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ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Demonstrating Replicable, Innovative, Large-Scale Heat Recovery in the Industrial Sector

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Natural Gas-Related Transportation

Demonstrating Replicable, Innovative, Large-Scale Heat Recovery in the Industrial Sector is the final report for Agreement Number PIR-19-005 conducted by Trevi Systems, Inc. and T2M Global, LLC. The information from this project contributes to the Energy Research and Development Division's Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

The Opportunity

Twenty-five of the 100 quadrillion British thermal units of fuel consumed per year in the United States are wasted as low-level heat (less than 300 degrees Fahrenheit [149 degrees Celsius]). This costs the United States economy more than $200 billion per year and contributes to increased greenhouse gas emissions. The cost of metallic heat exchangers has increased from less than $100 per kilowatt thermal to between $500 and $1000 per kilowatt thermal, making them undesirable for low-level heat recovery. An eighty percent recovery of this low-level waste heat would create more than $50 billion per year of opportunity.

The Solution Technology

Plastic heat exchangers recover this low-level heat at 80-percent lower cost than conventional metallic heat exchangers, without incremental emissions. Plastic heat exchangers are a low-cost, mass manufacturable, modular technology that is easy to deploy in disadvantaged communities. The assembly can be three-dimensionally printed for rapid prototyping and cost advantages. Heat conduction in plastic tubes is enhanced by innovative design and material choices. Plastic materials offer significant weight reduction and flexibility in sensitive applications such as food processing and pharmaceuticals.

Technology Progress

The feasibility of plastic heat exchanger manufacturing and assembly processes has been successfully demonstrated in a laboratory environment. Plastic heat exchanger performance for low-level heat transfer has been successfully validated at a kilowatt-class level, followed by scaleup to 10 kilowatt-class level. Plastic heat exchanger units with additional components were successfully installed and commissioned for testing at a brewery and a winery in California. Performance recovering low-level heat met all goals for this California Energy Commission project, with excellent stability. The technology promises to be a highly effective tool in achieving California's mandated decarbonization goals.

Keywords: plastic heat exchanger, low-level heat transfer, decarbonization, grid resiliency, heat recovery efficiency

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

Background

Problem of Low-Level Waste Heat: Twenty-five of the 100 quadrillion British thermal units of fuel consumed per year in the United States are wasted as low-level heat (less than 300 degrees Fahrenheit [°F] or 149 °Celsius [°C]). [1] This costs the United States economy more than $200 billion per year and contributes to greenhouse gas emissions. Conventional metallic heat exchangers (M-HEX) are cost prohibitive for the recovery of low-level heat. The M-HEX cost has increased from less than $100 per kilowatt thermal to between $500 and $1000 per kilowatt thermal, making them undesirable for low-level heat recovery. This low-level heat waste increases fuel consumption and its associated costs. In addition, the manufacturing industry is often located in disadvantaged communities, which may suffer disproportionately from these harmful emissions.

Solution for Cost-Effective Waste Heat Recovery: Plastic heat exchangers (P-HEX) have the potential to recover low-level heat at lower cost than conventional M-HEX; P-HEX is a low-cost, mass manufacturable, modular technology that is easy to deploy. Plastic materials are cheaper and more versatile than metals, especially for highly aggressive applications involving corrosive working fluids with fouling potential. Unlike the metal tubes in M-HEX, the thin-walled plastic tubes in P-HEX can be manufactured at very high speeds and in a variety of shapes and compositions as needed for heat transfer. The assembly can be three-dimensionally printed for rapid prototyping and low cost. Plastic materials offer significant weight reduction for reduced shipping, handling, and installation costs. This is particularly advantageous for retrofit applications. An 80-percent recovery of low-level waste heat would create more than $50 billion per year in economic opportunity.

Project Purpose and Approach

The overall objectives for this project were to increase heat recovery efficiency for P-HEX from 40 percent to 80 percent and validate at one kilowatt-class level in the laboratory; scaleup P-HEX technology to 10 kilowatt-class level and evaluate its performance in real environments at a micro-brewery and a winery, then follow up with parametric technoeconomic analyses to estimate benefits to California stakeholders. Analyze test results to update benefits to the host sites, overall cost savings, greenhouse emission reductions, economic and environmental benefits to California (especially to disadvantaged communities) and develop manufacturing and deployment plans to advance commercialization. The innovative approach used in developing high-performance and low-cost P-HEX for low-level waste heat recovery is shown in Figure ES-1. The Figure provides logical steps to cost-effectively increase the heat transfer capabilities of P-HEX to that of an M-HEX.

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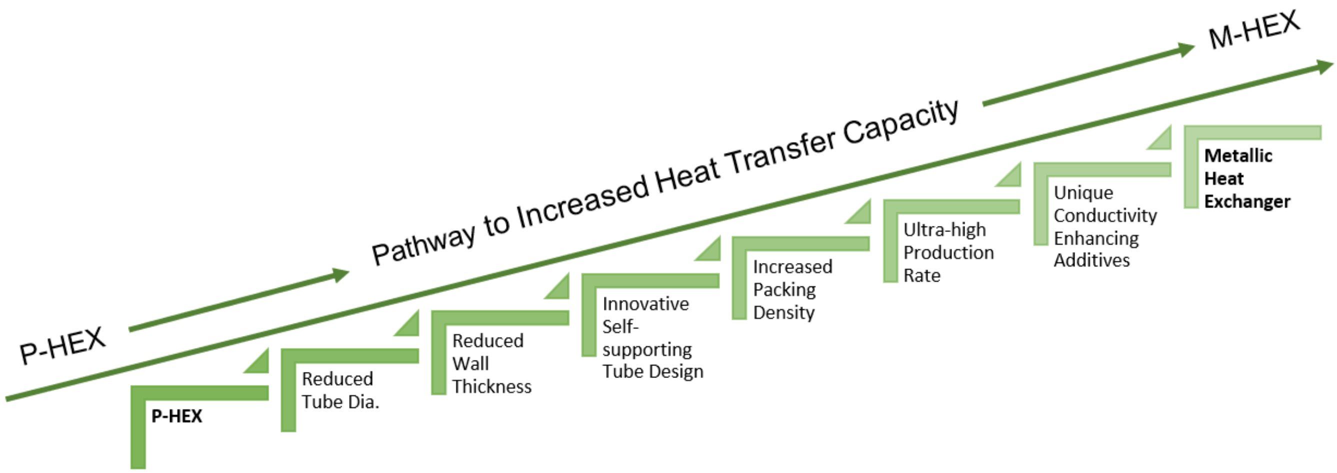
[1] U.S. Energy Information Administration. 2023 (April). *Monthly Energy Review*, Table 1.3 and 10.1. U.S. Department of Energy, Office of Energy Statistics. Available at https://www.eia.gov/totalenergy/data/monthly/archive/00352304.pdf.

Figure ES-1: Innovative Approach for Low-Level Heat Recovery



Strategy to improve P-HEX performance cost-effectively

Source: Trevi Systems

Key Results

The results from this project include the following:

- Successfully demonstrated in a laboratory environment the feasibility of P-HEX manufacturing for both kilowatt-class and 10 kilowatt-class as shown in Figure ES-2.
- Successfully designed, fabricated, installed, and operated baseline and advanced (carbon doped) 10-kilowatt-class P-HEX units in two real-world environments: a brewery (Figure ES-3) and a winery (Figure ES-4), both in California.
- Successfully identified and resolved all the site-specific installation requirements and challenges. The P-HEX units were installed and commissioned and P-HEX performance on low-level heat sources was excellent and met all goals for this California Energy Commission project.
- Cost and benefit analyses indicate that P-HEX technology promises to be a highly effective tool to achieve California's mandated decarbonization goals. P-HEX recovers low-level waste heat that could improve the economic competitiveness of the manufacturing industry while reducing greenhouse gas emissions by up to 25 percent.
- Met and exceeded the project target heat exchanger effectiveness, which is the ratio of the actual amount of heat transferred to the maximum possible amount of heat that could be transferred with an infinite heat transfer area. The heat exchanger effectiveness progressively increased effectiveness from 40 percent → 60 percent → 80 percent.
- Increased heat transfer capacity from 1 → 10 → 30 kilowatt-thermal levels, which met project goals.

- Showed excellent performance stability of P-HEX at the two host sites over more than nine months of operation, meeting the project goal.
- Met and exceeded the target overall heat transfer coefficient (U-factor) of between 200 and 280 watts per square meter degree Celsius → achieved 342 watts per square meter degree Celsius. These values are comparable to M-HEX.

Figure ES-2: P-HEX Technology Scaleup

Successful proof of concept: 1 kW-class → 10 kW-class

Source: Trevi Systems

Figure ES-3: P-HEX Demonstration at Old Caz Brewery

A successfully designed, fabricated, installed, and operated baseline and advanced (carbon doped) P-HEX at a brewery in California

Source: Trevi Systems

Figure ES-4: P-HEX Demonstration at Black Kite Winery

A successfully designed, fabricated, installed, and operated baseline P-HEX at a winery in California

Source: Trevi Systems

Knowledge Transfer and Next Steps

The outreach of project results to California stakeholders included early adopters, gas and utility industry representatives, combined heat and power centers in California, and both California and national government sponsoring agencies. Technical advisory committee members provided valuable guidance to foster adoption, and recommendations for commercialization, and near-term opportunities. The communication tools included the P-HEX Fact Sheet, benefits questionnaire, and PowerPoint presentations.

The next steps for this promising P-HEX technology are: scaleup to 100 kilowatt building block level, durability testing, and market-responsive product design to advance entry into multiple market sectors. The team is planning to manufacture and sell P-HEX inhouse utilizing raw materials from specialized vendors. The team will use gas utility companies as market channel partners for introducing P-HEX units in California markets. Technical advisory committee members, including the investor-owned utilities Southern California Gas and the Pacific Gas and Electric Company, have shown interest in identifying early adopters.

Benefits of Waste Heat Recovery to California Stakeholders

- More than 20 percent savings in fossil gas use (~1 billion therms per year)
- Significant cost savings to California ratepayers (~$1 billion of fuel cost savings)
- The fuel savings can be used to support intermittency of renewables, a critical requirement in California during high-peak evening hours. This will improve grid resiliency and provide much needed protection against forest fires.
- Accelerate transition to a zero-emission economy: P-HEX can help mitigate greenhouse gas (GHG) emissions (with the goal of 13 million tons carbon dioxide equivalent per year)
- Easier deployment and retrofit: Beneficial to disadvantaged communities for healthier environment and better economic opportunities

CHAPTER 1: Introduction

Problem Statement and Project Scope

Problem of Low-Level Waste Heat: Twenty-five quadrillion British Thermal Units (Quads) of the 100 Quads of fuel consumed per year in the United States[2] are wasted as low-level heat (less than 300 degrees Fahrenheit [°F], or 149 degrees Celsius [°C]). This costs the United States economy more than $200 billion per year and contributes to associated greenhouse gas (GHG) emissions. Conventional metallic heat exchangers (M-HEX) are very expensive for recovery of low-level heat. The M-HEX cost has increased from less than $100 per kilowatt thermal ($\$/kW_{th}$) to between $\$500/kW_{th}$ and $\$1000/kW_{th}$, making M-HEX undesirable for low-level heat recovery. Recovery of this low-level waste heat could create more than $50 billion per year of opportunity and increase United States competitiveness. Conventional plastic heat exchangers suffer from poor heat transfer properties. The scope of this project was to improve these heat transfer properties to a level comparable to their M-HEX counterpart.

Solution for Cost-Effective Low-Level Waste Heat Recovery: Plastic heat exchangers (P-HEX) developed under this project offer the following benefits:

- Eighty percent recovery of wasted low-level heat: resulting in reduced operating cost.
- Lower capital costs: resulting in savings of up to 80 percent as compared to conventional M-HEX.
- Attractive for decarbonization applications. Heat recovery is without an incremental increase in emissions, making it a value-added technology for California.
- P-HEX is a modular, lower-cost, mass manufacturable technology, and easily deployable.
- Application flexibility. Plastic materials are more versatile than metals, especially for highly corrosive applications involving challenging working fluids with fouling potential, such as the food processing and pharmaceutical industries.
- High-speed manufacturing. Unlike metal tubes in M-HEX, the thin-walled plastic tubes in P-HEX are manufactured at very high speeds and in a variety of shapes and compositions needed for recovery of low-level waste heat.
- The assembly can be three-dimensionally (3-D) printed for rapid prototyping and cost advantages.
- The heat conduction in plastic tubes is enhanced by innovative design and materials.

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[2] U.S. Energy Information Administration. 2023 (April). *Monthly Energy Review*, Table 1.3 and 10.1. U.S. Department of Energy, Office of Energy Statistics. Available at https://www.eia.gov/totalenergy/data/monthly/archive/00352304.pdf.

- Weight reduction. Resulting in up to 80 percent reduction in weight compared to M-HEX, substantially reducing shipping, handling, and installation costs.

Scope and Goals of the Project

The overall objectives for this project were to increase heat recovery efficiency for P-HEX from 40 percent level to 80 percent, scaleup from a one kilowatt (kW)-class to 10 kW-class level, evaluate P-HEX performance in real environments, and to perform parametric technoeconomic analyses to estimate benefits to California stakeholders. Test results were analyzed to update benefits to the host sites, overall cost savings, GHG emissions reduction, and economic and environmental benefits to California, especially to disadvantaged communities. Manufacturing and deployment plans were developed to facilitate commercialization. P-HEX development and demonstration were performed through a seven-task structure, which met or exceeded California Energy Commission (CEC) project targets.

