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CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

WASTE HEAT TO ULTRA-HIGH EFFICIENCY OSMOTIC POWER (WHOP)

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DISCLAIMER

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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

Measuring Innovation Progress to Guide Future Investments: Evaluation of Electric Program Investment Charge Benefits Methodology is the final report for the Measuring Innovation Progress to Guide Future Investments project (Contract Number: 300-17-004) conducted by Industrial Economics, Inc. 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: 25 quadrillion British Thermal Units per year are wasted as low-level heat, costing the US economy over $200 billion per year, and contributing to associated greenhouse gas emissions. Ten percent recovery of this waste heat would create over 700 terawatt hours of emission-free electricity annually. At 20 cents per kilowatt-hour (¢/kWh), this translates to $140 billion worth of clean electricity to support decarbonization efforts.

The Solution Technology: A Waste Heat to Osmotic Power Engine upgrades low-level heat into electricity without any incremental emissions. The Waste Heat to Osmotic Power technology converts chemical potential into hydraulic potential, to produce clean electricity using a water turbine. The conventional heat to power cycles, such as Organic Rankine Cycle or Kalina Cycle, use gas turbines and steam turbines that are expensive and suffer from lower efficiency. Water turbines, on the other hand, are much lower in capital cost, higher efficiency, and require significantly less maintenance. The working fluid in the Waste Heat to Osmotic Power engine is pressurized in specially designed water purification membranes. The waste heat is used to regenerate the working fluid to its original chemical potential, thus creating a continuous power cycle for currently stranded waste heat.

Technology Progress: The working fluid pressure was progressively increased from 5 pounds per square inch (psi) to 1000 psi. This is equivalent to more than a 2,300-foot-high hydroelectric dam, an unprecedented accomplishment. As a matter of comparison, most conventional hydroelectric dams are about 500 feet high. This first of a kind Waste Heat to Osmotic Power engine promises to be a game-changer technology by upgrading currently stranded waste heat.

Keywords: waste heat, Osmotic Power Engine, hydraulic potential, conversion of low-level heat, waste heat to electricity, waste-to-power, hydraulic turbine, California Energy Commission

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Background

A Waste Heat to Osmotic Power (WHOP) Engine, also known as an osmotic engine, converts low grade heat into electricity without any harmful emissions. It does so by storing the osmotic power of a solution after regeneration in a large tank, and then feeding that solution to a specialized membrane to generate hydraulic energy, which is then converted into electricity through a hydroturbine/generator. The low-level waste heat is used to regenerate the working fluid to its original chemical potential needed for the next cycle.

Currently, low-level heat (less than 100°C) is a wasted resource. As per a US Department of Energy Advanced Manufacturing Office workshop held in 2018, this low-level waste heat is too expensive to recover. This workshop identified that industrial plants and commercial buildings consume approximately 7.5 quadrillion British Thermal Units per year (quads/year). This energy use contributes to more than 300 million tons of on-site carbon dioxide (CO_2) emissions annually in the United States.[1] About one-third, or around 2.5 quadrillion British Thermal Units of that energy, is lost as waste heat. Additionally, on-site steam generation in the United States uses about 5 quadrillion British Thermal Units per year of energy and produces one quadrillion British Thermal Units per year of waste heat, adding up to a total of 3.5 quadrillion British Thermal Units per year of waste heat. It is estimated that up to 60 percent of this waste heat is lost as low-level waste heat.[2] This means that there is approximately 2.1 quadrillion British Thermal Units per year of available low-level waste heat nationally from process heat and on-site steam generation to be re-used for electricity.

However, this low-level waste heat is too expensive to recover and there are no cost-effective pathways to convert this waste heat to electricity. The unused waste heat from natural gas combustion sources contributes to greenhouse gas emissions, including harmful emissions of criteria pollutants, such as nitrogen oxides, sulfur dioxide and particulate matter. These criteria pollutants are strictly regulated by California Air Resources Board and Air Quality Management Districts. Any recovery of this waste heat to higher value electricity will result in corresponding reduction of these greenhouse gas emissions and criteria pollutants. Converting this wasted resource to significantly higher-value electricity results in reduced plant operating costs while reducing the carbon footprint of the industrial process. The efficient conversion of this low-level waste heat to electricity at competitive costs will render greater sustainability and fewer emissions to industrial operations.

