically much smaller than any type of contact mechanical bearing.

As shown in Figure 1, there are two fluid streams. Fluid 1 (low pressure cold CO_2 vapor) and fluid 2 (high-pressure warm supercritical CO_2) enter the rotor from axially opposite ports (HPin port and LPin port), which are separated circumferentially. During stage 1, fluid 1 (LPin) fills the duct. As the duct continues the rotation (stage 2 of the process), this LP duct gets sealed by the land area of the stator and its pressure is preserved. As the duct further continues its rotation during stage 3, the LP duct gets exposed to the high-pressure port and an acoustic compression wave is generated that pressurizes the low-pressure fluid in the duct almost instantaneously (speed dictated by acoustic wave velocity). This compression process also increases the temperature of this fluid plug similar to a traditional compressor. The incoming fluid 2 stream (HPin) drives the now compressed high-pressure fluid in the duct out of the HPout port. The pressure of this fluid coming out of the HPout port is almost the same as the HPin fluid stream minus 1-2 bar pressure loss in the PX G and in the piping due to inertia and viscous losses. Additionally, because this HPout fluid stream is hotter due to compression, it is ready for heat rejection in the gas cooler. A small diffusion mixing zone exists between fluid 1 and fluid 2 inside the duct, however this mixing zone is kept minimal through design of geometry and controls. Hence fluid 2 never leaves through the HPout port (see results by Thatte et. al. [3,7]). At the end of the stage 3, fluid 2 (HPin fluid) occupies most of the duct. As the duct continues rotation (stage 4), fluid 2 gets sealed by the land area of the stator and there is no appreciable mass transfer in or out of the duct. During stage 5, further rotation of the duct exposes it to the low-pressure LPout port and at the moment of this exposure, an instantaneous expansion wave is generated and propagates through the high-pressure duct. This expansion wave depressurizes fluid 2 in the duct to the same pressure as the low-pressure LPout port. More importantly, this depressurization follows a thermodynamic process between an isentropic and isenthalpic expansion and produces a cold two-phase liquid-vapor mixture at LPout. The liquid mass fraction of this cold LPout fluid is ready for heat absorption in the evaporator.

The detailed working physics of the PX G are described by Thatte et. al., [3, 4, 7, 9]. Several other research studies led by Thatte et. al. [2, 3, 7, 13] discuss the gas dynamics, species and thermal transport taking place inside the PX G rotor during transcritical compression-expansion processes using the high-fidelity 3D computational fluid dynamics (CFD), which demonstrates how the high-pressure supercritical CO_2 exchanges pressure with low pressure CO_2 vapor without pass-through, while the two fluid streams come in direct contact with each other. Dr. Thatte along with the researchers from Norwegian University of Science and Technology (NTNU) have also published rigorous test data [3, 10] on expansion work recovery and compression of flash gas by the PX G over the full 70 bar differential pressure from the receiver (flash tank) to the gas cooler. Readers are encouraged to refer to these publications co-authored by Energy Recovery, along with the Oak Ridge National Lab (U.S.), NTNU (Norway), SINTEF (Norway) and EPFL (Ecole Polytechnique, Switzerland) for a deeper understanding of the inner workings of the PX G and its energy savings potential.

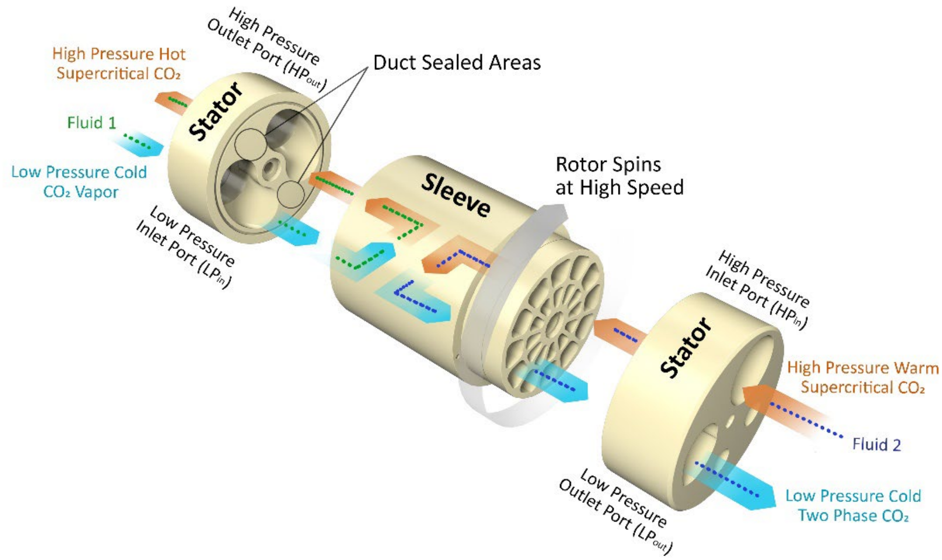


Figure 1: Geometry of the PX G with two inlet and two exit fluid streams

3.2 System architecture example

Figure 2 illustrates an example of CO_2 refrigeration system architecture incorporating a PX G1300, which is referred to as PX Energy Optimizer. In this setup, a subcooler is strategically positioned between the gas cooler and the PX G. A portion of the flow from the gas cooler is diverted for subcooling the main gas cooler flow. This subcooled flow is then directed to the high-pressure inlet (HPin) port of the PX G. Upon entering the PX G, this flow expands and exits through the lower pressure outlet (LPout) port as a two-phase liquid-gas mixture, functioning similarly to a high-pressure valve.

The bypass flow, initially used for subcooling, is subsequently heated through heat exchange with the subcooler flow. Assuming ideal heat exchange conditions, the gas exiting the subcooler is at a temperature equivalent to that at the main gas cooler's exit. This superheated gas is then fed into the low-pressure inlet (LPin) port of the PX G. Exiting the high-pressure outlet (HPout) port, the gas releases heat via an Auxiliary Gas Cooler (AGC). The AGC operates at slightly lower pressure than the main gas cooler, because the HPout flow coming out of the PX G is at lower pressure than at the HPin due to pressure losses. This cooler can either be a separate unit or integrated with the main gas cooler. The two-phase mixture after expansion from the auxiliary gas cooler is then routed to the flash tank.

The combination of subcooling and the expansion process through the PX G results in a lower quality of the mixture in the flash tank. Consequently, this leads to a reduction in the amount of flash gas produced, thereby decreasing the workload for the medium-temperature (MT) compressors for a given evaporator duty.