P-HEX Technology Overview

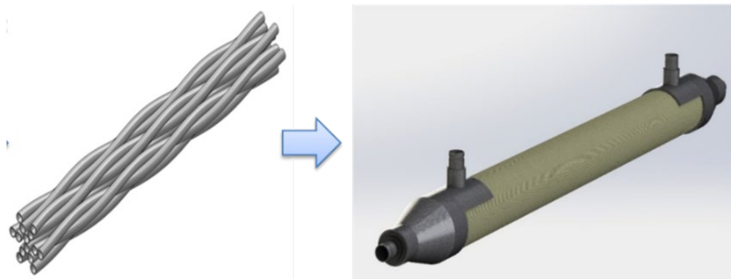
Strategy for Enhanced Heat Transfer

As illustrated previously in Figure ES-1, the P-HEX performance was increased using a seven-step approach to match commercially available M-HEX performance while reducing overall cost. This was accomplished by improving the tube design-shape and tube wall thickness to maximize heat recovery. A typical tube-in-shell heat exchanger (HEX) cannot fully exchange all the thermal energy due to "bypass" in its internal design, which leads to its "pinch" or approach temperatures being a few (or more) degrees apart. This leads to lower heat recovery. The difference in the approach temperatures is typically 13°F to 18°F (7°C to 10°C), leading to heat recovery of between 50 percent and 70 percent. Plate and frame manufacturers can achieve much higher heat recovery (90 percent, pinch point: 4°F to 9°F [2°C to 5°C]) due to their ability to control "bypass," allowing all the fluid to exchange its thermal energy. Since flat plastic plates have low structural strength, a self-supporting design is required for plastic heat exchangers.

Light-weight Design for Low-Cost Manufacturing

Tubes are by nature a far stronger structure than flat plates and self-supporting. Plastic tubes can be mass produced at extremely low cost using high-speed extrusion processes. This is not possible with conventional M-HEX. The problem with thin-walled tubes was solved by cleverly designed flow guides that also act as self-supporting ribs. This leads to a dramatic reduction in cost while maintaining high heat recovery performance. Plastic extrusion allows co-extrusion of spacing 3-D elements. Figure 1 shows one such shape for co-extrusion with self-supporting flow guides between the hollow tubes. Plastic materials typically offer more than 80-percent reduction in material costs as opposed to materials in M-HEX. The high-speed processes in P-HEX further lower manufacturing costs by as much as 80 to 90 percent, depending on the composition of the polymer formulation. Thus, the P-HEX promises more than an 80 percent reduction in manufacturing cost when compared with M-HEX.

Figure 1: High-performance Low-cost P-HEX Module



Self-supporting thin-walled tubes with 3-D printed manifolds for high-speed manufacturing

Source: Trevi Systems

Modular Design

P-HEX modules assembled with a common building block offer unique advantages of application flexibility for multiple markets. The tube and shell diameter, as well as their length, determines the heat transfer capacity of the building block. Based on the commercial availability of the plastic fittings needed for assembly, shell diameters of 2 inches (2”), 3”, 4”, 6” and 8” and tube lengths of 4 feet (4’), 6’, 8’, 10’ and 12’ were identified as key parameters for a modular design with lower cost. A key aspect of this project was the fabrication of large quantities of low-cost, thin-walled tube bundles.

Metrics Measured

The P-HEX technology development goal was to achieve high heat exchange performance at low cost for various low-level waste heat applications. In some cases, its intended advantages were reduced cost, weight, and a footprint that competes with commercially available M-HEX, such as plate and frame, shell and tube, brazed plate, and tube in tube. The Project Performance Metrics and Targets are shown in Table 1. Detailed formulas and assumptions used to validate the performance metrics targets are provided in Appendix B.

Table 1: Project Performance Metrics, Targets, and Significance

Performance Metric	Benchmark Performance	Low Target Performance	High Target Performance	Evaluation Method	Significance of Metric
Overall Heat Transfer Coefficient (W/m^2 °C)	170	200	280	Test data $U = Q/(A*T_{LMTD})$	This is a measure of how efficiently the heat exchanger transfers heat between fluids.
Module Cost ($/unit)	70,000	1,200	650	Projected high volume manufacturing costs	Economic efficiency of capital cost per unit of heat transferred.

Performance Metric	Benchmark Performance	Low Target Performance	High Target Performance	Evaluation Method	Significance of Metric
Cost per (U*A) ($/[W/°C])	0.25	0.12	0.05	Calculated from Module Cost and Heat Transfer	Reduced CapEx is critical for low-level waste heat recovery.
Surface Area Packing Density (m^2/m^3)	280	500	600	Calculated from the tube surface area	Compact P-HEX reduces facility footprint and costs.
Weight per Unit Surface Area (kg/m^2)	8.9	0.9	0.8	Calculated from the physical design of the heat exchanger	Lightweight P-HEX reduces shipping, handling and installation costs.

All key performance targets were successfully met

W/m^2 = watts per square meter; $/(W/°C) = dollar per watt per degree Celsius; m^2/m^3 = meter squared per meter cubed; kg/m^2 = kilograms per meter squared; U = U-Factor; Q = heat transferred; A = surface area; T_{LMTD} = logarithmic mean temperature difference; CapEx = capital expenditure
Source: Trevi Systems

Benefits to Ratepayers

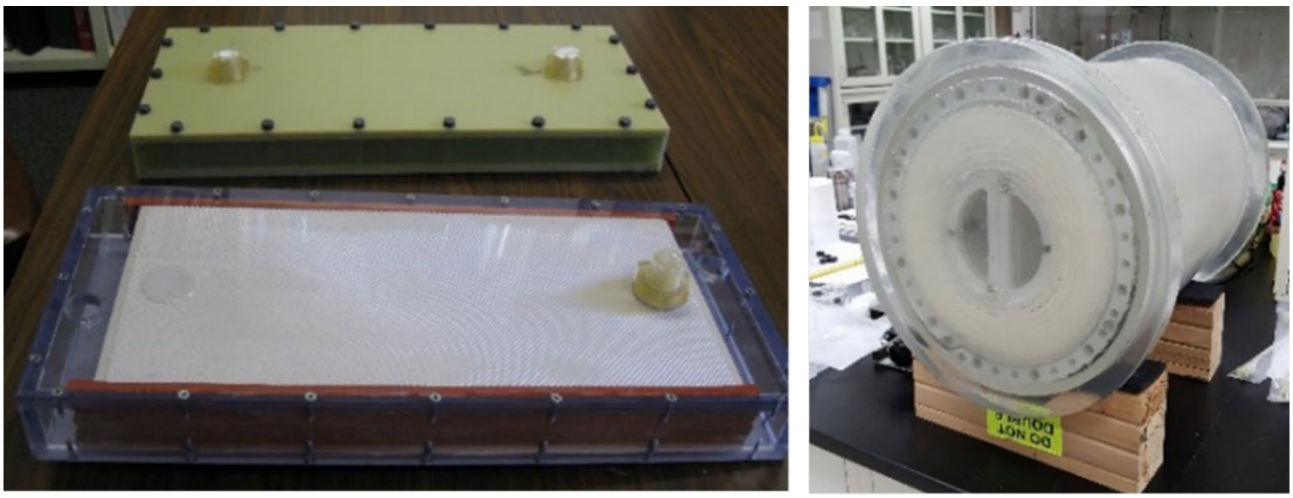
Benefits include significant reductions in fossil gas use, cost savings to California ratepayers, and reduced GHG emissions. P-HEX technology features bring unique benefits to disadvantaged communities such as a healthier environment from reduced emissions. Improved economics in manufacturing promises higher paying jobs within these communities.

CHAPTER 2:
Project Approach

Project Team

P-HEX development was led by Trevi Systems (Trevi), with support from T2M Global. Team members had extensive backgrounds in advanced heat transfer systems for water purification, hydrogen fuel cells, and hybrid systems. An example is shown in Figure 2.

Figure 2: Plastic Heat Exchanger: Foundation for the Project



(a) (b)

Plastic plate and frame heating, ventilation, and air conditioning (HVAC) HEX (a), and plastic spiral HEX (b).

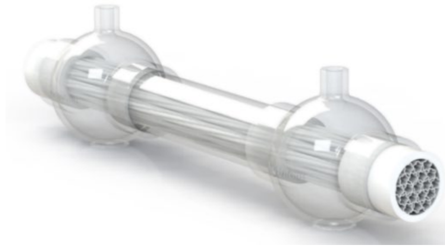
Source: Trevi Systems

Trevi led P-HEX development, fabrication, installation, and testing efforts at the two host sites. Project partner T2M Global contributed engineering and measurement and verification support, tech-to-market expertise, and comprehensive benefits analyses. The technical advisory committee (TAC) consisted of experienced organizations from key California stakeholders. The TAC members helped to identify early adopters and provided guidance for application development.

P-HEX Design Options Evaluated

The P-HEX heat transfer capacity depends upon the heat transfer surface area in each tube assembly. The heat transfer surface area and effectiveness depend on the number of tubes; tube diameter, length, and wall thickness; and the thermal conductivity of the P-HEX material. In addition, the mechanical strength of the tubes for pressure capability depends on tube geometry and composition. The components of P-HEX include tube bundle assembly, shell, and manifolds for hot and cold fluids (Figure 3). Following is a summary of the efforts for P-HEX design, development, and validation testing.

Figure 3: Lab-Scale P-HEX Assembly

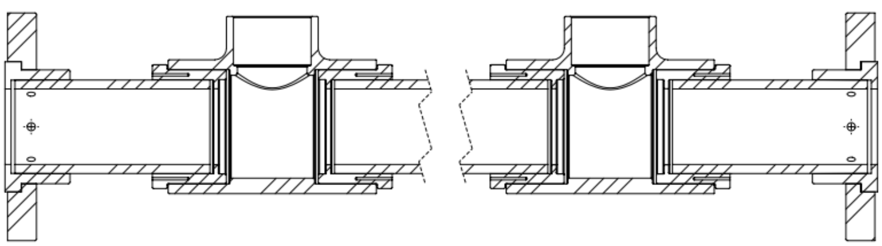


Constructed from tube extrusion and 3-D printed parts.

Source: Trevi Systems

2.5-Inch Diameter Unit With Poly Ether Ketone (PEEK) Round Tubes With Ribs: The 2.5-inch diameter unit was developed, designed (Figure 4), and assembled. It consisted of an array of PEEK 1.5-millimeter (mm) diameter round tubes with thin walls and ribs along the outside diameter down the length of the tubes. The ribs provided structure that established consistent spacing between tubes, which provided the designed flow cross sectional ratio between the fluid flowing within the tubes and the fluid flowing between the tubes, within the shell of the heat exchanger. This eliminated the need for spacers used in initial prototypes. Flow patterns were designed so that fluid running through the shell was brought into the unit through side ports so that the flow distributed throughout the shell, then along the length of the heat exchanger, then is finally collected in a side port on the downstream end. The flow through the tubes was brought in through an end port into a chamber that distributed the flow into the tubes along the length of the heat exchanger and collected at the other end before being passed out through an end port.

Figure 4: 2.5-Inch P-HEX Design

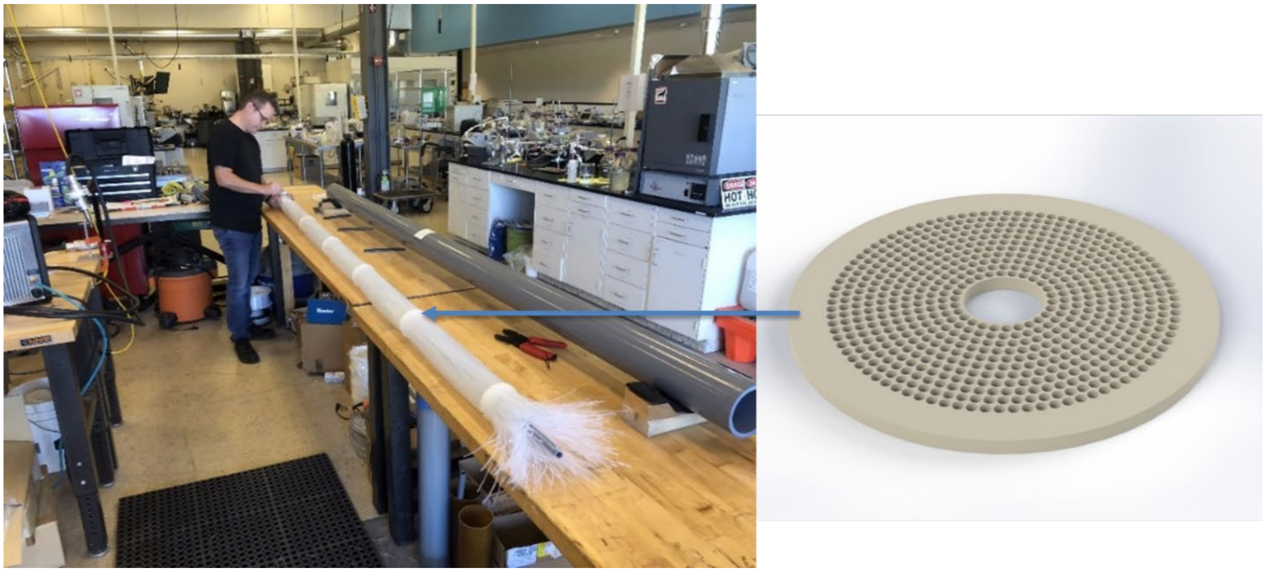


Major components for P-HEX assembly.