For on-site power generation, the WHOP cycle has the potential to offer higher efficiency and lower costs compared to conventional heat-engines and existing solid-state generators such as piezo-electric. The successful validation of the WHOP Engine has opened new pathways for

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[1] Manufacturing Energy and Carbon Footprint: Sector: All Manufacturing (NAICS 31 33). https://www.energy.gov/sites/default/files/2022-01/2018_mecs_all_manufacturing_energy_carbon_footprint.pdf

[2] US DOE: Waste Heat Recovery: Technology and Opportunities in U.S. Industry. Waste Heat Recovery: Technology and Opportunities in U.S. Industry (energy.gov)

waste heat to electricity. This emerging technology will lead to new applications in the manufacturing sector, enhancing its global competitiveness.

Project Purpose and Approach

The project's purpose was to develop and demonstrate a cost-effective Waste Heat to Power Engine that is capable of greater than 15 percent electrical efficiency using low-temperature (≤ 400˚F or 205˚C) waste heat at a kilowatt capacity. Additionally, this project validated the benefits of this technology to California stakeholders, including natural gas ratepayers.

The approach for the innovative power generation system is the use of a hydraulic turbine for energy conversion from pressurized fluid solutions. This, first of its kind engine, allowed the determination of output power and heat to power efficiency. Improvement in WHOP Engine power output required supply chain development for the membrane module to convert osmotic potential to hydraulic pressure, a hydroturbine suitable for higher pressure with lower flow rate, and an energy-efficient regeneration.

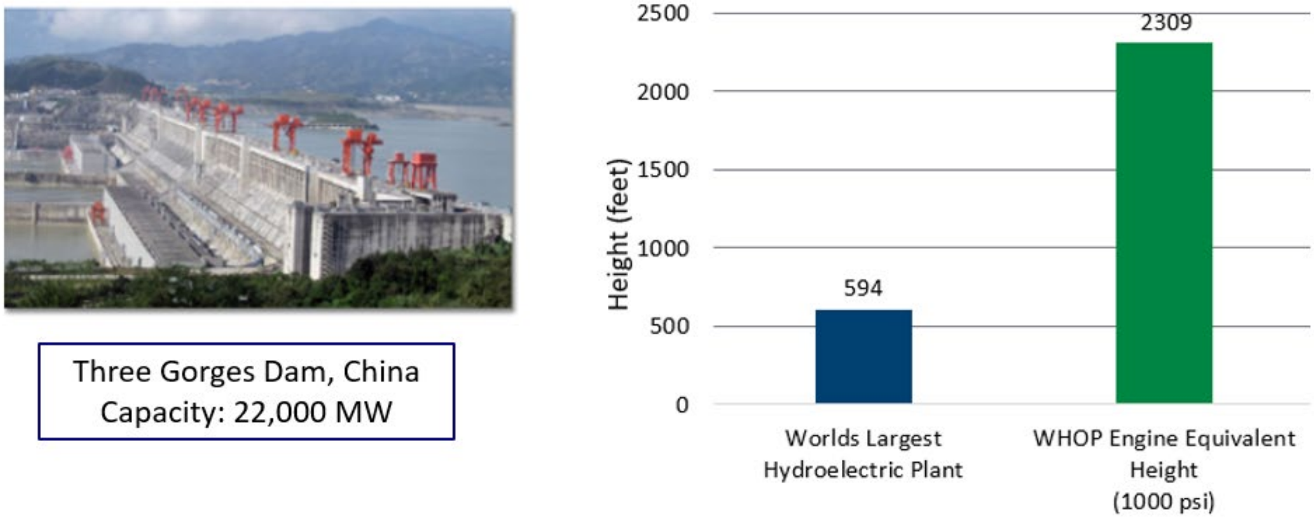
The membrane module in the WHOP Engine is a critical component to produce pressurized working fluid needed for power production using a hydroturbine. One of the key factors affecting WHOP Engine performance is the dilution rate, or the amount of water that crosses the membrane versus the amount sent to the membrane. The project team developed an advanced membrane technology that could withstand ultra-high pressures, which was a critical aspect of the WHOP Engine.