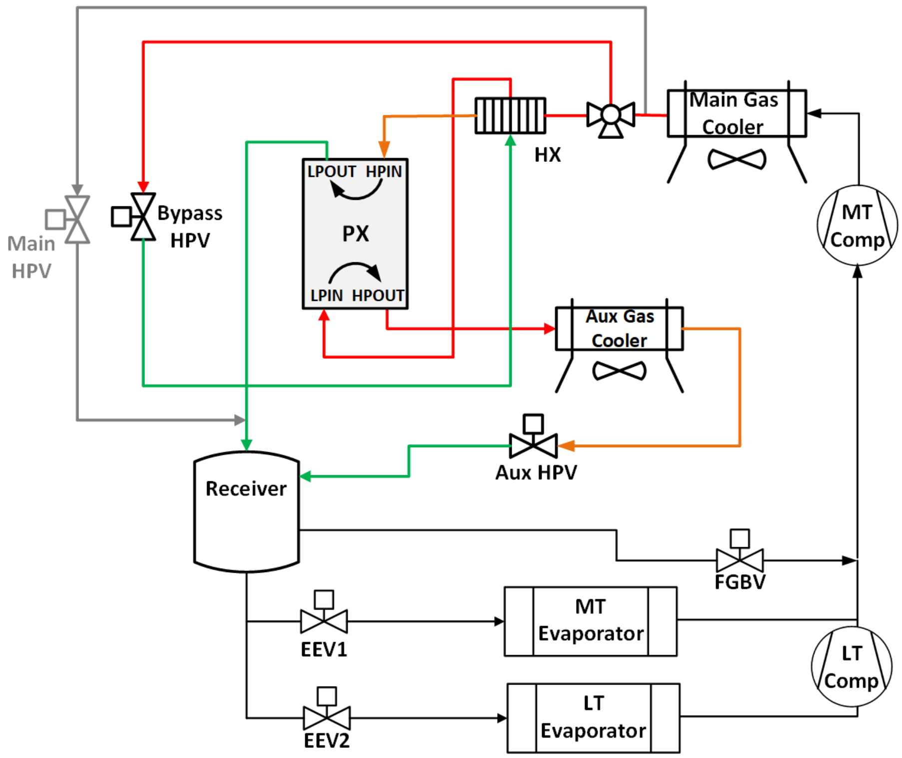


Figure 2: CO_2 refrigeration system architecture utilizing the PX G

SECTION 4: PX G1300 INSTALLATION SITES

The PX G1300 has been installed across two continents and multiple countries in North America and Europe. Figure 3 shows a world map of PX G installations as of September 2024. Some the sites have multiple PX G running in parallel. By the end of 2024, we expect around 30 projects to be commissioned.

Figure 3: Map of PX G installations

Table 1 shows the operating history of the PX G as of September 2024. Due to confidentiality agreements with some of our customers, specific names of stores have not been disclosed. It must be noted that several of these sites have other energy efficiency improvement devices such as an adiabatic gas cooler, parallel compressor, and/or a heat reclaim circuit. PX G has proved to be a resilient, adaptable, and retrofitable device that provides energy savings on top of these existing energy improvement devices.

No	Location	No. of PX-Gs	System Size	Site Type
1	San Leandro, CA (Energy Recovery HQ)	Several	120 kW	Laboratory
2	California # 1	1	155 kW	Grocery store
3	California # 2	1	216 kW	Grocery store
4	Belgium # 1	2	240 kW	Grocery store
5	Belgium # 2	2	240 kW	Grocery store
6	Italy	1	160 kW	Grocery store
7	Canada	1	150 kW	Grocery store
8	Hungary	1	180 kW	Grocery store

Table 1: List of PX G locations with active M&V campaigns as of September 2024.

Figure 4 shows pictures of modules that offer efficient integration of the PX G1300 into existing CO_2 systems. Installations with PX G modules have been built with required instrumentation and a simplified control scheme that can be readily integrated into any commercial controller to allow measurement and verification of PX G performance. See Figure 5 for pictures of PX G module.

The PX G1300 has been integrated into end user sites through modules designed by OEMs and Energy Recovery's PX Energy Optimizer module. The PX Energy Optimizer module offers an efficient design option for all end users to easily integrate the PX G into their existing systems. All module options have a simplified control scheme that can be readily integrated into any commercial controller.

All sites referenced in this paper were outfitted with additional instrumentation equipment to capture data for the M&V analysis.

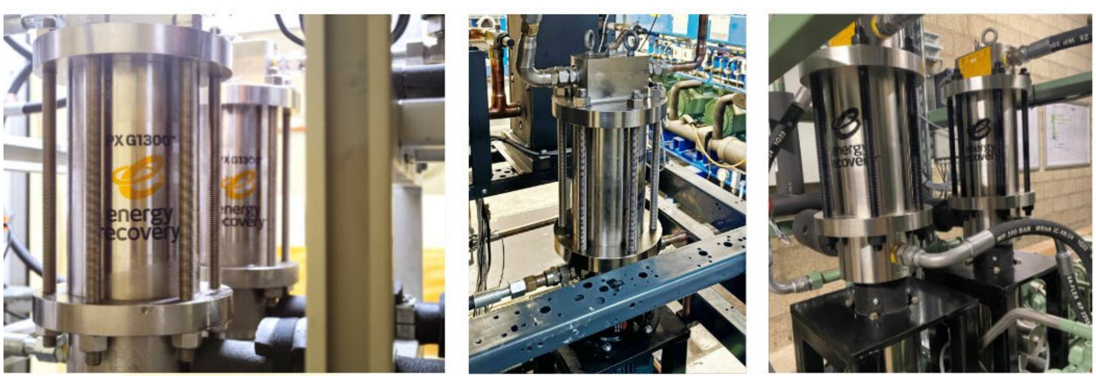


Figure 4: Pictures of PX G1300 installations

SECTION 5: MEASUREMENT AND VERIFICATION (M&V) PROCESS

Measurement & Verification (M&V) broadly consists of the following steps. The first three steps focus on ensuring site readiness for the PX G installation, followed by assembly of the PX G module onto parent rack, followed by a start-up process. Extensive work goes into each of these steps, and thorough training documentation and standard operating procedures have been developed to ensure a robust commissioning process. However, the focus of this paper is on steps 4 and 5, which concentrate on procedure, data analysis, and results of M&V campaign.