Source: Trevi Systems

Four-Inch Diameter P-HEX With 2.5 mm Ethylene Tetrafluoroethylene (ETFE) Round Tubes: The larger diameter unit developed was designed with an array of ETFE 2.5mm diameter round tubes with thin walls. The flow patterns were designed so that fluid running through the shell entered the unit through a centrally located tube so that the flow distributed radially outward, then along the length of the heat exchanger, then finally collected in a centrally located tube on the downstream end. The flow through the tubes was brought in through a side port into a chamber that distributed the flow into the tubes along the length of the heat exchanger, then collected at the other end and passed out through a side port. The tubes were spaced using spacers produced on the 3-D printer (Figure 5).

Figure 5: 4-Inch P-HEX Tube Bundle Assembly With Spacers



The thin-walled tubes were manufactured by a high-speed extrusion process.

Source: Trevi Systems

P-HEX for Real Environment Testing at Host Sites

The baseline P-HEX was fabricated using only polymer materials. The advanced P-HEX used polymer-plus, conductivity-enhancing additives. Figure 6 illustrates installation of both baseline and advanced P-HEXs at the Old Caz Brewery (Brewery) site. This configuration features flexibility for series, parallel, or independent operation. The installation at the Black Kite Winery (Winery) site, which used baseline P-HEX, is shown in Figure 7.

Figure 6: Baseline and Advanced P-HEX Installation at Old Caz Brewery

Data confirmed excellent performance in achieving all target metrics. Durability testing in progress.

Source: Trevi Systems

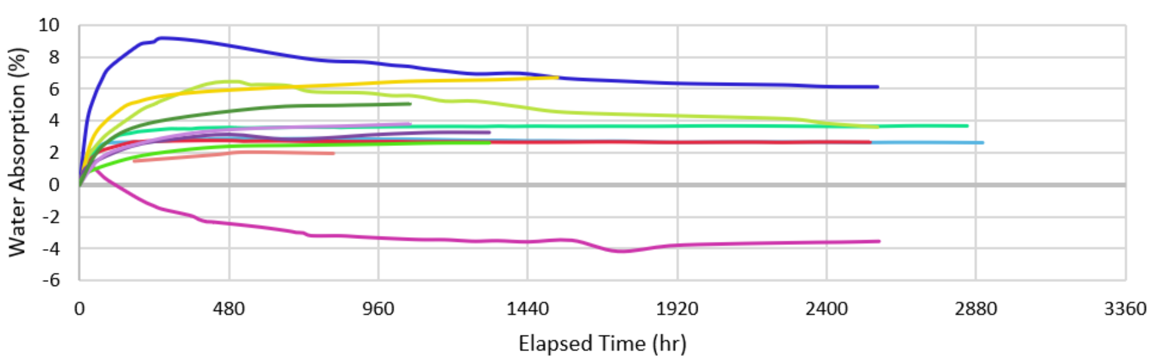
Figure 7: Baseline P-HEX Installation at Black Kite Winery

Solar thermal low-level heat recovery conduit.

Source: Trevi Systems

Sealant for Tube Assembly Selection: Testing was conducted on numerous commercially available sealants for their suitability in P-HEX assemblies. These sealants provided leak-proof operation under a variety of pressure conditions. They were used to seal the ends of the tubing to create the necessary tube sheet barriers that controlled the two fluids passing through the heat exchangers and maintained a seal between them to prevent the fluids from mixing. Screening tests were performed to select a suitable sealant for the P-HEX application. A high-level summary of these tests is shown in Figure 8, Figure 9 and Table 2. Testing was ongoing throughout the project and the samples were still being monitored beyond the project end date. Figure 10 shows the result of long-term durability testing of one sealant that failed. Figure 11 illustrates the successful application of sealant to the P-HEX tube bundle.

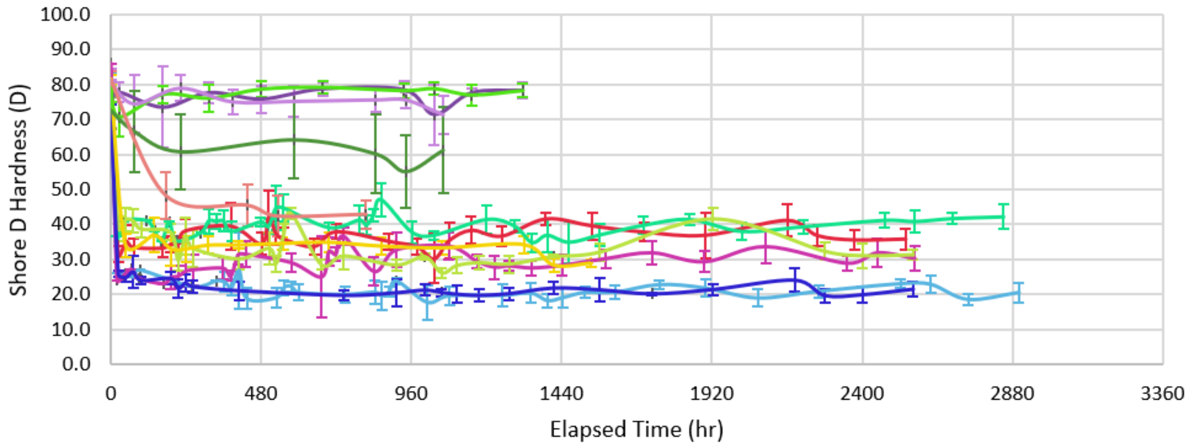
Figure 8: Long-Duration Adhesive Testing



Change in mass percent of adhesives over time in aqueous conditions at 212°F (100°C).

Source: Trevi Systems

Figure 9: Long-Duration Adhesive Shore Hardness Testing



Change in hardness of adhesives over time in aqueous conditions at 212°F (100°C).

Source: Trevi Systems

Table 2: Hardness Testing of Candidate Sealants

Average:	47.0	24.9	42.2	44.9	36.2	42.2	23.8	38.8	78.8	79.9	76.0	65.6
StD:	13.6	12.3	13.4	11.0	15.0	14.1	11.3	12.0	2.7	2.5	2.1	3.9

Hardness is one parameter affecting sealant durability.

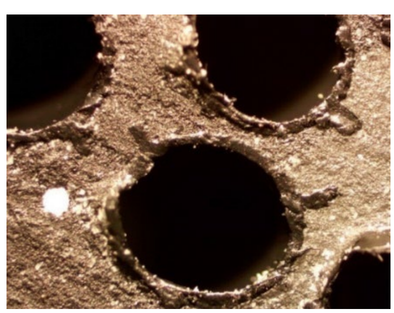
StD=standard deviation
Source: Trevi Systems

Figure 10: Long-Term Material Stability and Durability

Example of a failed sealant.

Source: Trevi Systems

Figure 11: Sealant Fill and Bond



Good sealant bond application to P-HEX tubes after long-term testing.

Source: Trevi Systems

High Performance Tube Development

The P-HEX requires thin-walled tubes for low-level heat recovery. However, reduced wall thickness decreases both mechanical strength and pressure capabilities. A variety of tube configurations and shapes to optimize these properties were investigated. Specially configured heat exchanger tubes were developed for the purpose of improving performance while maintaining manufacturability, using high-speed extrusion processes as shown in Figure 12 and Figure 13.

Figure 12: Extruded Tube Design

Pressure-capable thin-walled tubes that are mass-extrudable.

Source: Trevi Systems

Figure 13: P-HEX Tube Extrusion Equipment

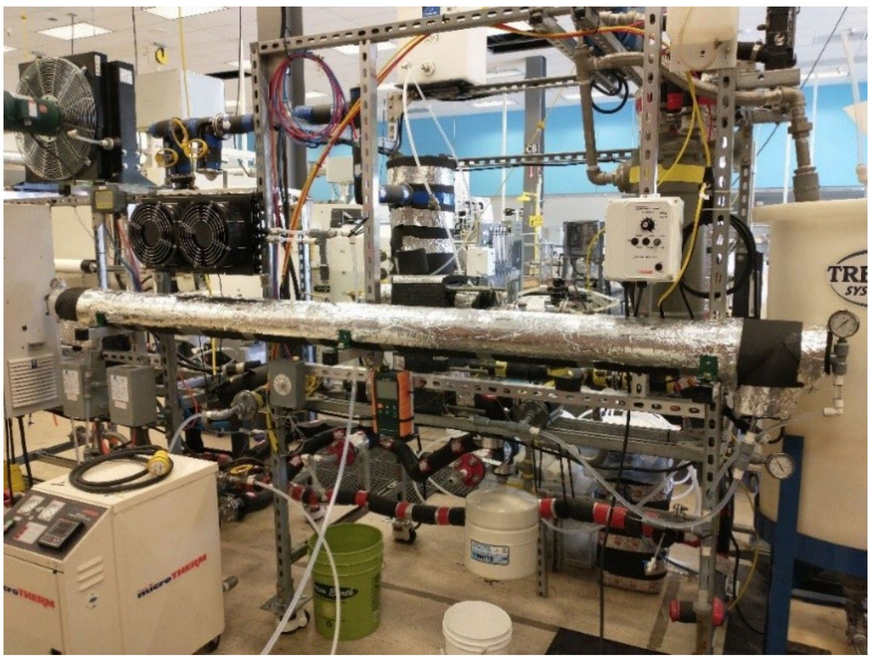
High-speed manufacturing for thin-walled tubes.

Source: Trevi Systems

P-HEX Bench-Scale Testing

A custom test rig was designed and built to validate laboratory P-HEX performance (Figure 14). The testing was conducted using water flow through both the tube side and the shell side. Heat was provided by a 24-kW heater and hot water flowed through a heat exchanger. The heat was transferred into the water for testing, and this hot water was introduced into the P-HEX tubes, where it flowed through the length of the plastic heat exchanger. Low temperature water was passed through the shell side of the heat exchanger, along the length of the heat exchanger. Heat was then transferred from the tube flow into the shell flow. Flow rates were measured along with the input and output temperatures on both the tube side and the shell side.

Figure 14: Kilowatt-Class P-HEX Test Apparatus (Bench-Scale)



Testing to recover low-level waste heat.

Source: Trevi Systems

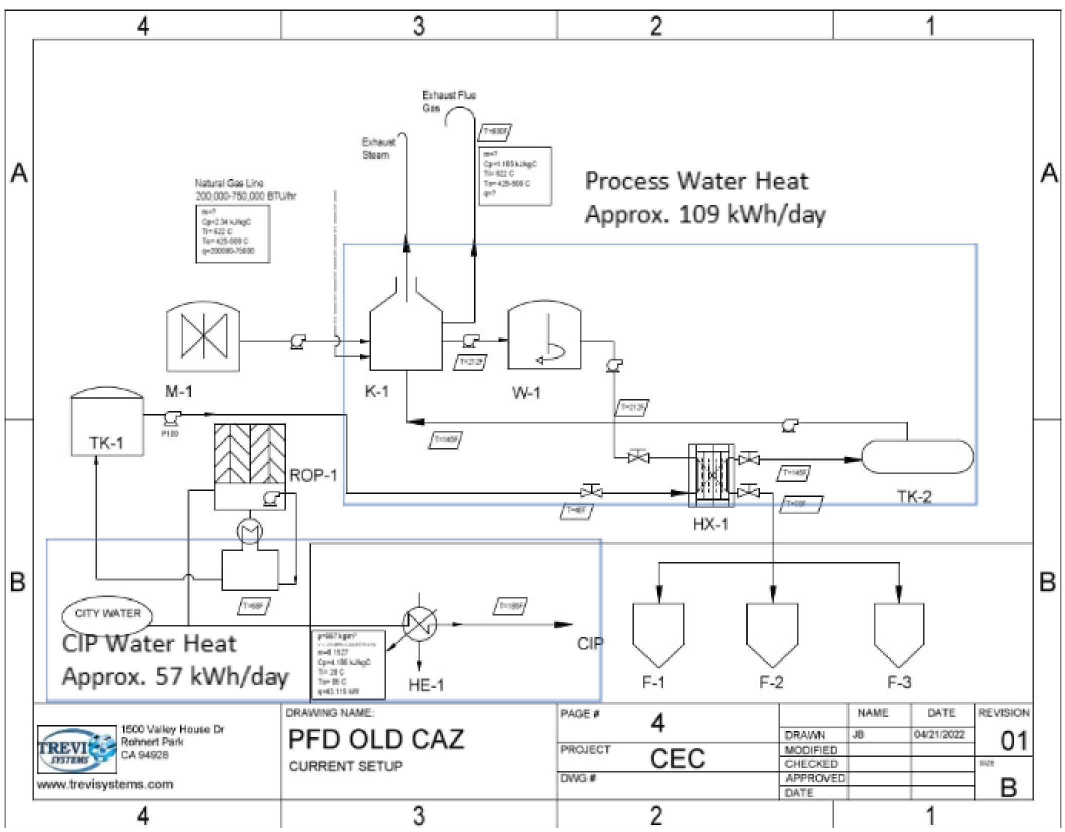
During the testing, the tube side was supplied with hot water at 185°F (85°C) and the shell side with ambient water at 86°F (30°C). The flow rates on both sides were varied in sync with each other from between two to three gallons per minute. The heat exchange was measured at 33 kW at a 3 gallons per minute flow rate. Through a number of P-HEX design iterations and tests, the heat recovery efficiency was progressively increased from 40 percent to 60 percent to 80 percent. These encouraging results were used to design the P-HEX for demonstration at the host sites.