Another aspect of the program was the evaluation of a novel draw solution and its subsequent (low) regeneration energy promise. Various draw agents were evaluated including operating at elevated temperatures, which upon cooling separate from the water supplied, but were not used as the membranes developed could not operate above 40˚C (104˚F). Several organic salts and CO_2-phillic agents (agents optimized for CO_2 capture) were investigated that could be regenerated at low temperature using a new form of spray evaporative drying, where an ultrasonic nozzle was used, for the first time, to allow low-temperature drying.

Key Results

Tremendous improvements were made in the membrane technology used by the WHOP Engine. The membrane pressure capacity was increased starting from 30 pounds per square inch (psi), until a 1,000 psi membrane was demonstrated. The 1,000 psi pressure is equivalent to more than a 2,300-foot-high hydroelectric dam. This translates to four times the height of the tallest dam in the world, without the environmental impact, as shown in Figure 1.

Figure 1: WHOP's Pressure Capability of 1000 psi is Four Times that of the World's Largest Dam

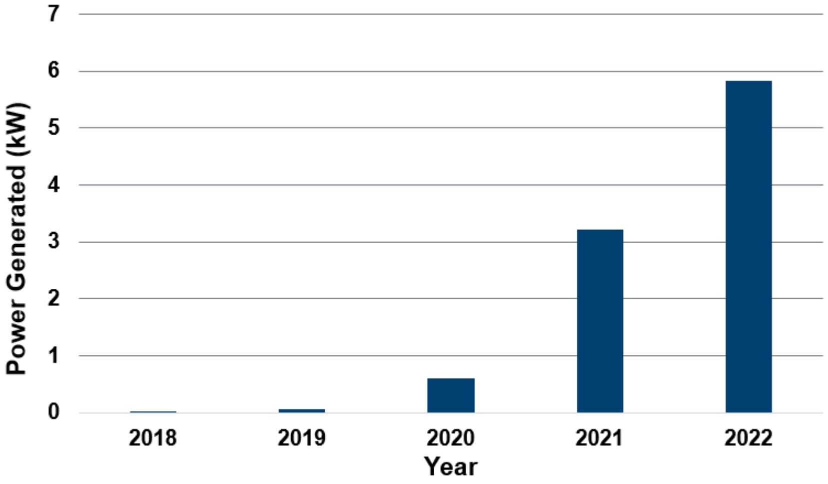


Osmotic pressure translates to hydraulic pressure, which generates clean electricity.

Source: T2M Global

The successful demonstration of this WHOP technology has opened new economic pathways for currently wasted heat from industrial and other operations, especially to create higher-value electricity from low-temperature heat sources without any incremental greenhouse gas emissions. Throughout the project's lifespan, the WHOP made a 1,000 times increase in energy production as the power ouput increased from 6 W to 6 kW, as shown in Figure 2.

Figure 2: Demonstrated WHOP Engine Power Output Over Time



A 1,000 times scale-up in WHOP Engine power generation has been validated.

Source: T2M Global

Knowledge Transfer and Next Steps

T2M Global has taken advantage of numerous clean technology conferences and expositions to garner interest in the WHOP cycle. These opportunities include the CleanTech Open and the VERGE Energy Conference, where T2M Global presented the WHOP technology. It was well received by investors, policymakers, and stakeholders with an interest in clean energy.

The following strategy for outreach to key stakeholders assisted the outreach for WHOP Engine performance and deployment strategy:

- Technical partners – supply chain;
- Demonstration partners – early adopters;
- Funding partners – nondilutive from public sponsors, private equity funding;
- Market penetration partners – gas industry and aggregators;
- Utilities – investor-owned utilities, American Public Power Association members.