1. Sensor and instrumentation checks, calibration, baseline rack system stability review
2. Installation and commissioning of PX G-based system into an existing CO_2 rack
3. Controls verification and startup of PX G system
4. Methodically designed test campaign to run baseline system and PX G system back-to-back
5. Analysis of energy consumption metrics and other operational data

5.1 Measurements

Measurements are divided into two categories:

1. Critical measurements in order to accurately calculate the effect of the PX G on a given system are highlighted below:
   - Temperatures: ambient, gas cooler exit, gas cooler air inlet (for parent racks using adiabatic)
   - Pressures: gas cooler exit
   - Power meters: rack compressors, main gas cooler, PX G1300 motor and accessories
   - Other: PX G RPM, PX G enabled/disabled signal

2. Additionally, there are certain measurements that are useful for determining the operational stability and health of the system, but not necessarily critical for calculating energy savings. Sites with these measurements available have been recorded. They give further evidence of the impact of the PX G on the refrigeration systems, which is outlined below.

   - Temperatures: compressor suction and discharge
   - Pressures: compressor suction and discharge, flash tank, PX G inlet, exit
   - Other: compressor run signals, rack average phase voltage
   - Valve openings: flash gas valve percent, main HPV opening percent
   - Flash tank liquid flow meter (installed in selected sites)

5.1 M&V operational procedure

In order to truly distinguish the effect of the PX G on an existing system, a procedure was developed to methodically run the system with the PX G1300 enabled and disabled. This is facilitated by providing appropriate control signal to the PX G that keeps it enabled (ON) or disabled (OFF) for a pre-determined period of time. Figure 5 shows the recommended runtime protocol for a system with a PX G. By systematically enabling and disabling the PX G, the energy consumption of the baseline and PX G-enabled system can be compared directly over a certain period of time. We recommend running such a campaign with a weekly ON/OFF schedule for three to six months in order to gather sufficient data to allow for a direct comparison between baseline and PX G systems. Although the recommended protocol is one week ON and one week OFF, certain customers might choose to do it with a different frequency depending on their preference: for example, three days ON and one day OFF. The actual ON/OFF period is less important than running the campaign during similar weather profiles and months of the year, such that the overall conditions and loads on the store will be normalized.

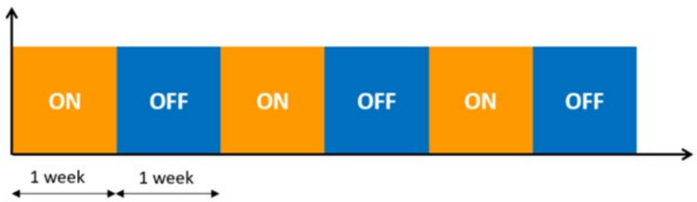


Figure 5: PX G1300 runtime protocol for M&V process

After this ON/OFF campaign is completed, the power consumed by the system when the PX G was enabled versus disabled can be compared.

- PX G data = when PX G is enabled
- Baseline data = when PX G is disabled

This process was also discussed with and approved by DC Engineering. In CO_2 refrigeration systems, it is common to benchmark energy usage compared to outside ambient conditions. The variable of interest is outdoor dry bulb temperature for dry gas coolers, and the depressed dry bulb at the inlet of the coil air temperature for adiabatic gas coolers. This process of benchmarking is a widely used methodology within the energy efficiency and supermarket community.

Polynomial regression curves are generated to compare regression trends. Example below is for 2nd degree, but first degree polynomial can be also used depending on the data available.

System power when PX G is running:

$$P_{PX}(T_{sel}) = A_p(T_{sel})^2 + B_p(T_{sel}) + C_p \quad (1)$$

System power when baseline is running:

$$P_{Baseline}(T_{sel}) = A_b(T_{sel})^2 + B_b(T_{sel}) + C_b \quad (2)$$

Average Power Savings with Temperature: Data points along with the polynomial regression will be generated to compare the overall trends observed within the data. For a given inlet temperature value, the analysis will calculate average power (kW) consumed when the PX G was running and when the HPV (baseline) was running as follows:

$$P_{saved}(T_{sel}) = P_{Baseline}(T_{sel}) - P_{PX}(T_{sel}) \quad (3)$$

For calculating cumulative energy savings (kWh) over a given period, the analysis calculates the estimated power that would have been consumed if the PX G was not enabled using the regression curves. These data points will then be summed up to calculate continuous energy usage over the given period. The difference between net energy of baseline and PX G gives the savings.

$$E_{PX} = \sum_{t=1}^{t=end} P_{PX}(t(i)) \quad (4)$$

$$E_{Baseline} = \sum_{t=1}^{t=end} P_{Baseline}(t(i)) \quad (5)$$

$$E_{saved} = E_{HPV} - E_{PX} \quad (6)$$

SECTION 6: M&V RESULTS AND DISCUSSION

6.1 Data analysis process

Comprehensive data analysis is conducted for each of these sites using automated data analysis from Python and MATLAB. In general, the data analysis process consists of the following steps:

- For a given site, raw data can come from variety of sources such as:
  – Sensor data from Energy Recovery National Instrument-based or Commercial controllers
  – Rack sensor data from dedicated servers in the store
  – Rack power meter data from energy dashboards

- After collecting raw data, the data is processed and merged into a single, time- synchronized data frame (or table). Current protocol involves creating one minute per row of data for each site. If the data timesteps are more than one minute, then the best minimum resolution available is used.
- Data is exported to various entities such as Energy Recovery, DC Engineering, and OEM engineers for data analytics.

After the data is processed and merged into time-synchronized formats, a variety of visualizations are generated in order to ensure that the system is running as expected. These visualizations typically consist of:

- Time series of various sensors: temperatures, pressures, compressor power, PX G RPM, enabled/disabled signal, valve openings, various rack parameters, etc. This is to ensure that the system is running as expected and there are no anomalies.
- Scatter plots such as gas cooler pressure vs. temperature, gas cooler temperature vs. ambient temperature, power vs. ambient temperature, etc., to ensure that the PX G is controlling the pressures to desired values and overall system operation is similar to when baseline system is running versus when PX G is running.
- Histograms of key rack parameters such as flash tank pressure, MT/LT suction pressure and temperature, compressor discharge temperatures to ensure that the rack parameters are not affected by the presence of the PX G.

A controls verification tool has been developed to make sure that various quantities associated with both the PX and main rack are operating within desired ranges before starting an ON/OFF campaign. These tools have been automated to quickly verify a system after the PX G is installed by analyzing about two hours of data.

The overall process of calculating energy savings is shown in Figure 6 below. Initially, data from sensors is visualized in form of a time series to ensure there are no peculiarities with the data. Data is then averaged into hourly buckets to reduce the quantity of data and noise. This hourly averaging procedure has also been suggested and approved by DC Engineering. The power consumption metric can be visualized against temperature and then an average value of power consumption can be determined. The plots in Figure 6 show clear differentiation for a specific site, especially at warmer temperatures. The system already goes into operation at +10 °C (+50°F), but at temperatures above +40 °C (+104°F) it allows saving of more than 30% compared to a traditional transcritical system.