The Trevi team decided to use water as the flow medium for testing both fluids (inside the tubes and around the tubes within the spacing inside the shell). This decision was made because the performance of a heat exchanger was determined to be the overall U-factor, which was dependent on the overall resistance to heat flow. This was calculated as a series of the resistance to the heat flow of each of the two fluids (and the heat exchanger wall in between the fluids) as an inverse function of their respective thermal conductivities. Water is highly thermally conductive and its use as heat exchanger fluid minimizes the impact of the fluids on the U-factor of heat exchange performance and maximizes the impact of the tube material. Thus, the heat exchanger performance could be best evaluated with minimal impact on the fluids used to exchange heat. The tests were conducted by running the hot water through the shell side and cold water through the tube array (and vice-versa), with similar results.

P-HEX Demonstration at Brewery Site

The heat source at the Old Caz Brewery is the exhaust heat from the brewing kettle boiler at 400°F (204°C). The demonstration of P-HEX at the Brewery was successful despite challenges to integrate P-HEX at the site with highly constrained access and high temperature waste heat (requiring an additional M-HEX). This installation includes a baseline P-HEX as well as an advanced P-HEX configured for flexibility by allowing parallel, serial, or independent operation. The M-HEX preconditions the higher temperature heat (400°F [204°C]) to the low-level heat targeted for P-HEX operation. The waste heat captured by the P-HEX was transferred to clean-in-place water for use in Brewery operations. Long-term-duration testing is in progress with very stable heat transfer performance. Figure 15, Figure 16, and Figure 17 show the design and process, through installation, at the Brewery. Figure 18 shows one screen of the human-machine interface developed for Brewery P-HEX operation and data collection.

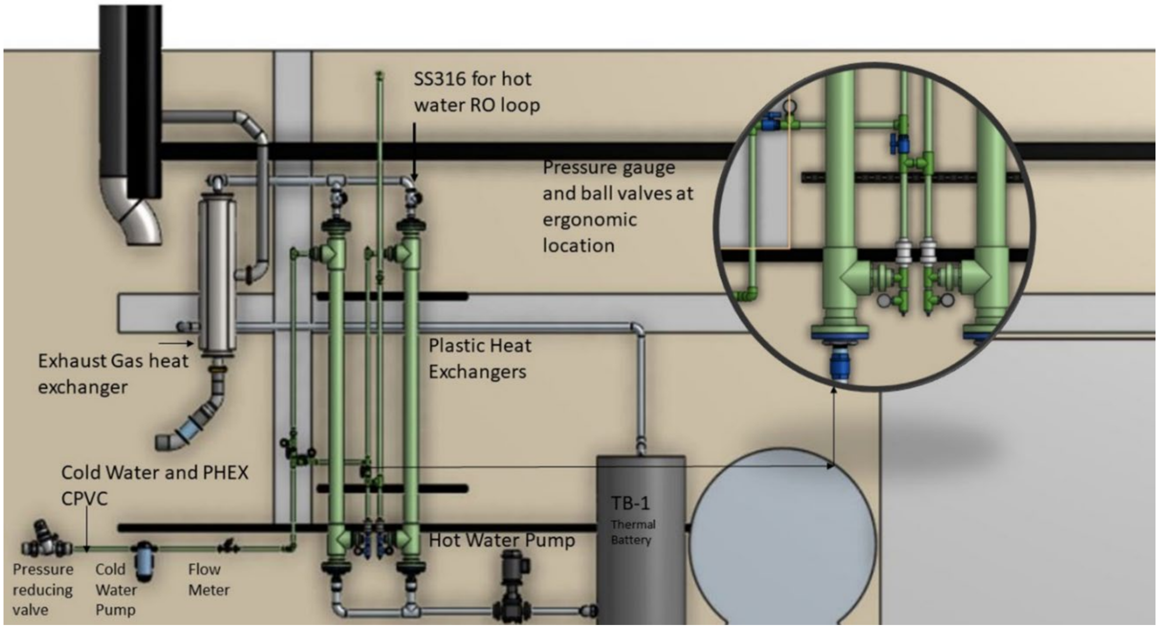
Figure 15: Heat Recovery System Layout for Old Caz Brewery



A successful P-HEX integration that required significant modifications to the existing brewery mechanics.

kWh/day=kilowatt-hour per day
Source: Trevi Systems

Figure 16: Physical Layout Design of Brewery P-HEX



The successful design for installation in a space-restricted area.

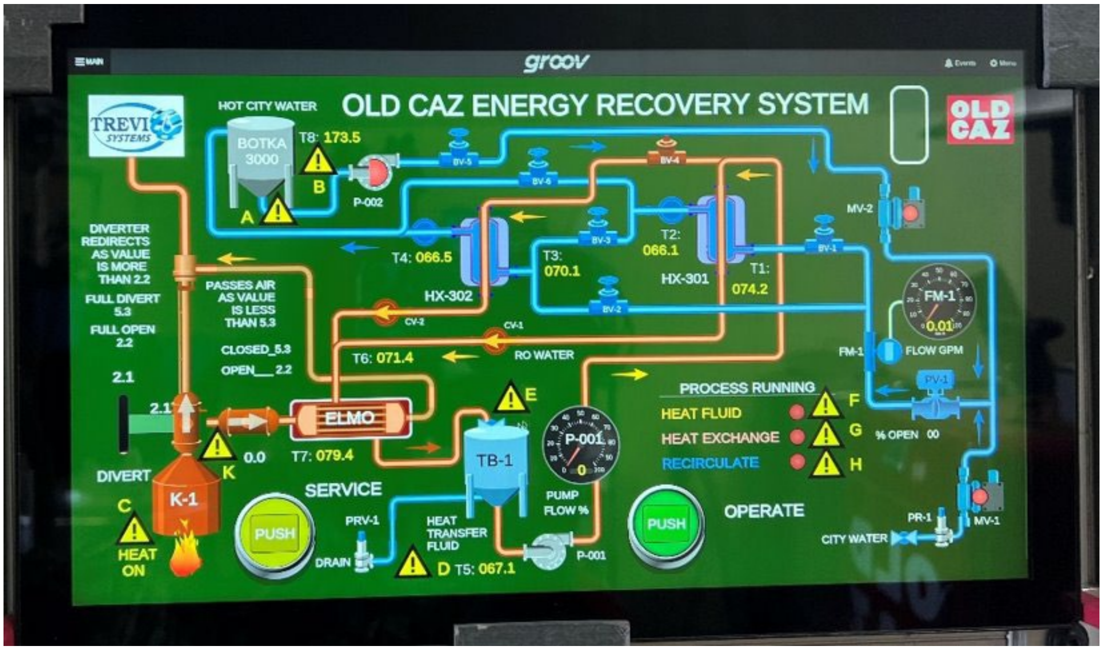
RO=reverse osmosis; CPVC=chlorinated polyvinyl chloride
Source: Trevi Systems

Figure 17: P-HEX Installation at Old Caz Brewery

Baseline P-HEX (Left) and Advanced P-HEX (Right).

Source: Trevi Systems

Figure 18: Old CAZ Programmable Logic Controller for Operational Control



Designed for ease of operation and automated data collection.

Source: Trevi Systems

P-HEX Demonstration at Winery Site

At the Winery, demonstration, data collection, and analyses of baseline P-HEX progressed well throughout the process. In this application, the P-HEX recovered solar thermal tube heat and exchanged it from the solar loop to washdown water stored in an insulated tank at approximately 149°F (65°C) for use in Winery operations (Figure 19 and Figure 20).

Figure 19: P-HEX Demonstration at Winery

Solar thermal heat recovery to supply hot washdown water.

Source: Trevi Systems

Figure 20: Winery Installation Upgrade

Installed additional pressure monitoring after over-pressurization incident.

Source: Trevi Systems

CHAPTER 3: Results

P-HEX development, laboratory testing, and validation testing at the two host sites were successfully completed and either met or exceeded all P-HEX performance targets for this CEC project. The laboratory testing of P-HEX was performed for liquid-liquid systems using a simulated source of low-level waste heat (electric heater). Table 3 compares P-HEX performance for 2.5-inch diameter and 4-inch diameters, with different tube designs and diameters. Overall, scaleup from kW-class was successful, as shown in Table 3. The recovery of low-level waste heat was increased from 40 percent to approximately 80 percent. Over the nine-month demonstration period, more than 2,000 therms were saved per brewing tank per site. If P-HEX is fully integrated at a given site with multiple tanks for continuous operation of P-HEX, the fuel saving increases to 8,000 therms per year for each site. There is the opportunity for subsequent programs to further increase the fuel savings by using multiple, larger-size (100 kW-class) P-HEX units to more fully recover waste heat.

The methodology for heat transfer analysis is summarized in Appendix B. The heat recovery effectiveness used the following equations:

- Heat Exchanger Effectiveness, $\varepsilon = Q / Q_{Max}$
- $Q = \dot{m}_{hot} * c_{p\_hot} * (T_{hi} - T_{ho}) = \dot{m}_{cold} * c_{p\_cold} * (T_{co} - T_{ci})$
- $Q_{Max} = \min(\dot{m}_{hot} * c_{p\_hot}, \dot{m}_{cold} * c_{p\_cold}) * (T_{hi} - T_{ci})$
    - Where:
        - Q = Heat transferred
        - $\dot{m}$ = Mass flow rate
        - c_p = Specific heat capacity
        - T_{ho} = Temperature hot out
        - T_{hi} = Temperature hot in
        - T_{co} = Temperature cold out
        - T_{ci} = Temperature cold in
        - Min = Lesser of given functions

The U-factor is calculated using the following equation:

- $U = Q / (A * T_{LMTD})$
    - Where:
        - U = Overall heat transfer coefficient
        - Q = Heat transferred
        - A = Heat exchanger surface area
        - T_{LMTD} = Logarithmic mean temperature difference

Table 3: Laboratory Testing of P-HEX

Parameter	Units	4" Diameter with Round Tubes	2.5" Diameter with Ribbed Tubes
Total Heat Exchange Surface Area	m^2	11.1	12.2
Effectiveness	%	78%	78%
Heat Exchange Capacity	kW	37	34
Approach Temperature – Logarithmic Mean Temperature Difference (LMTD)	°C	10	12
U-Factor – Overall Heat Transfer Coefficient	$W/(m^2 °C)$	342	226
Packing Density of Surface Area (Surface Area per Unit Volume)	m^2/m^3	482	1,125
Packing Density of Heat Exchange (Heat Transfer per Unit Volume)	kW/m^3	1,620	3,090

Heat recovery increased from 40 percent to approximately 80 percent.

Source: Trevi Systems

P-HEX Demonstration at Host Sites

Automated Data Acquisition: Measurement of key performance parameters for both hot fluid and cold fluid was done through appropriate sensors. The input and output data were monitored through specially programmed data acquisition systems with a human-machine interface. The data collection for the Old Caz Brewery system was automated. The programmable logic controller logged these data into a comma separated values (CSV) data file. Microsoft Excel was used for CSV data analysis and trending. An example data file is shown in Table 4.

Table 4: P-HEX Testing at Old Caz Brewery

Hot Bore Side				Cold Shell Side					
Flow (GPM)	Temp In (°C)	Temp Out (°C)	Pressure Drop (PSI)	Flow (GPM)	Temp In (°C)	Temp Out (°C)	Pressure Drop (PSI)	Heat Exchanged (kW)	Effectiveness (%)
5	90.4	74.5	17	1	15.2	86.4	3	18.6	94.3
5	83.5	54.8	14	2	15.2	74.2	5	30.9	86.4
5	71.6	44.1	20	3	14.8	60.5	6	35.8	80.3
2.9	70.8	55.1	12	1	15.2	66.8	1	13.5	81.7
2.9	78.9	39.5	15	2	15.2	68.1	4	27.7	82.9

Met and exceeded heat recovery goals for the project with excellent durability.

GPM=gallons per minute; PSI = pound per square inch
Source: Trevi Systems

Data collection at the Winery was done manually. The flow rates were set by the pump speed settings and measured by flowmeters. The temperatures in and out of the P-HEX were measured by temperature gauges. The data were collected and manually input into Microsoft Excel spreadsheets for analysis and calculation of the parameters. Table 5 shows one set of data collected at the Winery. The P-HEX for this site is baseline technology without any thermal conductivity enhancing additives. Depending on the operating flowrates for hot and cold fluids, the heat exchange capacity ranged from approximately 10 kW to approximately 30 kW. Heat recovery efficiency of up to 73 percent for low-level heat (approximately 176°F [80°C]) was measured, indicating satisfactory performance of the baseline P-HEX technology. Table 6 and Table 7 show P-HEX performance accomplishments and environment test results.

The notable difference in performance of the P-HEX at the Winery (approximately 50 percent to 70 percent effectiveness) versus bench-scale and Brewery P-HEX performance (approximately 75 percent to 90 percent effectiveness) was due to customer site constraints. The hot water produced by P-HEX from recovered solar thermal heat is used by Winery operations and is temperature-safe for winery staff to wash their hands. This requirement caused adjustments to the P-HEX process parameters to prevent recovering excess solar thermal heat. These deliberate, non-optimal conditions meant that the site was unable to benefit from the full potential of the P-HEX.

Table 5: P-HEX Testing at Black Kite Winery

Hot Bore Side			Cold Shell Side				
Flow (GPM)	Temp In (°C)	Temp Out (°C)	Flow (GPM)	Temp In (°C)	Temp Out (°C)	Heat Exchanged (kW)	Effectiveness (%)
2	80	52	1	28	58	7.8	57.7
2	79	48	2	29	56	14.1	54.5
2	79	30	3	21	49	22.0	73.1
3	78	60	1	14	55	10.7	64.1
3	78	47	2	14	54	20.9	62.5
3	79	39	3	21	53	25.1	55.7
5	78	58	2	15	58	22.5	68.3
5	78	52	3	16	51	27.5	56.5

The baseline P-HEX achieved greater than (>) 70 percent heat recovery.