These outreach activities contributed to enhance WHOP Engine's value proposition and developed strategy for potential revenue streams.

Emerging technologies, such as hydrogen, biogas, and renewable natural gas producers were identified as the near-term opportunities. These technologies are enablers for the transition to a zero-emission economy. They also have significant financial incentives available to help with early market entry. This is because of an urgent need to decrease hydrogen, biogas, and renewable natural gas production cost in California and the regulatory certainty of the Low Carbon Fuel Standard incentives. The low-level waste heat (<120°C or 250˚F) is a stranded asset at most application sites due to prohibitive cost associated with conventional recovery methods and Carnot cycle limitations. The Carnot cycle is defined as the ideal efficiency for conversion of heat to power. The WHOP technology being developed by T2M Global's team offers a unique opportunity to upgrade this stranded asset into higher value electricity. The WHOP products are expected to sell with minimal competition from other waste-to-power technologies that suffer from ultra-high costs.

In the future, there are plans to optimize and improve the WHOP Engine's capabilities upon a scale-up to a 100 kW-class module. The improvements include further optimization of the membrane and regenerator design, additional research into the regenerative capabilities and stability of the osmotic agent, customization of the hydroturbine, an optimization of both the draw solution and working fluid, as well as the integration of more efficient plastic heat exchangers.

CHAPTER 1:
Introduction

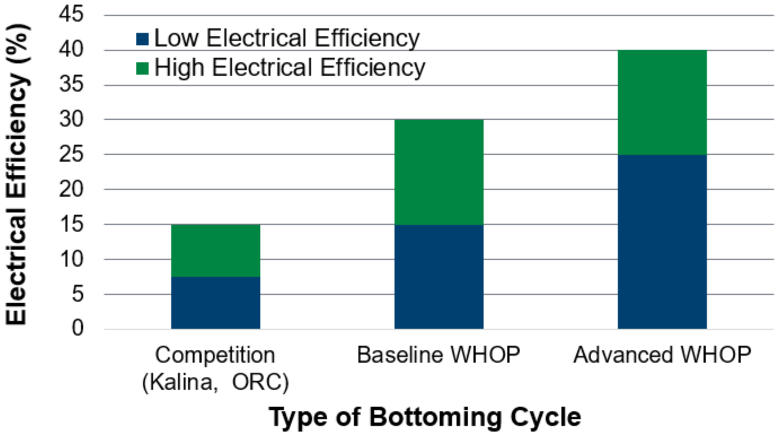
Problem Statement and Scope of the Project

It is estimated that as much as half of the energy used in industry goes towards producing waste heat.[3] The largest amount of waste heat is in the low-temperature group, defined as waste heat in the temperature region of less than 400oF. Captured and reused waste heat is an emission-free substitute for costly purchased fuels or electricity. All the various technologies currently under investigation for such a temperature regime have low efficiency and high capital costs, when used for low-temperature waste heat sources for power generation.

The efficiency of generating power from waste heat recovery is heavily dependent on the temperature of the waste heat source. In general, the ideal efficiency for conversion of heat to power is defined by the Carnot cycle where economically feasible power generation from waste heat is limited primarily to medium- to high-temperature waste heat sources (greater than 500°F), using the Steam Rankine Cycle. Emerging technologies, such as the Organic Rankine Cycle, can operate at lower temperatures (less than 100°C) though these technologies are hampered by low power conversion efficiency (ranging from 1 to 5 percent).

The WHOP Engine is an innovative technology not subject to Carnot cycle limitations that offers significantly higher efficiencies than the existing competition as shown in Figure 3. The project addressed cost reductions and efficiency improvements in collecting and managing low-temperature waste heat, improving its quality for power generation, and improving the systems that take in the waste heat.

Figure 3: Baseline WHOP Engine offers 2X Higher Efficiency



The osmotic cycle eliminates the Carnot Cycle limitations.