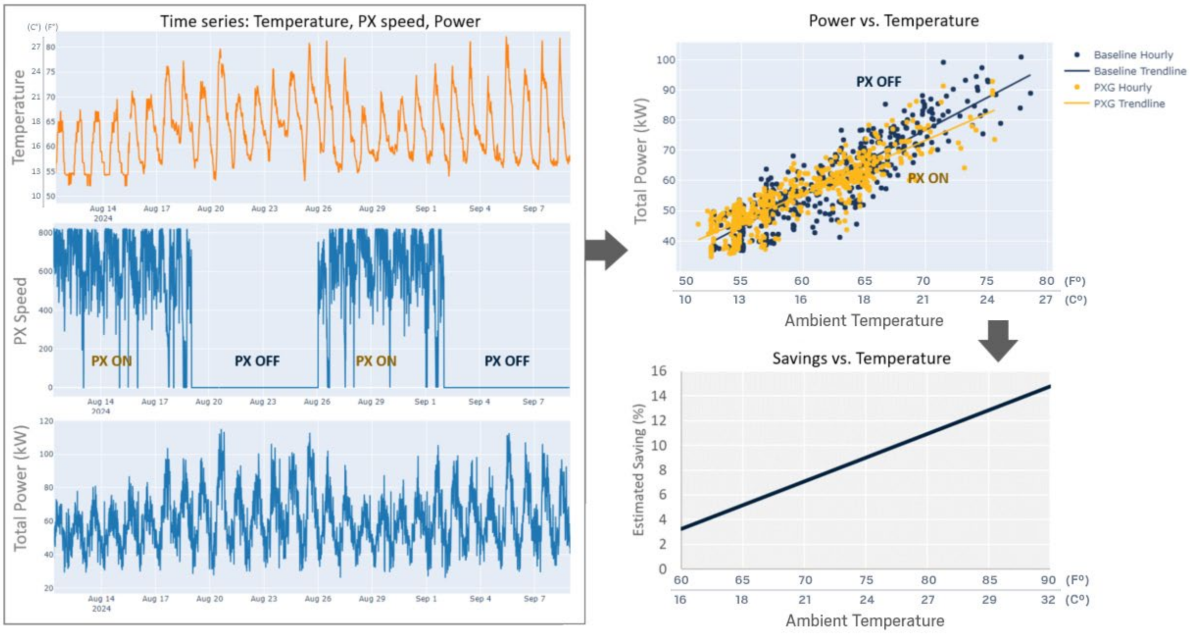


Figure 6: Data post-processing example (site: California # 2): Time series, raw power data vs. temperature, average power vs. temperature

6.2 PX G1300 benefits to CO_2 refrigeration system

The PX G1300 can provide benefits in the following ways:

- **Annualized energy savings**: After generating the trendlines between power consumption (or COP) of the baseline system and PX G as a function of temperature, the annual weather data for a given location can be used for calculating cumulative savings. Weather data is typically available on an hourly basis for 8,760 hours of the year, which can be used for estimating the savings. Furthermore, based on either the average annual rate or hour-by-hour rate of electricity, the annual savings amount in dollars or euros can be estimated.

$$E_{Annual\ Saving}(kWh) = \sum_{t=1}^{t=8760} P_{Baseline}\big(t(i)\big) - \sum_{t=1}^{t=8760} P_{PX}(t(i)) \quad (7)$$

$$E_{Annual\ Saving}(\%) = E_{Annual\ Saving}(kWh)/(\sum_{t=1}^{t=8760} P_{Baseline}\big(t(i)\big)) \quad (8)$$

$$Annual\ Electricity\ Savings = E_{Annual\ Saving}(kWh) \times Average\ Rate(\$/kWh) \quad (9)$$

- **Capacity increase and avoiding food spoilage**: Energy savings provided by the PX G generally increase with increasing temperature. During heat waves, when a certain 'trigger point' temperature is reached, compressors in the rack can start reaching their capacity limit. In such events, the cases might start running at warmer temperatures than design set-points, which in turn would lead to product integrity issues and possibility of product temperature exceeding the ~41 °F (~5 °C) food safety requirement.

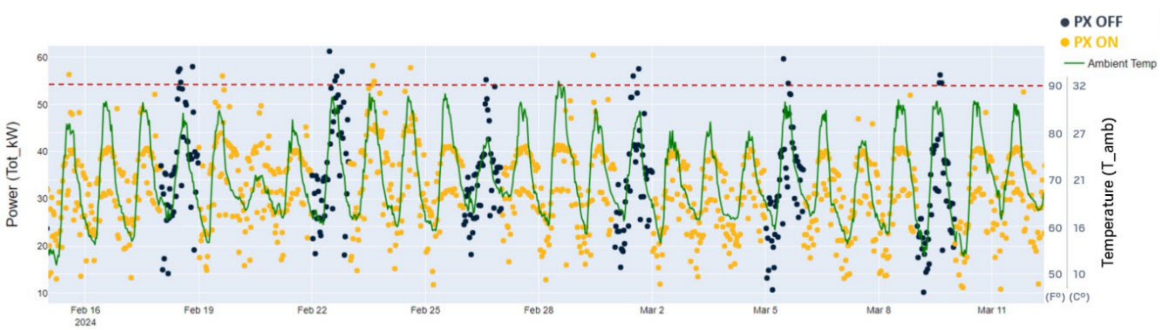
$$Capacity\ Increase\ Savings = \%Capacity\ increase\ at\ trigger\ point\ \times Value\ of\ fresh\ food\ inventory\ in\ store\ \times Number\ of\ days\ with\ T_{Ambient} > Trigger\ point \quad (10)$$

- **Operational Expenditure (OPEX) savings:** PX G typically requires almost no maintenance and water usage, compared to other energy efficiency devices such as an adiabatic gas cooler.