Source: Trevi Systems

Table 6: P-HEX Performance Accomplishments

Performance Metric	Baseline Performance	Target Performance	Evaluation Method	Measured Performance	Metric Significance
Installation Cost	$125/tube	$65/tube	Labor Hours	$50/tube	Medium Impact
Operations and Maintenance Costs	$240/year, 5-year interval	$100/year, 5-year interval	Steam Cleaning hours	No Cleaning was Required	Low

Performance Metric	Baseline Performance	Target Performance	Evaluation Method	Measured Performance	Metric Significance
Simple Payback	2.2 year	1 year	Capex/kWh saved	1 year	Medium
Heat Transfer/Unit	18-kW	30-kW	Field Trial Site Data	50 kW	High Impact on Cost

Test data validated the feasibility of these performance parameters for volume production.

Source: Trevi Systems

Table 7: Real Environment Performance Evaluation

Performance Metric	Benchmark Performance	Low Target Performance	High Target Performance	Evaluation Method	Results
U-factor – Overall Heat Transfer Coefficient W/(m^2°C)	170	200	280	Calculation using measured performance test data $U = Q/(A*T_{LMTD})$	More than 200
Module Cost ($/unit)	$70,000	$1,200	$650	Projected high volume manu-facturing costs	Less than $500
Cost per (U*A) ($/[W/°C])	$0.25	$0.12	$0.05	Calculated from Projected Module Cost and Measured Performance Data	$0.12
Surface Area Packing Density (m^2/m^3)	280	500	600	Calculated from the physical design of the heat exchanger	More than 600
Weight per Unit Surface Area (kg/m^2)	8.9	0.9	0.8	Calculated from the physical design of the heat exchanger	0.9

All key performance targets were either met or exceeded.

Source: Trevi Systems

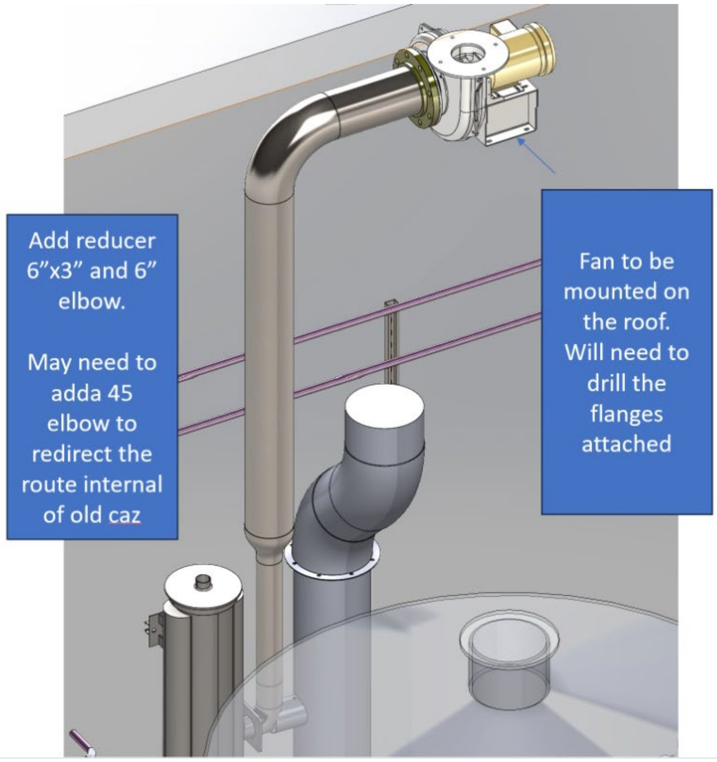
Technical Barriers, Challenges, and Lessons Learned

Execution of the project during the COVID-19 pandemic encountered serious supply chain issues. Specifically, the polymer formulations thermal conductivity additives were a significant challenge to obtain. Additional efforts were required to develop supply chains within California, the United States, Canada, Europe, and Asia. The high-speed manufacturing of P-HEX tubes using the extrusion process for these composite polymer formulations adversely impacted extrusion equipment performance, requiring frequent maintenance. A larger scale, advanced extrusion equipment was designed, procured, and installed to mitigate these negative impacts. The technicians were trained to operate the new extrusion equipment. The equipment was used to manufacture the high-performance P-HEX tubes needed for the demonstration at both the Winery and the Brewery. The overall cost of this equipment was $500,000.

Host Site Problem – Brewery Installation: The waste heat source (kettle exhaust) at the brewery was available at 400°F (204°C), significantly higher than P-HEX designed for low-level waste heat recovery (<250°F [121°C]). An additional M-HEX to reduce the heat source temperature was designed, procured, installed, and commissioned. However, additional problems were encountered and are summarized here.

- Heat available from the stack recovery heat exchanger (M-HEX) at the brewery was less than anticipated, indicating a flow distribution problem.
- Additional diagnosis was performed to identify the root cause. It was determined that the actual heat in the exhaust stack was considerably less than originally calculated.
- Measurement of pressure drop through the various equipment revealed flow distribution issues. The higher pressure drop through the recovery heat exchanger restricted exhaust gas flows through the P-HEX.
- **Solution:** Fluid flow calculations were revised to correct this flow distribution issue. Additional equipment was designed and installed. This included adding a draft-induction fan (Figure 21 and Figure 22) to the waste heat recovery heat exchanger (M-HEX) to overcome the high pressure drop and increase the flow rate for low-level waste heat recovery in the P-HEX. This additional equipment, unplanned for demonstration testing, was a critical lesson learned for future deployment of P-HEX.

Figure 21: Draft Induction Fan Needed for P-HEX Integration at Host Site



Solution to manage high pressure drop and increase waste heat recovery.

Source: Trevi Systems

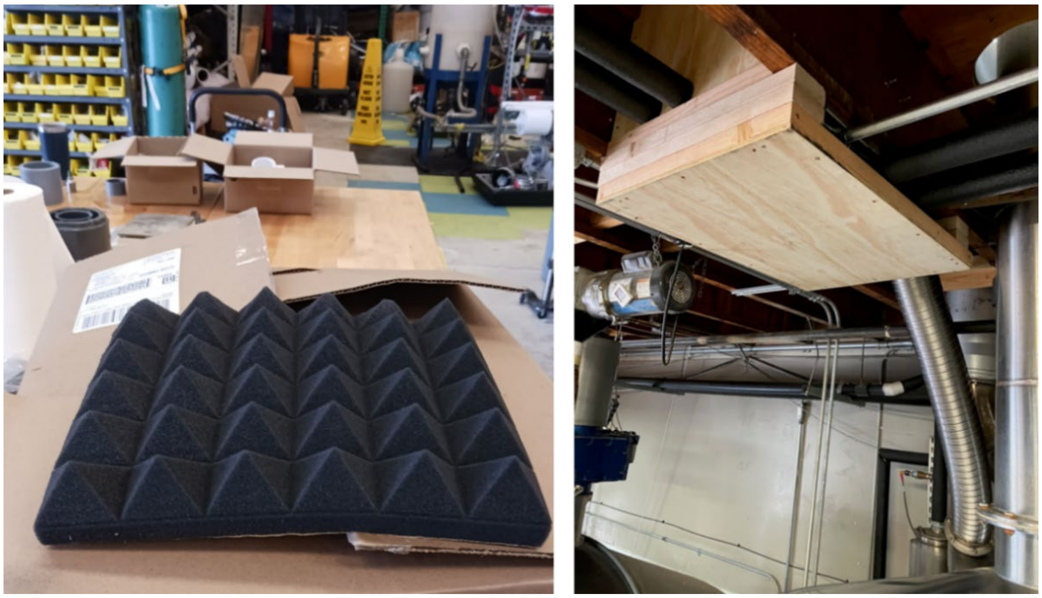
Figure 22: Draft Induction Fan Installation at Old Caz Brewery

Successfully installed and validated: testing in real environment.

Source: Trevi Systems

After successful installation and commissioning of the draft induction fan, a noise abatement system was designed and installed. This consisted of a sound enclosure containing sound absorption material (Figure 23). These upgrades highlighted the Trevi team's ability to adapt to site specific technical requirements as well as customer specific needs.

Figure 23: Noise Abatement Upgrade at Old Caz Brewery



Rapid problem solving to support unique customer requirements.

Source: Trevi Systems

Host Site Problem – Winery Installation: During commissioning of the Winery P-HEX, an over-pressurization event caused irreparable damage to the baseline P-HEX.

Solutions

- Fabricated and installed a new P-HEX
- Identified need for additional pressure gauges and implemented them
- Improved technician awareness and adherence to procedures and valve lineups
- Future strategy for market-responsive P-HEX system installations:
    - Proper relief valve sizing and installation
    - Improved pressure capability of P-HEX
    - More robust operator training to eliminate operational errors leading to equipment damage

Future Research and Development Opportunities

Work done during this P-HEX development yielded encouraging models and test results while identifying additional opportunities for scaleup and improvement. Testing focused on liquid-to-liquid heat transfer demonstrated excellent performance and offered highly promising data. The success in this area underscores the viability and potential impact of P-HEX technology in various real-world applications, in addition to its significant decarbonization potential.

The high-speed manufacturing process for the ultra-thin walled microtubes was highly successful. For the commercial success of P-HEX, additional development must be performed on other aspects of high-speed manufacturing and assembly. In particular, the tube-sheet and its adhesion to the tubes represent a significant opportunity for further development. Additionally, rapid and repeatable quality control measures such as leak testing, need to be developed and validated.

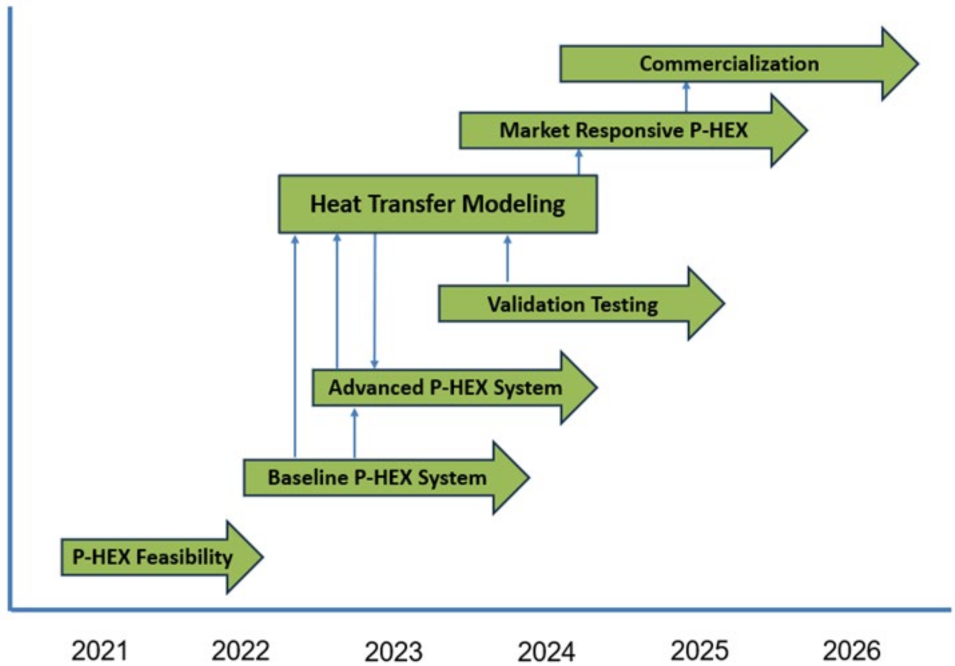
Gas-to-gas heat transfer development presents an important opportunity for P-HEX improvement. The inherent challenge is the fact that the heat transfer coefficient for gases is typically lower than that for water and other liquids, coupled with potential pressure requirements that may surpass the existing capabilities of P-HEX. To address this opportunity, additional modifications are required to develop a market-responsive product. These modifications may require exploration of novel materials and components, along with quality assurance testing.

Future development opportunities will allow for continued scaleup and improvement of this game-changing P-HEX technology, as well as support for commercialization activities. This would allow deeper analysis into refining the P-HEX technology and manufacturing processes to broaden the applications, increase the heat transfer, and mitigate costs. The following focus areas for future development include several elements key to the commercial success of P-HEX:

- **Scaleup to 100-kW Building Block:** Innovating and optimizing the design of the P-HEX module to facilitate the transition to a 100-kW commercial scale building block; this includes considerations for efficient heat transfer, structural integrity, and overall performance, ensuring that the larger commercial module meets the demands of diverse industrial applications.
- **Manufacturing Process Development:** Streamline and scaleup the manufacturing process to allow for efficient and high precision assembly and adhesion of tens of thousands of thin-walled tubes with the tube sheet.
- **Tube Development:** Improving the design of tubing to further optimize heat transfer characteristics and pressure tolerance. This may involve exploring various shapes, integrating nano-coatings, and introducing fins along the tube.
- **Polymer Development:** Researching and developing polymers with enhanced heat transfer properties. This can include an examination of a series of lab-scale test heat exchangers to investigate the efficacy of different polymers and composites under a range of conditions to determine the ideal materials for various applications.
- **Sealant Development:** Exploring novel sealants for improved durability and performance in various applications. Of interest are sealants within U.S. Food and Drug Administration guidelines for additional applications in the food and drug industries.