Source: T2M Global

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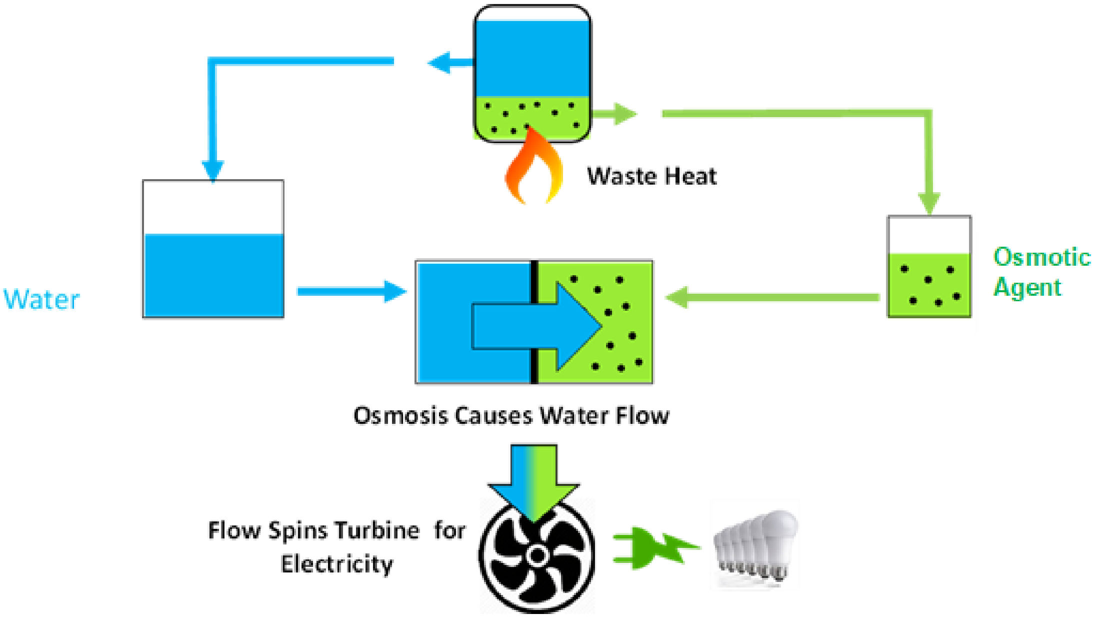
[3] "Waste Heat Recovery Resource Page." Energy.gov. https://www.energy.gov/eere/amo/articles/waste-heat-recovery-resource-page#:~:text=It%20is%20estimated%20that%20between,equipment%20surfaces%20and%20heated%20products

WHOP Technology Overview

The Waste Heat to Osmotic Power (WHOP) system is an innovative technology to convert chemical potential into a higher-pressure working fluid to drive a hydroelectric turbine and generate electricity (Figure 4). The working fluid is regenerated using low-level waste heat to its original chemical potential, thus completing the WHOP cycle for continuous power production using waste heat. Osmotic agents with large chemical potential can process substantial amounts of water across semi-permeable membranes and generate pressurized water at high flow rates to run turbogenerators for emission-free electricity production. The working fluid is regenerated using low-level waste heat by restoring it to its original chemical potential.

Figure 4: Simplified WHOP Engine Principle



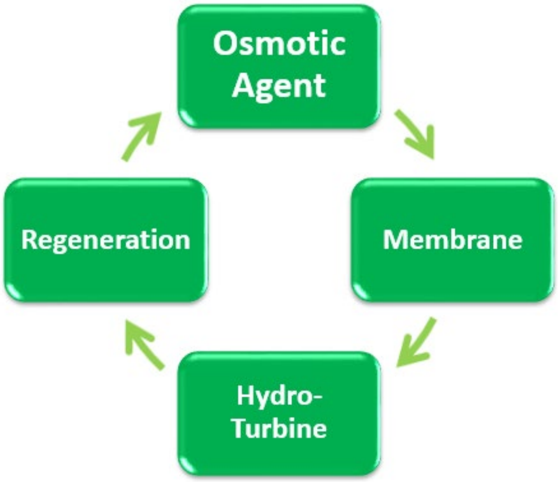
Water turbine offers the highest efficiency, lowest cost, and greatest reliability.