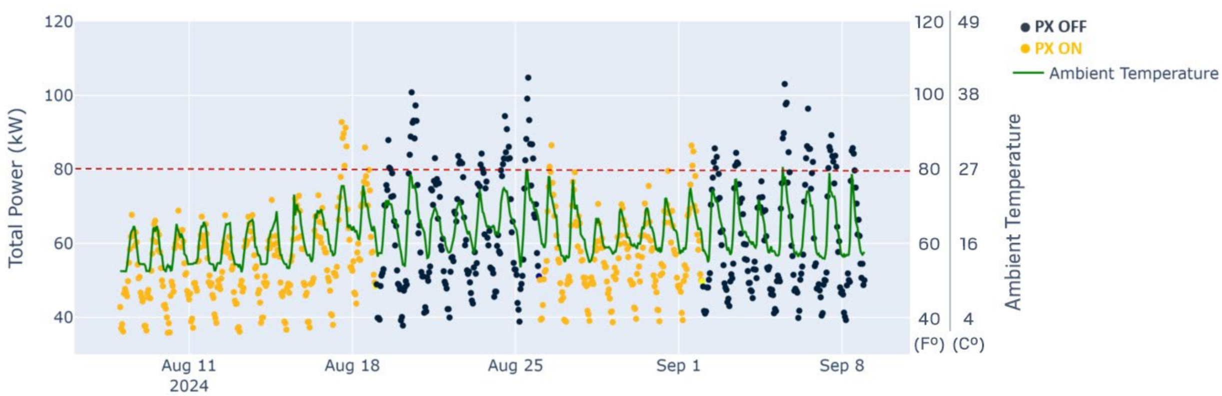
6.3 Energy savings

6.3.1 Time series: avoidance of additional compressor onset

The PX G1300 provides energy savings by reducing the amount of flash gas that goes to Medium Temperature (MT) compressors, thereby reducing the overall work they need to do. This is because extra MT compressors do not need to turn ON when the PX G is running. By avoiding use of extra compressors, the PX G reduces the number of power spikes observed in power time series. A couple of examples of this are shown in Figure 7. In California # 1 site, there are about 9 power spikes (when power > ~55 kW) in 20 days (~0.5 per day) when PX G is enabled, whereas 17 power spikes in 6 days when PX G is disabled. Time series for California # 2 site shows about 13 spikes (when power > ~80 kW) with PX ON in 18 days (~0.7 per day) and about 61 spikes with PX OFF in 14 days (~4.3 per day). It must be noted that the temperature when PX G was OFF in California # 2 was higher on average basis. Power spikes when additional compressors turn ON are intermittent and can last from few minutes to few hours at a time, which can be reduced by the PX G. The time series data is then processed systematically as a function of temperature to further determine energy savings as discussed earlier. Two examples of this are shown in Figure 7.



(a) California # 1 site: power time series shows about 9 power spikes in 20 days with PX G is ON (0.5 per day), and 17 spikes in 6 days with PX OFF (~3 per day)



(b) California # 2 site: power time series shows about 13 power spikes in 18 days with PX G is ON (0.7 per day), and 61 spikes in 14 days with PX OFF (~4.3 per day)

Figure 7 : Power time series examples for two sites (a) California # 1, (b) California # 2

6.3.2 COP lift across all sites

Figure 8 shows results of energy savings utilizing analysis conducted by Energy Recovery as well as third-party OEMs. For each site, average savings is calculated as a function of temperature for a given period of data, which is then converted to COP lift % assuming similar loads, during the PX G and baseline runs. For some of the sites, COP is directly calculated because there is additional data available to calculate evaporator load as well as measurement of compressor work. Each point on the plot shows average energy savings and COP lift over roughly a two-week period (one ON and one OFF week). Depending on how long the PX G was enabled, the number of points corresponding to each site may vary. The chart also includes data collected in dedicated M&V campaigns that is a subset of overall runtime described in Table 1.

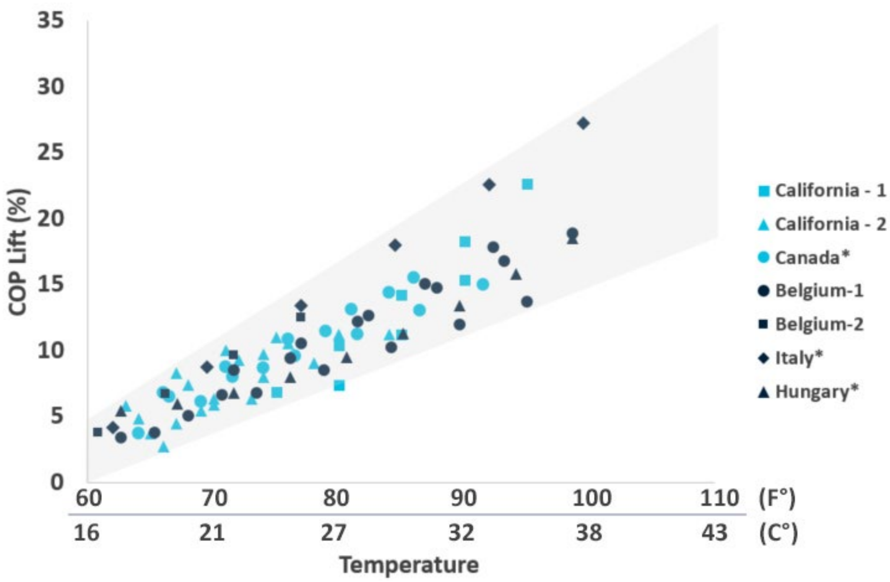


*Figure 8: COP lift percent across multiple sites in North America and Europe. Each point represents an average of roughly two hours of data. *Indicates analysis from OEM partners.*

6.4 System stability

In addition to providing energy savings, it has been observed over multiple sites that the introduction of PX G in refrigeration systems reduces fluctuations of gas cooler pressure and flash tank pressure. Figure 9 shows an example of this behavior. When the PX G is operational, the main high-pressure valve (HPV) is closed, and all of the gas cooler flow is passed through the PX G. Because the PX G is operated by a motor, it can adjust the flow with a finer resolution and a faster response, which likely leads to a finer control than the main valve controller. Reduced variation of gas cooler pressure for a given temperature can offer several advantages such as:

- There is less likelihood of pressure falling below the saturation line in the subcritical region, thereby providing more assurance that the optimal pressure is maintained.
- When pressure can be consistently controlled within a narrow band, the subcooling amount can be reduced, providing more optimal operation. Electronic Expansion Valves (EEVs) can maintain a tighter control over superheat at the exit of evaporators.
- By reducing upper portions of pressure fluctuations, there is less likelihood of the system reaching the pressure limits.