Pathway and Timeline to Commercialization: P-HEX technology is following a strategic pathway and timeline marked by significant milestones and achievements. Figure 24 outlines the P-HEX commercialization roadmap.

Figure 24: Roadmap for P-HEX Commercialization



Next steps: technology scaleup, manufacturing process development, and demonstrations.

Source: T2M Global

Market Opportunities for the P-HEX

T2M Global conducted market studies used to identify various potential deployment opportunities for P-HEX. Oak Ridge National Laboratory assessed the waste-heat-to-power market, and BCS, Inc. analyzed waste heat recovery technologies and opportunities in United States industry. A summary of the findings is presented in Table 8.[3,4] Examples of industrial sector companies with significant low-level waste heat include Exxon Mobil, Shell, Chevron Texaco, U.S. Steel, Cleveland-Cliffs, PCC Structurals, Spartan Light Metal Products, Mohawk Industries, and Maples Industries.

Table 8: P-HEX Market Opportunities

Industrial Sector	Low-grade Waste Heat Source	Potential Market (MW)	No. of P-HEX Units (100kW Modules)
Petrochemical	Stack gas from crude distillation	2780[3]	27,800
	Stack gas from vacuum distillation		
	Exhaust from ethylene furnace		

[3] Elson, Amelia, Rick Tidball, Anne Hampson. 2015 (March). *Waste Heat to Power Market Assessment*. ICF International, Oak Ridge National Laboratory. Available at https://info.ornl.gov/sites/publications/files/Pub52953.pdf.

[4] BCS, Incorporated. 2008 (March). *Waste Heat Recovery: Technology and Opportunities in U.S. Industry*. US Department of Energy, Industrial Technologies Program. Available at https://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf.

Industrial Sector	Low-grade Waste Heat Source	Potential Market (MW)	No. of P-HEX Units (100kW Modules)
Iron/Steel Making	Waste gas from coke oven	1198[4]	11,980
	Blast furnace gas		
	Blast stove exhaust		
Aluminum Casting	Exhaust from aluminum casting with a stack melter	135[4]	1,350
Textile	Dyed wastewater	330[3]	3,300
	Stenter exhaust from fabric drying and finishing		
	Wastewater rejected from heat exchangers		

Potential market size for low-level waste heat recovery is immense.

MW=megawatt
Source: T2M Global

Near-term market segments include industrial applications in the food and beverage sector with approximate P-HEX capability of 1 million British thermal units per hour (MMBtu/hr) each, which corresponds to the 30-kW-sized unit successfully developed in this project. The market is big enough with total natural gas energy usage of 248.82 million (MM) therms. Larger P-HEX system opportunities (100+ kW) exist in other industrial sectors such as chemical, petrochemical, refinery, and large manufacturing facilities. This market is expected to be served by modular systems, with the potential to reach megawatt (MW) scales as combined units. Ultimately, the flexible scalability (MW+ range for commercial applications and sub-kW for residential) allows penetration opportunities into all sectors.

Customer Outreach Strategy: The project team developed a strategic approach to identify and capture specific customer segments for P-HEX technology. Incorporating insights from customer interviews, data gathering, and industry expertise, the goal was to systematically approach and engage various industries for waste heat recovery, as follows.

- **Market Analysis and Segmentation:** Conducted a comprehensive market analysis to refine and validate identified customer segments. Used a combination of customer interviews and insights from advisors to further delineate specific needs and opportunities within each segment.
- **Forged Strategic Connections:** Leveraged established connections with specific companies within each identified segment. Strengthened partnerships and collaboration efforts that both enhance market entry and facilitate the adoption of P-HEX technology.
- **Customer Segment Plans:** Numerous customers in multiple sectors, including food and beverage, hydrogen, biogas, renewable natural gas, manufacturing sectors, are actively being investigated. This broad focus resulted from a combination of established connections, motivation to decrease production prices and emissions in California, and

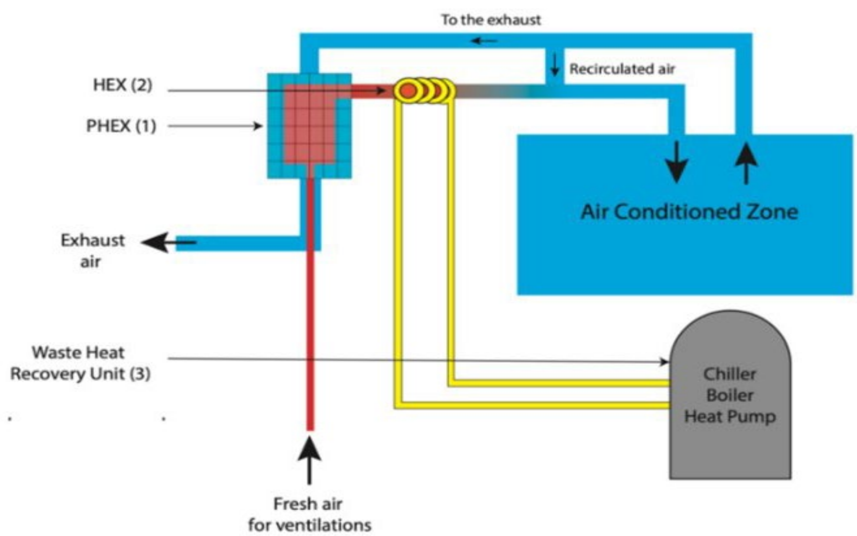
the fact that the waste heat is in a range (< 248°F [120°C]) that is only usable in this technology.

- **Implementation and Feedback Loop:** Continues to actively engage with stakeholders and gather feedback. Regular assessments of the effectiveness of these strategies guide adjustments and refinements based upon evolving market dynamics.

P-HEX Uses for Buildings, Industry and Utility Applications: P-HEX is poised to transform diverse sectors ranging from buildings and industries to utility markets. P-HEX promises significant advancements in energy efficiency and environmental sustainability in the following applications:

- **Building:** Outreach efforts within the building sector focused on highlighting the transformative impact potential of P-HEX technology. The team worked with building consultants and retrofitters as well as heating, ventilation, and air conditioning (HVAC) and infrastructure developers to gain knowledge of this environment. Figure 25 shows one HVAC application for P-HEX that will reduce building energy use. Both state and federal incentives, coupled with evolving building certification codes emphasizing reduced energy consumption and improved ventilation, underscore the critical need for innovative solutions such as P-HEX. California, in particular, is a lucrative market for P-HEX, aligning with the state's ambitious mandates to increase building efficiencies by 2030.

Figure 25: P-HEX Integration into a Building's HVAC System

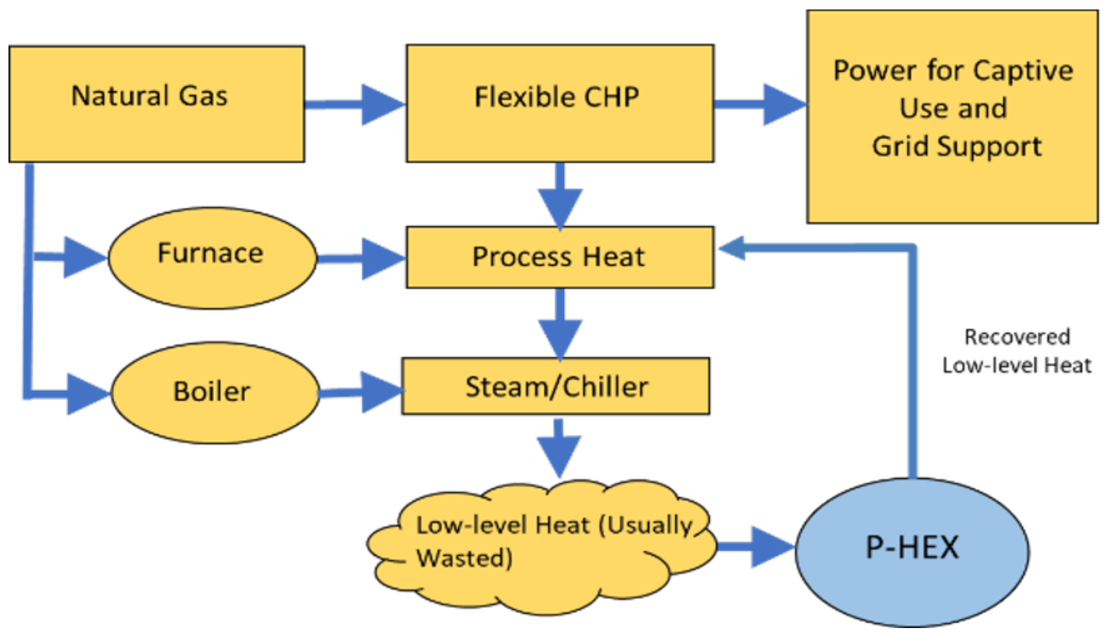


Promotes healthy air ventilation and reduces heating bills by up to 25 percent.

Source: T2M Global

- **Industry:** P-HEX is a versatile and scalable solution, providing efficient and sustainable heat recovery opportunities for industries across various sectors. Figure 26 illustrates a conventional industrial P-HEX application fueled by fossil gas. Outreach efforts prioritized engagement with small industries requiring low-level heat, such as micro-breweries and wineries. These industries are prime future recipients, poised to reap immediate benefits from small-scale P-HEX units. As the P-HEX technology proves its effectiveness within the food and beverage energy sector, Trevi's strategic vision extends to larger industrial P-HEX system opportunities, specifically in the 100+ kW range. The broader industrial landscape, including chemical, petrochemical, refinery, and large manufacturing facilities, are promising areas for P-HEX applications. Recognizing the diverse needs of these sectors, the team's approach emphasized the adaptability of modular systems, with potential scaleup to the megawatt level.

Figure 26: Efficient Recovery of Low-Level Waste Heat for Enhanced Value



High-performance low-cost P-HEX designed to recover up to 80 percent of lost energy.

Source: T2M Global

- **Utility Market for P-HEX:** Strategic partnerships include prominent utilities supporting continued development of a robust deployment strategy for P-HEX. Notable engagements within the California utilities sector encompassed key players including Pacific Gas and Electric Company, Southern California Gas Company, San Diego Gas and Electric Company (SDG&E), and Sacramento Municipal Utility District. In the refinery domain, the team's collaborative endeavors involved industry leaders like Tesoro, Chevron Texaco, Exxon, and Shell. Furthermore, the team plans to engage prominent hydrogen infrastructure developers, including General Motors and Toyota.

Market Size: The P-HEX market size is largely dependent upon the availability of waste heat. Waste heat is heat that is present downstream of any process and typically vented into the atmosphere and wasted. This surplus heat has various origins, such as the thermal processes requiring heat generation, the heat expelled during mechanical operations, and the heat generated from exothermic chemical processes. Table 9 shows the diverse sources of waste heat across various market segments in California. It also outlines the addressable market, quantifying it in terms of the number of P-HEX units (each with a 100-kW capacity) necessary to efficiently exchange this underutilized energy for reuse. The addressable market for retrofit applications was assumed to be 20 percent of the total potential market, while for emerging markets it was assumed to be 50 percent. These markets will benefit directly from P-HEX integration by reducing their total fuel use and its associated emissions.

Table 9: P-HEX Market Segments in California and Their Potential Sizes

	Potential Market		Addressable Market		No. of Units (100 kW modules)
	MW	$	MW	$	
Furnaces	3,607	1.18 Billion per year	721	236 Million per year	**7,210**
Chemical Manufacturing	9,030	11.7 Billion per year	1,806	1.76 Billion per year	**18,060**
Metal Manufacturing	8,980	11.6 Billion per year	1,796	1.63 Billion per year	**17,960**
Emerging Markets	20,000	23 Billion per year	10,000	11 Billion per year	**100,000**

These market segments will need more than 140,000 P-HEX units of 100 kW each.

Source: T2M Global

Market and Policy Barriers

Because P-HEX systems produce no criteria pollutant emissions, the team expects to receive a blanket permit for rapid deployment following this CEC demonstration project. While GHG and criteria pollutant emissions are not an issue for P-HEX, energy recovered from waste heat is currently not classified as a renewable resource. Additionally, carbon credits are not available for clean energy projects that make use of stranded resources produced through non-renewable methods. P-HEX is a case where wasted thermal energy may be recovered with no incremental carbon dioxide (CO_2) emissions. To this end, the California Air Resources Board (CARB) has been contacted to modify the policy to include heat recovered from wasted resources as a renewable resource.

Technology/Knowledge Transfer Activities

The project information was shared with California stakeholders, especially with TAC members representing those stakeholders. The TAC members included early adopters, gas and utility industry representatives, combined heat and power centers in California, government sponsoring agencies such as CARB, air quality management districts (AQMD) and U.S. Department of Energy (U.S. DOE). Committee members provided valuable guidance to advance adoption, recommendations for commercialization, and near-term opportunities. Communications with stakeholders was performed through a project fact sheet, takeaways using PowerPoint presentations, sharing prospects for broader adoption, and informing policy and planning.

The next steps for P-HEX technology development include further scaleup to the 100-kW building block level and performance stability testing. A market-responsive prototype design is needed to assure successful entry into multiple market sectors. These sectors include fossil gas users in the building, manufacturing, power generation, and eventually the transportation energy sectors. Near-term specialty markets include food processing and pharmaceutical manufacturing, where the impact of the construction materials is a huge health concern. Manufacturing development for high-speed processes and their integration to develop P-HEX at <$100/kW$_{th}$ will be simultaneously pursued.