Source: T2M Global

The major sub-systems of WHOP were developed using the following strategy (Figure 5):

- **Osmotic Agent:** High stability during cycling, high osmotic pressure, and low cost.
- **Membrane:** Produces high hydraulic pressure and maintains high flux with good stability during operation.
- **Hydroturbine:** High electrical efficiency, lowest capital cost, greatest reliability manages low flow at high pressure.
- **Regeneration System:** The working fluid is efficiently regenerated to its original chemical potential.

Figure 5: Major WHOP Engine Subsystems



The osmotic system is emission free – Efficiency is not limited by the Carnot Cycle.

Source: T2M Global

Project Goals

- Develop and demonstrate a cost-effective kW-class Waste Heat to Osmotic Power system for California Industries, capable of efficient conversion of low-temperature (less than 400oF) waste heat to power.
- Develop a new class of osmotic agents for the WHOP system capable of regeneration using low temperature waste heat, as well as ≥ 80 percent efficient hydraulic turbogenerators at kW-class level.
- Develop a membrane module capable of withstanding ultra-high pressures of 1,000 pounds per square inch (psi) and working with the chosen osmotic agents.
- Identify process metrics and improvements for designing and deploying larger scale systems, starting at 100 kW, to improve efficiency and capital cost.

Metrics Measured

- Power generated by the turbine generator (W → kW)
- Thermal input into the system (kW, heat recovery)
- Electrical input into the system (kW, parasitic)
- System Efficiency (low-level heat → kW, percent)

Benefits to Ratepayers

Recovery of waste heat to produce higher value electricity means reduced greenhouse gas emissions for a healthier environment, while reducing electricity bills. Large-scale deployment of the WHOP Engine will result in rate-payer benefits such as greater electricity reliability, a cleaner environment, lower costs, and an array of new quality jobs. It will enhance the reliability of local microgrids and add flexibility to manage increased penetration of renewables.

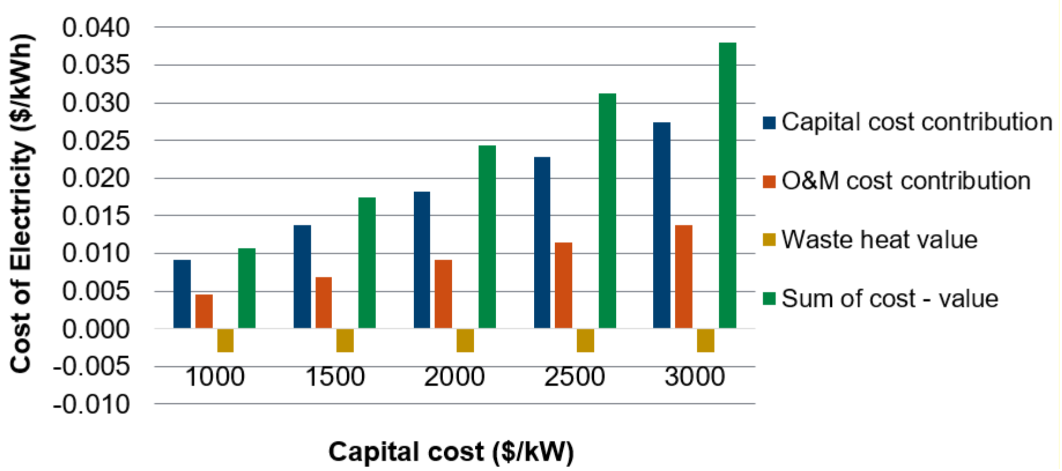
The cost of electricity when using the WHOP Engine is expected to be lower compared to conventional methods. The main factors responsible for this lower cost are:

- Lowest cost generator: water turbines are less than $500 per kW
- Lower maintenance system: no high-temperature components
- Lower operating cost:
  - Higher efficiency water turbine (greater 80 percent)
  - No fuel cost, the energy from the waste heat is used to produce electricity
  - Reduced duty on cooling towers or radiators to dispose of waste heat
  - Closed-loop working fluid: no consumption of chemicals
  - No water discharge, the water is recovered, recycled, and reused
- Emission-free: no combustion, does not require expensive components for emission control

The WHOP system is expected to require little maintenance, thanks to its use of hydroturbine technology with over 100 years of track record of robust performance. Figure 6 provides an estimation of the cost of electricity for different capital costs for the entire WHOP engine system. The highest cost component, being water turbine, is commercially available at less than $500 per kW. The other components are relatively lower cost as they are similar to a hydropower plant. In the near term, for a smaller production rate, WHOP may cost between $2,000 to $3,000 per kW. With increase in deployment and market penetration, the system capital cost is expected to reduce to approximately $1,000 per kW. This sensitivity on capital cost and its impact on cost of electricity, is illustrated in Figure 6. For the near-term relatively high cost for $3,000 per kW, the electricity cost is expected to be approximately 4¢ per kWh. For full-scale deployment, the cost of electricity is expected to reduce by 75 percent to approximately 1¢ per kWh. This cost of electricity is extremely attractive compared to conventional power generation systems.

Overall, the WHOP Engine is expected to provide low-cost electricity without any incremental emissions. This low-cost clean electricity will assist local businesses in staying competitive, leading to improved job retention and potential creation of new jobs in California. Therefore, all ratepayers will significantly benefit from reduced constraints on the grid, improved grid reliability, health benefits from reduced need for polluting powerplants, the creation of high-quality jobs, and potentially reduced cost of electricity.

Figure 6: WHOP Offers Competitive Low-Cost Electricity

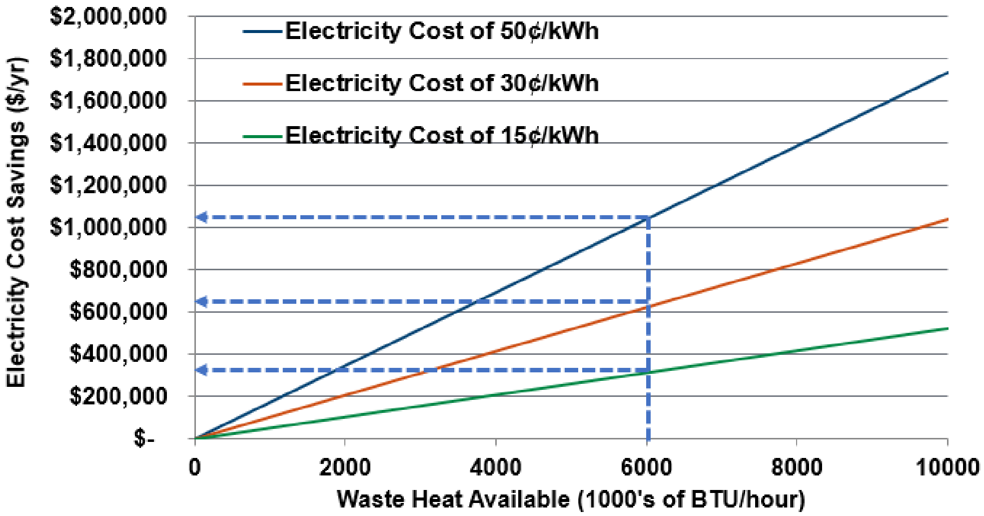


California ratepayers can save significantly in annual electricity bills.

Source: T2M Global

The annual savings from reduced purchases of grid electricity are illustrated in Figure 7 as a function of available waste heat and cost of grid electricity. Given 6 million BTUs/hour of available waste heat, as illustrated by the dashed lines in Figure 7, WHOP can create savings greater than $300,000 per year in low-cost electricity areas, and over $1,000,000 per year in high-cost electricity areas. Nationwide, if all waste heat below 300˚F were converted to electricity using WHOP, it would translate to electricity cost savings of over $5 billion (as explained in further detail in the market opportunities sections, under Table 2).