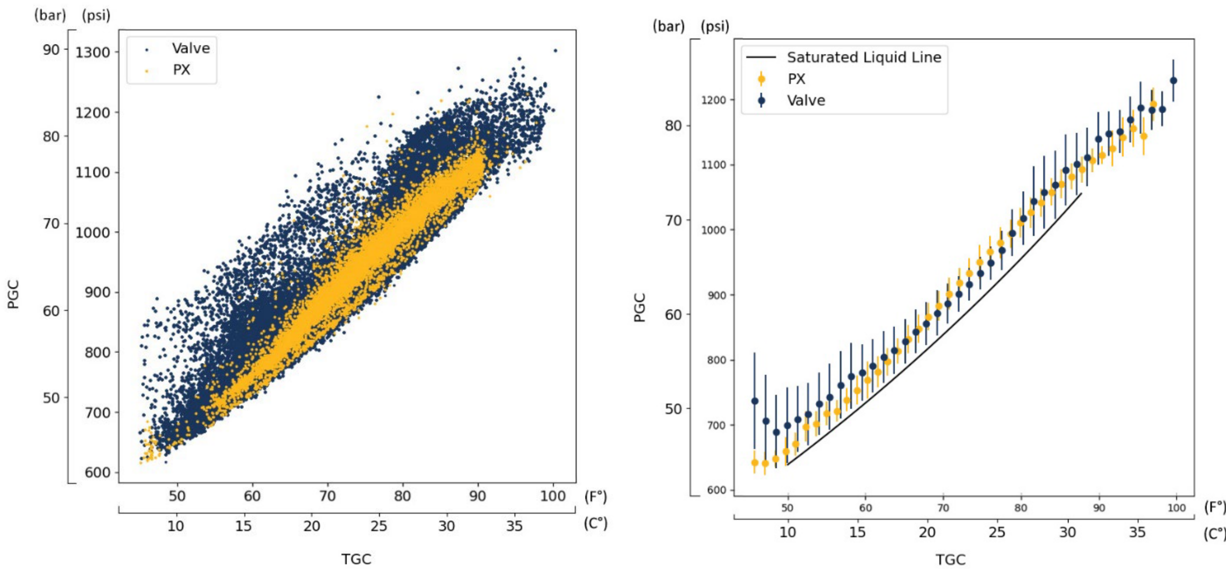
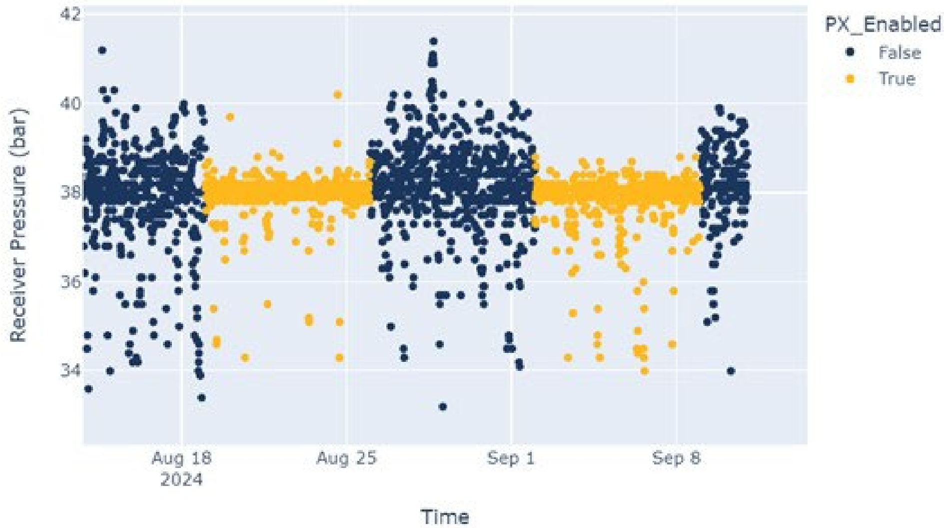


Figure 9 : Gas cooler pressure vs temperature (site: California # 1): Gas cooler pressure shows less fluctuations when PX G is operational

Similar behavior has also been observed in flash tank pressure fluctuations. Figure 10 shows reduced fluctuations in flash tank pressure when the PX G is running. Reduction of fluctuations in flash tank pressure can also benefit the system by:

- Providing consistent liquid refrigerant temperature entering the evaporators, which enables the operator to use more aggressive energy saving setpoints.
- If there is a parallel compressor, stable flash tank pressure can provide predictable suction conditions.

(a) Belgium #1 site: flash tank pressure



(b) Belgium #2 site: flash tank pressure

Figure 10: Flash tank pressure profile (a) Belgium #1, (b) Belgium #2

6.5 Flash gas reduction and capacity increase

The PX G provides benefit to the system by reducing flash gas passing through the flash gas bypass valve, which results in net reduction of compressor mass flow. Depending on the architecture, a PX G-based system can either process part of the flash gas from the flash tank or it can reduce the overall amount to begin with. In either case, the reduction in flash gas can be quantified by measuring the flash gas valve opening. In some instances, Energy Recovery had access to the rack data related to flash gas valve opening. An example of this data set over two months of operation is shown in Figure 11 from California # 2 site. It can be observed that the amount of flash gas, which can be gauged by flash gas valve opening, is reduced by around 21-22% at ambient temperatures of around 75-80 °F (24-27 ℃). This reduction in flash gas entering the MT compressor allows the compressors to handle additional capacity. Furthermore, it must be noted that the reduction in flash gas percentage increases as ambient temperature rises. In the events of extreme temperatures, the amount of flash gas generated by refrigeration systems can increase to the limits of available compressor capacity. When systems are pushed to run beyond compressor capacity, the cases could run at warmer temperatures than design set-points. This can lead to wasted retail space as food is moved to other locations or food spoilage if perishable inventory is out of temperature for extended periods. Incorporating the PX G can not only provide year-round energy savings, it can also increase system capacity to safeguard against the consequences of extreme heat waves. Flash gas reduction from the field data can be used for estimating capacity increase. This is achieved by taking the ratio of flash gas reduction to capacity increase in an ideal system model, and then calibrating that model with the field data for flash gas reduction. This capacity increase projection is shown in Figure 12, which demonstrates potential increase in capacity by up to 11 °F (6 °C) at around 95 °F (35 °C), or 15% higher capacity at 95 °F (35 °C).