Impact of P-HEX on California's Clean Energy and Climate Goals

Lowering Natural Gas (NG) Usage and Reducing California GHG Emissions: California is required to meet mandated state GHG emission goals and its ambitious Senate Bill 100 clean energy laws by 2045. The state's dependence on fossil gas must be significantly reduced to meet these mandates. The recovery of waste heat using P-HEX offers an important opportunity to reduce fossil gas consumption by as much as 25 percent. Fossil gas consumption for different energy sectors in California, based on state data, is shown in more detail in Appendix A.

- Total fossil gas consumption in different market sectors is approximately 11 billion therms/year.
- At an average of 25 percent waste heat, 2.75 billion therms/year are available for P-HEX.
- Assuming P-HEX can address 50 percent of this waste heat, the market size would be 1.38 billion therms/year.
- At 75 percent recovery using P-HEX, 1 billion therms/year of fossil gas could be saved.

Quantitative Benefits to California

- **Monumental Reduction in Fossil Fuel Use:** The 1 billion therms/year heat recovery translates to more than 20 percent savings in fossil gas use. These savings of fossil gas enhance both energy security and economic benefits.
- **Significant Cost Savings to California Ratepayers:** Approximately $1 billion of NG savings, assuming $10/MMBtu of NG.
- **Increased Deployment of Renewables:** Increased fossil gas reserves will support intermittency of solar and wind, as well as microgrids needed for resiliency during wildfires.
- **Dramatic Reductions in GHG Emissions:** One billion therms/year savings of fossil gas translates to GHG emission reductions of more than 5.3 million tons/year of CO_2. This is about 40 percent of the CEC mandate to reduce GHG emissions at a rate of 13 million tons carbon dioxide equivalent (CO_2e) per year.
- **Benefits to Disadvantaged Communities:** Reduction in harmful emissions is expected to improve air quality, particularly benefiting disadvantaged communities, which are

commonly co-located with manufacturing and industrial operations, by creating healthier environments and improved economic opportunities via P-HEX deployment.

The P-HEX technology development and validation testing results are highly encouraging. The next step to validate the benefits at pilot scale is highly warranted. It provides an opportunity for CEC investments to achieve its decarbonization goals.

Examples of Potential Benefits to California Stakeholders

California is the fifth largest economy in the world. The state's large consumption of fossil fuels and electricity is also associated with large production of low-level waste heat. The following examples of sources of this low-level waste heat are excellent opportunities for P-HEX.

- **Fossil Fuels:** Natural gas burners for boilers and furnaces for industrial and residential applications
- **Renewable Electricity:** Deep decarbonization for burners and furnaces using electricity from solar photovoltaic and wind needing low-level waste heat recovery
- **Chemical Process Heat:** Syngas production, fuel cells, oxidizers
- **Decarbonization of Semiconductor Industry:** Exhaust from high-temperature furnaces has low-level waste heat.
- **Flare Gas:** Oil and gas production, refineries, wastewater treatment plants
- **Power Plants:** Cooling towers, engine radiators
- **Specialty and Safety-Sensitive:** Food and pharmaceutical waste heat

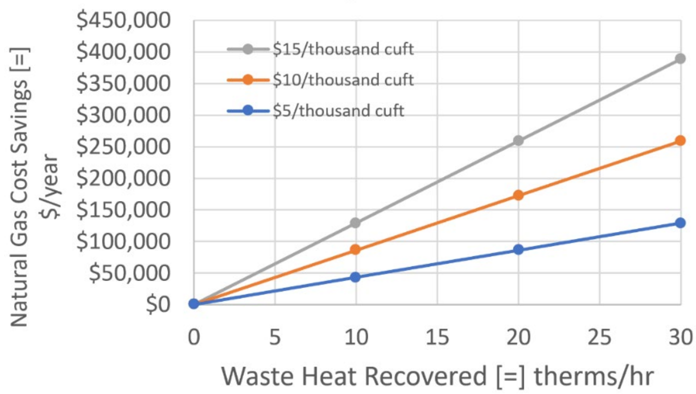
Scenario 1 Benefits to Host Site: The host sites for this CEC project were a brewery and a winery in Napa Valley, California. Heat recovery data from these sites were collected and analyzed for different operating conditions, using P-HEX equipment integrated with the actual plant equipment operating in real environments. Three cases of recoverable low-level waste heat at 10 therms/hour (hr), 20 therms/hr, and 30 therms/hr were analyzed, as illustrated in Figure 27. These values account for baseline conditions where 30 percent of fossil gas used for boiler is wasted. In a conservative scenario, 60 percent of low-level heat would be recovered using P-HEX. The host site boilers contribute most significantly to this waste heat. The P-HEX integrated with these host sites recovered waste heat for reuse. This leads to direct fossil gas savings, reducing corresponding operating costs.

- **Economic Benefits to Host Sites:** Assuming sites where 30 therms/hr of waste heat can be recovered using P-HEX and a fuel cost of $10 per thousand cubic feet, fossil gas annual savings could be as much as $250,000.
- **Reduction in GHG Emissions for Host Sites:** Figure 28 illustrates estimated GHG emission benefits for these host sites. Estimated GHG savings for each host site is up to 2 tons per year.
- **GHG Emissions Reduction for California:** For 1,000 host sites equipped with P-HEX, the GHG reduction of 2,000 tons per year have been estimated. This reduction

in fossil gas use reduced GHG emissions, a valuable contributor to California's decarbonization mandates.

- **Deep Decarbonization Using Electrically Heated Systems:** Figure 29 shows the benefits of low-level heat recovery from renewables at approximately $2MM/yr for approximately 6 MW (150 MWh/day).
- **Deep Decarbonization Statewide Benefit:** One thousand systems deployed at 6 MW each, translates to approximately $2 billion/yr, providing the state with a unique opportunity for investment in P-HEX technology validation, at MW-scale.

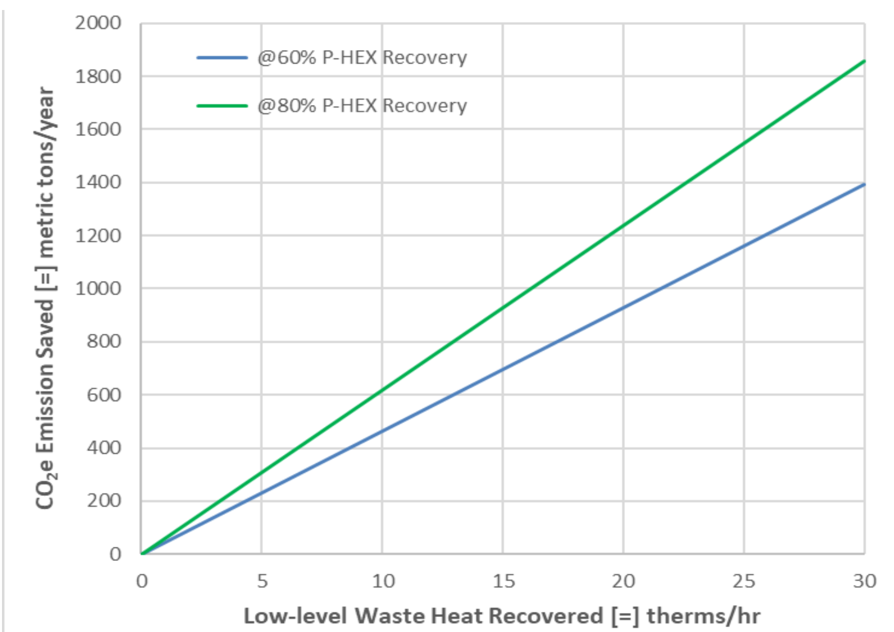
Figure 27: Natural Gas Cost Savings Using P-HEX Technology



Potential of as much as $400,000/year savings.

cuft=cubic feet
Source: T2M Global

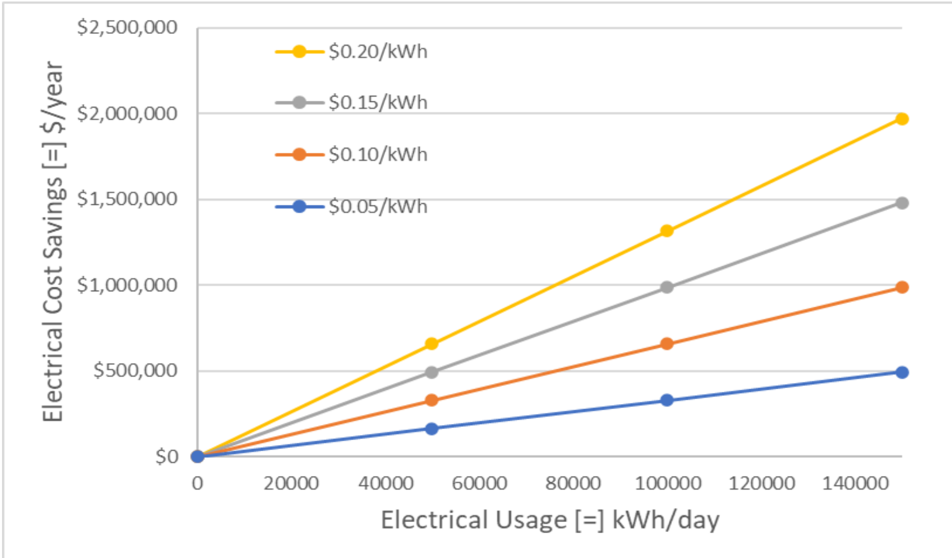
Figure 28: Estimated GHG Emission Reduction at Brewery and Winery Host Sites



Potential of up to approximately 2 tons per year GHG emissions reduction per site.

Source: T2M Global

Figure 29: P-HEX for Electrically Driven Thermal Systems



Potential of approximately $2 million/year savings from wasted heat.

Source: T2M Global

Benefits of P-HEX Deployment – Scenario Analyses: Progressive increases in P-HEX deployment are expected to bring multiple benefits to California. Table 10 summarizes estimated benefits for three different scenarios of P-HEX deployment: conservative deployment Scenario 1, moderate deployment Scenario 2, and full deployment Scenario 3.

- **Scenario 1:** Baseline deployment case for early market entry with conservative assumptions.
- **Scenario 2:** Moderate penetration where P-HEX is incorporated in all food and beverage industrial operations in California. The food industry used 5,126.26 gigawatt-hours of electricity and 248.42 MM therms of energy in 2015, shown in Appendix A.
- **Scenario 3:** The most ambitious scenario where P-HEX is incorporated across the entire industrial sector. The grand total of 43,695.23 gigawatt-hours of electricity and 5,486.81 MM therms of energy in 2015 was based on data included in Appendix A. Figure 30 illustrates statewide benefits at full deployment of P-HEX for different waste-heat availability and use cases.

Table 10: Cumulative Benefits to California Investor-Owned Utility Ratepayers

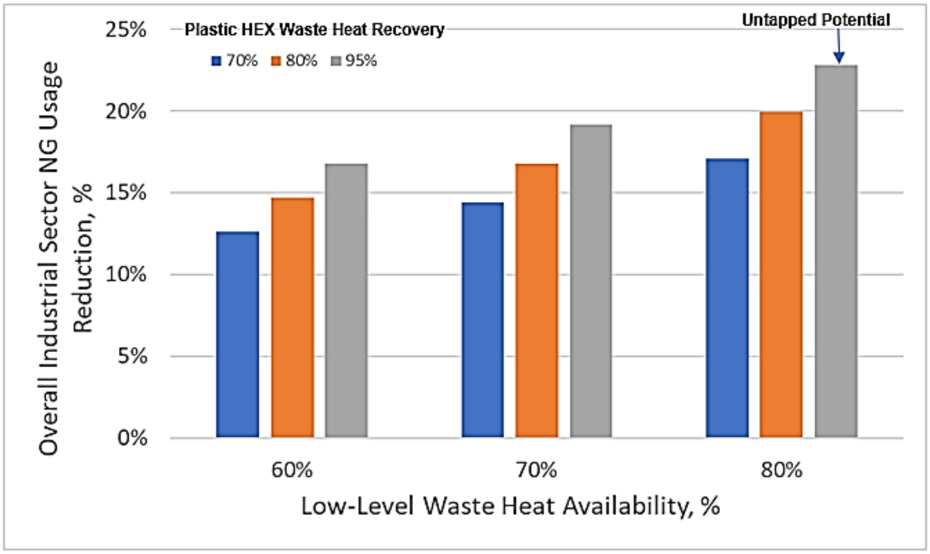
Benefit	Scenario 1 (Baseline)	Scenario 2 (Baseline)	Scenario 3 (Stretch)
NG Usage Reduction (MM therms/year)	31.30	691.31	938.24
NG Equivalent Electricity Usage Reduction (MM therms/year)	~0.10	0.82	1.12
Rate Payer NG Cost Savings – Heat (MM $/year)	~28.81	~636.01	~864.78

Benefit	Scenario 1 (Baseline)	Scenario 2 (Baseline)	Scenario 3 (Stretch)
Overall GHG Emission Reduction (MM tons CO_2e/year)	~0.17	~3.67	~4.97

Win-win solution for natural gas users.

MM = 1,000,000
Source: T2M Global

Figure 30: Cumulative Benefits to California's Industrial Sector (Scenario 3)



More than 20 percent reduction in fossil gas use statewide at full deployment of P-HEX.

Source: T2M Global

CHAPTER 4: Conclusion

The P-HEX technology demonstration under this CEC project met all performance targets. The technical feasibility of using plastic heat exchangers to cost-effectively recover low-level waste heat is highly promising. Heat recovery efficiency was increased from 40 percent to 80 percent using mass-producible P-HEX technology. The P-HEX testing at the two host sites has validated that the currently stranded resource of low-level waste heat can be recovered for beneficial reuse without any incremental GHG emissions while creating economic benefits. Further scale-up of P-HEX technology to a 100 kW-class building block is highly warranted to bring this technology to market and realize the following benefits.

Benefits to California Stakeholders

- More than 20 percent savings in fossil gas use (approximately 1 billion therms of fossil gas)
- Significant cost savings to state ratepayers (approximately $1 billion of fuel cost savings)
- Increased deployment of renewables and resiliency to protect against wildfire
- GHG reductions to accelerate the transition to a zero-emission economy: P-HEX can contribute to reducing GHG emissions to meet California's goal of 13 MM tons CO_2e/yr reduction
- Deployment in disadvantaged communities for a healthier environment and better economic opportunities.

Near-Term Opportunities for Pilot-Scale Demonstration and Deployment:

- **Market Responsive P-HEX Product Development:** Accelerating commercialization is an essential next step, with a target building block size of 100 kW_{th}.
- **Seeding In Niche Markets:** Boilers, furnaces, and engines are prime candidates.
- **Early Adopters:** Gas and electric utilities, multi-purpose energy stations that include onsite hydrogen production for refueling, electric vehicle charging and grid support.
- **Specialty Markets:** Food processing and pharmaceutical industries can reduce operating costs and GHG emissions with P-HEX integration.
- **Power Plants:** P-HEX can recover wasted heat in cooling towers and recycle it to preheat boiler feed water. This would reduce the cost of electricity and reduce GHG emissions.

- **Commercial and Residential Buildings:** The low-level waste heat from HVAC and burners can be recovered using P-HEX technology. Higher pressure capability is needed (50 to 200 psi) to address this potentially lucrative market.
- **Biogas and RNG Market:** Recovery of low-level heat from the processing of biogas to renewable natural gas or other products represents emerging market segments for sustainable agriculture, dairy, and forestry operations. Deployment of cost-effective P-HEX will also decrease the cost of renewable fuels, creating a greater market pull.

Opportunity to Remove Policy Barriers:

- Low-level waste heat recovery is not adequately incentivized by CARB, AQMD, or the United States Environmental Protection Agency.
- P-HEX for waste heat recovery has no incremental GHG or other criteria pollutant emissions, which creates an opportunity for policy makers to catalyze sustainable development.
- Upgrading low-level waste heat to higher value products deserves to be classified as Renewable Portfolio Standard eligible, a designation similar to that of fuel cell power plants.[5]
- There is a nationwide opportunity to coordinate state level incentives with federal incentives to maximize national benefits and accelerate wide-scale deployment of waste heat recovery.

[5] Green, Lynette, Christina Crume. 2017. *Renewables Portfolio Standard Eligibility Guidebook, Ninth Edition*. California Energy Commission, Publication Number: CEC-300-2016-006-ED9-CMFREV. Available at https://www.energy.ca.gov/publications/2017/renewables-portfolio-standard-eligibility-ninth-edition.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
~	approximately
'	foot, feet
"	inch
< / >	less-than / greater-than
°C	degree Celsius
°F	degree Fahrenheit
3-D	three dimensional
∞	infinite
ΔT	temperature change
A	heat exchanger surface area
AQMD	Air Quality Management District
Brewery	Old Caz Brewery
Btu	British thermal unit (1 kWh = 3,413 Btus)
C	module cost
c_p	specific heat capacity
CapEx	capital expenditure
CARB	California Air Resources Board
CEC	California Energy Commission
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CPVC	chlorinated polyvinyl chloride
CSV	comma separated values
cuft	cubic feet
D / d_O	diameter / tube diameter
ε	heat exchanger effectiveness
ETFE	ethylene tetrafluoroethylene (fluorine-based plastic)
GHG	greenhouse gasses
gpm / GPM	gallons per minute (a measurement of flow rate)
HEX	heat exchanger
hr	hour
HVAC	heating, ventilation, and air conditioning

Term	Definition
kg	kilogram
kg/m^2	kilograms per square meter
kW	kilowatt
kW_e	kilowatt electric
kWh	kilowatt-hour (a measurement of energy)
kWh/day	kilowatt-hour per day
kW_{th}	kilowatt-thermal
$\$/kW_{th}$	dollar per kilowatt-thermal
L	length
LMTD	logarithmic mean temperature difference
m^2/m^3	meter squared per meter cubed, or square meter per cubic meter
mc_p	mass flow rate of specific heat capacity
$\dot{m}_f$	mass flow rate (subscript f stands for the appropriate fluid, hot side or cold side
M-HEX	metallic heat exchanger
min	minimum function
mm	millimeter
MM	million
MMBtu	million British thermal unit
MMBtu/hr	million British thermal unit per hour
MW	megawatt
MWh	megawatt-hour
MWh/day	megawatt-hours per day
n	number of tubes
NG	natural gas
O&M	operation and maintenance
PEEK	polyether ether ketone (thermoplastic)
P-HEX	plastic heat exchanger
psi / PSI	pounds per square inch (a measurement of pressure)
Q	heat transfer capability
quad	one quadrillion British thermal units
RO	reverse osmosis
SAPD	surface area packing density

Term	Definition
StD	standard deviation
T2M	T2M Global, LLC
TAC	technical advisory committee
TEA	techno-economic analysis
therm	A unit of heat equal to 100,000 British thermal units (1.054 × 108 Joules)
T_{ho} / T_{hi} / T_{co} / T_{ci}	temperature hot out / temperature hot in / temperature cold out / temperature cold in
T_{LMTD}	logarithmic mean temperature difference
Trevi	Trevi Systems, Inc.
U or U-factor	Overall Heat Transfer Coefficient (measured in W/[m^2°C])
U.S. DOE	United States Department of Energy
V	volume
W	weight
W / kW / MW	watt; kilowatt; megawatt (1,000 W = 1 kW; 1,000 kW = 1 MW)
W/m^2	watts per square meter
$/(W/°C)	dollars per watt per degree Celsius
WA	weight per unit surface area
Winery	Black Kite Winery

References

BCS, Incorporated. 2008 (March). *Waste Heat Recovery: Technology and Opportunities in U.S. Industry*. US Department of Energy, Industrial Technologies Program. Available at https://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf.

CEC (California Energy Commission). 2016. "California Electricity Consumption Database." Available at http://ecdms.energy.ca.gov/.

Elson, Amelia, Rick Tidball, Anne Hampson. 2015 (March). *Waste Heat to Power Market Assessment*. ICF International, Oak Ridge National Laboratory. Available at https://info.ornl.gov/sites/publications/files/Pub52953.pdf.

Green, Lynette, Christina Crume. 2017. *Renewables Portfolio Standard Eligibility Guidebook, Ninth Edition*. California Energy Commission, Publication Number: CEC-300-2016-006-ED9-CMFREV. Available at https://www.energy.ca.gov/publications/2017/renewables-portfolio-standard-eligibility-ninth-edition.

U.S. Energy Information Administration. 2023 (April). *Monthly Energy Review*, Table 1.3 and 10.1. U.S. Department of Energy, Office of Energy Statistics. Available at https://www.eia.gov/totalenergy/data/monthly/archive/00352304.pdf.

Project Deliverables

Project deliverables, including interim project reports, are available upon request by email at pubs@energy.ca.gov:

- CPR Report
- Installation and Instrumentation Plan
- Site Requirements and Layout Plan
- Measurement and Verification Report
- Diagnostic Software Report
- Commercialization Potential Report
- Final Meeting Benefits Questionnaire
- Final Project Fact Sheet
- Final Technology/Knowledge Transfer Plan
- Final Production Readiness Plan
- Final Report

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix A: Assumptions for Techno-Economic Analysis (TEA)

January 2025 | CEC-500-2025-001

APPENDIX A:
Assumptions for Techno-Economic Analysis (TEA)

Key Assumptions:

- All electricity and fossil gas usage per industrial sector obtained from the California Electricity Consumption Database[6]
- 30 percent of fossil gas usage is "wasted" and needs recovery per U.S. DOE Advanced Manufacturing Office Report
- Baseline: 60 percent of low-level (<200 °C) waste heat availability
- Stretch: 80 percent of low-level (<200 °C) waste heat availability
- Near-term: Plastic HEX heat recovery efficiency of 70 percent
- Mid-term: Plastic HEX heat recovery efficiency of 80 percent
- Long-term: Plastic HEX heat recovery efficiency of 95 percent
- 35 percent of Total CA Electric Generation from NG - CA CEC Almanac Information
- Combustion efficiency of 70 percent for NG engines
- 2015 statewide average industrial fossil gas price of $0.92/therm
- 2015 statewide average industrial electric price of $0.1175/kWh
- GHG emission factor of 5.3 kg/therm CO_2e for fossil gas and 0.331 kg/kWh CO_2e for electricity

[6] California Electricity Consumption Database http://ecdms.energy.ca.gov/

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Appendix B: P-HEX Heat Transfer Analysis Formulas and Assumptions

January 2025 | CEC-500-2025-001

APPENDIX B: P-HEX Heat Transfer Analysis Formulas and Assumptions

Formulas and Assumptions for Performance Calculations: The primary parameters of interest used in the analysis of P-HEX performance are related to the amount of heat exchanged and how effectively they can exchange the heat that is available. The other parameters are measures of the cost of the heat exchangers for the amount of duty and the parameters related to size and weight for the amount of duty. The formulas and definitions for each of these parameters are described below:

- Tube Diameter (d_o): The outside diameter of each tube within the tube bundle for the product measured in meters.
- Length (L): overall length of the product measured in meters.
- Diameter (D): Outside diameter of the product measured in meters.
- Volume (V): Volume occupied by the product measured in m^3 defined as:
    - $V = \pi * D^2/4 * L$
- Number of Tubes (n): Number of heat exchanger tubes within product.
- Surface Area (A): Total amount of outer diameter surface for the tubes available for heat exchange in mm^2 defined as:
    - $A = \pi * d_o * n * L$
- Module Cost (C): Heat Exchanger Cost measured in $, defined as C = Material Cost + Labor Cost + Overhead.
- Weight (W): Weight of the product measured in kg.
- Surface Area Packing Density (SAPD): How much surface area can be fitted into a given product volume measured in m^2/m^3 defined as:
    - SAPD = A/V
- Weight per unit surface area (WA Ratio): Measure of how much surface area can be realized per unit weight of the product measured in kg/m^2 defined as:
    - WA Ratio = W/A

Performance Parameters: The parameters of interest during the product testing are related to their heat exchange capabilities. Some are industry standard measurements and others are particular to the P-HEX to perform a comparison to the existing commercially available technologies. The ones to be measured are described here.

- Heat Transfer Capability (Q): The amount of heat that can be transferred by the product measured in kW, calculated by measuring several other parameters (below).

- Mass Flow Rate ($\dot{m}$): This is a measure of the fluids mass flow rates in kg/sec, typically used in the calculation of other parameters listed below. This is defined for the hot and cold fluids as:
  - $\dot{m}_f$ = $density_f$ (kg/m^3) * $flowrate_f$ (m^3/sec) where the subscript f stands for the appropriate fluid, hot side or cold side
- Specific Heat Capacity (c_p): The specific heat capacity of the heat exchange fluid and is a property of the fluid, measured in kJ/kg-C and is used for the hot and cold fluids, respectively.
- Delta T (ΔT): The temperature change from the input end to the output end for the heat exchange fluid as it passes through the P-HEX, measured in °C. It is defined as:
  - $\Delta T = T_{in\_f} - T_{out\_f}$, where the f is for the fluid, hot or cold.
- The amount of heat exchange can be calculated using the following formula:
  - $Q_f = \dot{m}_f * c_{pf} * \Delta T_f$
  - where f represents either the hot or cold fluid. The total heat lost is equal to the amount gained, but typically, Q_{hot} will be a somewhat larger value than Q_{cold} and the difference between the two represents the heat lost to the environment.
- Log Mean Temperature Difference (T_{LMTD}): This is a parameter used for counterflow heat exchangers, such as the P-HEX, used to represent the amount of temperature change the fluids undergo. It is derived since the hot and cold fluids may have different flow rates and thermal properties and, thus, may experience different changes in temperature in the heat exchanger. It is measured in degrees C and is defined as:
  - $T_{LMTD} =| [(T_{in\_hot} - T_{out\_cold}) - (T_{out\_hot} - T_{in\_cold})]/[\ln((T_{in\_hot} - T_{out\_cold})/(T_{out\_hot} - T_{in\_cold}))]|$
- U-Factor (U): This is a figure of merit for the performance of the heat exchanger and is measured in W/(m^2°C).
  - Its value is derived from the formula: $Q = U * A * T_{LMTD}$
  - With Q calculated as shown above, U can be calculated as:
- $U = Q / (A * T_{LMTD})$
- Effectiveness (ε): This is an industry standard measurement parameter that represents how efficiently the heat exchanger transfers heat. It is the ratio of actual heat exchange to potential heat exchange. It is used since the amount of heat that can possibly be transferred from the hot fluid to the cold fluid is limited by either the maximum amount of heat that the hot fluid can supply or the maximum amount of heat the cold fluid can absorb based on their specific heat capacities and flow rates. The limiter is whichever fluid has the lower amount of possible heat transfer between the highest temperature (T_{in_hot}) and the lowest temperature (T_{in_cold}). The effectiveness is defined as:
  - $\varepsilon = Q_{actual} / [\min(\dot{m}_{hot} * c_{p\_hot} , \dot{m}_{cold} * c_{p\_cold}) * (T_{in\_hot} - T_{in\_cold})]$