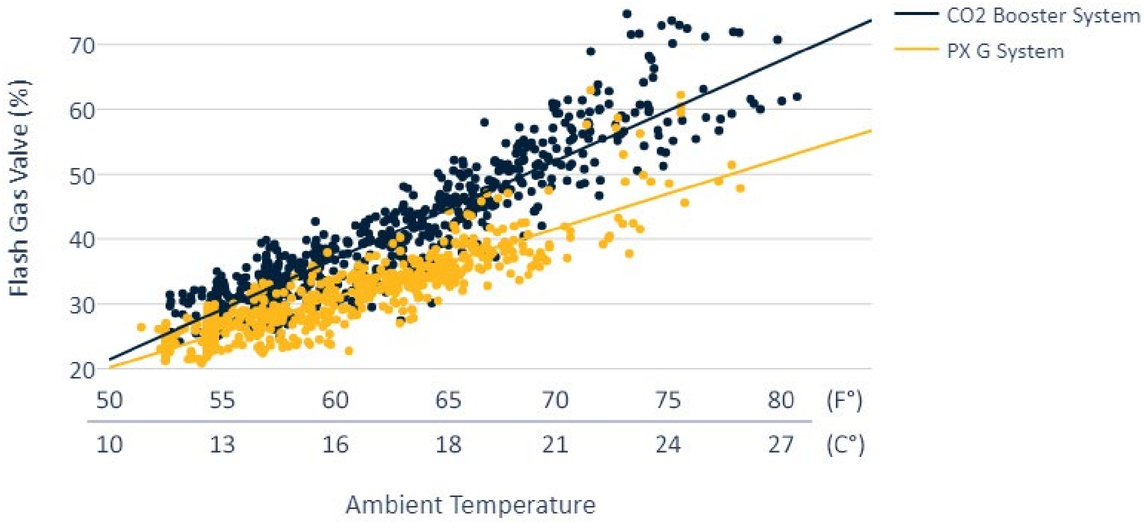


Figure 11: Flash gas valve opening % vs. temperature using raw data (site: California # 2): Around 21-22% reduction in flash gas is observed at temperatures of 75-80°F (24-27°C)

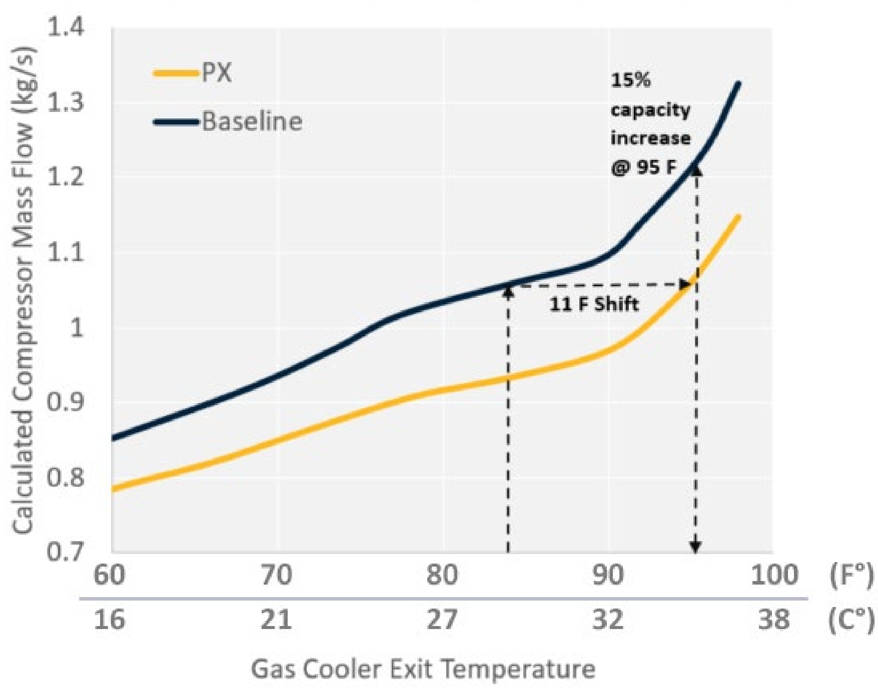


Figure 12: Projection of capacity increase for California # 2 site using measured flash gas data shows around 11°F (6°C) shift or 15% at 95°F (35°C) increase

To further validate the PX G benefit to the system, two of the sites were equipped with flowmeters that measure the liquid flow coming out of the flash tank before going to the evaporators. This liquid flow-rate measurement is usually directly proportional to the evaporator load. Figure 13 shows the plot of evaporator liquid flow as a function of net compressor work done from two of the European sites. Both these sites reached average maximum daily ambient temperatures of around 75 °F (24 °C). Using that data, around 6% and 8% increase in liquid flow for same amount of compressor work was observed for those two sites.

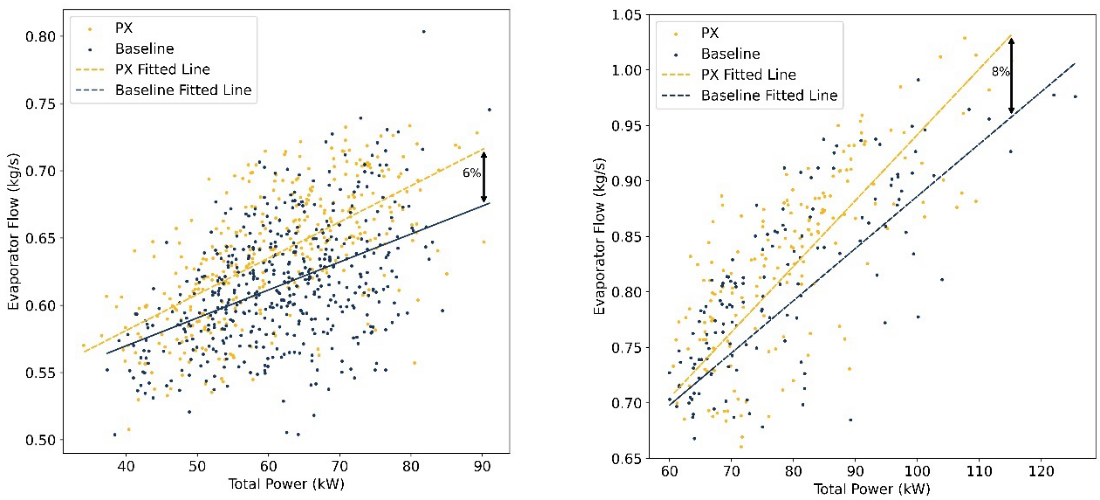


Figure 13: Liquid flow rate for given amount of compressor work: Data shows higher liquid flow for same compressor work -- up to 8% and 6% increase at 75°F(24°C). Left: Belgium #1, Right: Belgium #2

Increase in liquid flow can also be converted to evaporator load by multiplying the flow rate by enthalpy difference across evaporators. Implementation of a PX G1300 provides additional compression capacity for the refrigeration system. This manifests through reduced MT compression capacity usage, as PX G1300 compresses part of the refrigerant. This means that the MT compression works less at a similar load requirement, freeing up capacity. This also means that if the system was designed for a certain temperature, now the additional capacity of MT compression can shift the design point of the system further right, providing high-temperature rack stability and addressing unfortunate occurrences of a heat wave scenario. A cooling capacity increase of 6% and 8% was observed at two different sites at around 75°F (24°C) and PX G rpm was around 350-400. The PX G has unutilized capacity of 400-450 rpm, which is expected to provide an even higher benefit at 100 °F (40 °C) as discussed in Figure 12.

6.6 DC Engineering review

DC Engineering's Refrigeration team is a leader in refrigeration design, management, and compliance services. Many of its experienced staff have backgrounds in large retail refrigeration facilities, with expertise in engineering, operations, and facilities management. The group offers a full range of services, from design and equipment selection to controls development and compliance assistance through refrigerant tracking systems. DC Engineering's knowledge in commercial refrigeration has also led to partnerships promoting natural refrigerants and industry advancements. The Energy Services Group coordinates with various teams to establish cost-effective Energy Efficiency Measures (EEMs), providing Design Services, Energy Audits, Energy Modeling, and Measurement & Verification (M&V) plans to maximize ROI. Collaboration with the Commissioning team ensures project success through Functional Performance Testing (FPT).

Founded in 1998, DC Engineering operates across multiple disciplines with around 150-200 employees in 7 U.S. locations. Strong client relationships and industry partnerships have driven nationally recognized, sustainable initiatives.

DC Engineering have been an integral part of the M&V process, from instrumentation verification & calibration to devising the operation procedure, as well conducting data analysis and review across selected sites. Their independent data review from multiple sites is ongoing, and findings from two of those sites are listed below:

6.6.1 California #2 site findings

- The transcritical CO_2 refrigeration system is operating as expected.
- The energy use to the ambient conditions shows a strong correlation with R2 values of 0.71 and 0.78 for the baseline and PX G respectively.
- The cumulative energy savings of the PX G module is estimated at 2,100 kWh over the M&V period (55 days) compared to baseline.
- The estimated annual energy savings are approximately 11,000-19,000 kWh compared to baseline. This estimate is limited due to the amount of low temperature data collected during the M&V period.
- Flash gas valve opening data in Figure 11 was verified (up to 21% flash gas valve opening reduction)

6.6.2 Belgium #2 site findings

- The transcritical CO_2 refrigeration system is operating within reason of a functional supermarket.
- The flash tank pressure is maintained when the PX G is in operation, in baseline settings the system fluctuates over time.
- Baseline fluctuation may cause more instability in the low temp, medium temp and parallel compressors, which could cause higher suction temperatures. Flash tank pressure data observed in Figure 11b was verified.
- The overall energy use correlations are continuing to develop as additional data are collected. The portions of subcritical operations between 15-25 °C (59 - 77° F) are well developed. There is need for more measurement time to solidify the supercritical regression curve.

SECTION 7: CONCLUDING REMARKS

This paper gives an overview of the benefits provided by PX G1300 when incorporated into diverse parent rack designs and existing energy efficiency technology. With 30 projects and more than 25,000 cumulative hours the PX G1300 pressure exchanger has proven to increase energy efficiency, high-temperature rack stability, and cooling capacity. A follow up on this paper with more data from sites covered in this paper as well as additional sites will be released next year.

- Measurement & Verification (M&V) results from seven sites are presented in this paper across North America and Europe. The sites have a wide range of sizes from 80 kW to exceeding 240 kW. Two sites have two PX Gs running in parallel. Five sites have existing energy improvement mechanisms such as an adiabatic gas cooler and parallel compressor. Two sites have heat reclaim circuits. The PX G has proven to be a resilient and adaptable device that can be easily incorporated to work with a wide range of system sizes, configurations, and weather patterns, while still providing meaningful energy savings.
- A systematic procedure is developed to conduct M&V campaigns by periodically enabling and disabling the PX G, to distinguish its effect on the baseline system within similar operating conditions in alignment with commercial refrigeration best practices. Before commencing each M&V campaign, refrigeration systems are thoroughly evaluated to ensure the critical sensors are calibrated and that the system is running in a stable fashion.
- A third-party consultant (DC Engineering) is working on an independent data review for a few selected sites. Their reports will be available after around six months to one year of data collection across selected sites. Initial observations from their analysis have been reported in section 6.6.
- Data measured in the field shows the PX G1300 can provide up to 30 % peak COP lift depending on system configuration and weather profile, with projected annual energy savings of up to 15% or more.
- The PX G helps to reduce flash gas that needs to be processed by MT compressors, and its benefit increases with increasing temperature. Section 6.5 discusses flash gas valve opening reduction of around 21-22% at moderate temperatures of 70-75°F (24-27°C).
- Additionally, the PX G can help reduce pressure fluctuations in the system in certain cases as evidenced in section 5.4. Reduced pressure fluctuations can help to provide consistent operating conditions to the evaporator, as well as allow system optimization and tighter control settings to generate more energy savings.
- Furthermore, the PX G can provide safeguards against heat waves by reducing flash gas going to the MT compressors, and thereby increasing the system capacity. Estimated capacity increases of up to 15% at 95°F (35°C) have been discussed in section 6.5. The capacity increase is expected to increase further at higher temperatures. Additional capacity helps to safeguard against heat waves and other extreme temperature events, and potentially avoid significant costs associated with food spoilage.
- The PX G provides benefit to the system in following ways:
    1. Annual energy savings, which can be obtained as annual energy consumption reduction multiplied by Average electricity rate.
    2. Capacity increase savings, which can be obtained from % capacity increase at a given trigger point temperature multiplied by value of fresh food inventory in store for a given number of days in which temperature is expected to stay higher than trigger point.
    3. Operating expense of running adiabatic gas cooler. Depending on the variant of adiabatic cooler (mesh vs. one pass vs. recycle), this number can vary from $5K - $10K per year. [1] (water, electricity & maintenance).

Future work will involve the continuation of M&V campaigns around the world at additional sites. Additional whitepapers are scheduled for release in 2025 and beyond as more data is gathered. Energy Recovery will continue innovating the PX G design to improve its efficiency, and has begun development of PX Gs to handle larger system sizes. There is also ongoing work on system-level innovations, controls optimization and further rigor into data

[1] This does not take into account the initial capital expense of installing the adiabatic gas cooler

analytics to provide real-time indicators of PX G performance in the field. Applications of pressure exchangers in large industrial refrigeration systems and heat pump systems are being investigated as well [3].

SECTION 8: ACKNOWLEDGMENTS

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