Figure 7: Cost Savings Offered by WHOP Engine at 15 Percent Efficiency



As grid electricity becomes more expensive, the savings become more attractive.

Source: T2M Global

CHAPTER 2: Project Approach

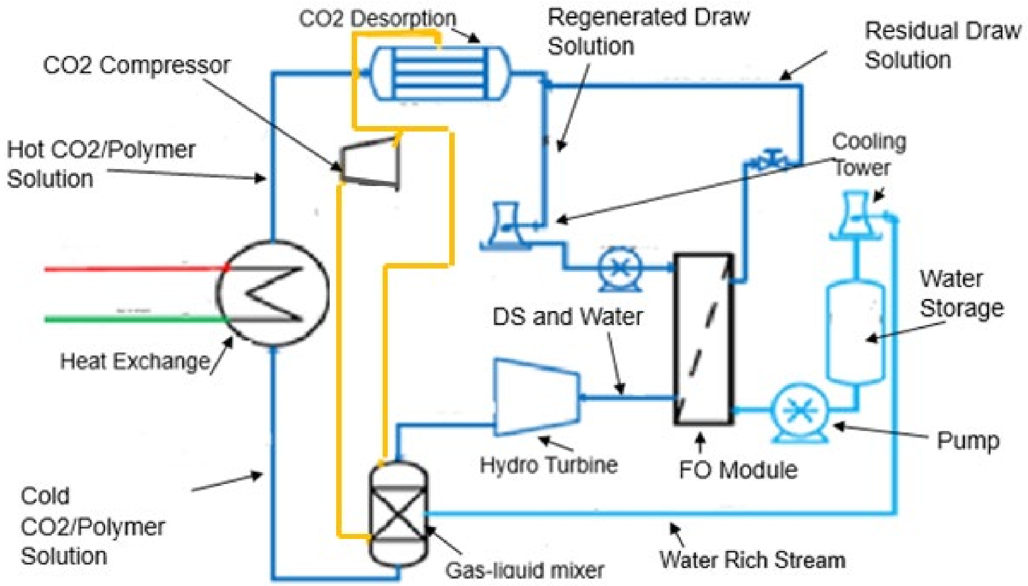
Project Team

The project was managed by T2M Global (T2M) as the prime recipient. This includes reporting, outreach, and coordinating the efforts of T2M's staff, subcontractors, advisors, and vendors. Subcontractors from T2M's California-based supply chain were instrumental in developing components of the WHOP Engine and assembling them at the host site. The Technical Advisory Committee consisted of individuals from eight different entities that provided highly valuable strategic input for the project. These included representatives from the gas industry, electric utilities (investor-owned utilities, municipal power producers), State and Federal representatives engaged in Combined Heat and Power technology, as well as entities that have waste heat available.

Initial Design Options Considered

The design for the WHOP Engine has evolved since its conception to develop a WHOP Engine working in a continuous closed loop. The original design concept for the WHOP Engine can be seen in Figure 8. This design concept, while still promising, had severe limitations in the existing supply chain. This included the polymer solution, membrane module, and hydroturbine capable of operating at an elevated pressure. For the proof-of-concept, the team focused on alternative options. This included existing supply chains that can deliver WHOP Engine components to produce electricity using osmotic agents.

Figure 8: Original Design Concept for the WHOP Engine



Made use of carbon dioxide for phase-separation during regeneration.

Source: T2M Global

Original draw solutions used a carbon dioxide (CO_2)-phillic osmotic agent (agents optimized for CO_2 capture) that absorbs carbon dioxide to effectively cause polymer phase-separation from water. Waste heat was then used to remove the absorbed CO_2 and regenerate the polymeric draw solution to its intrinsic state of high osmotic pressure, for use in repeated cycles of power generation through the WHOP process.

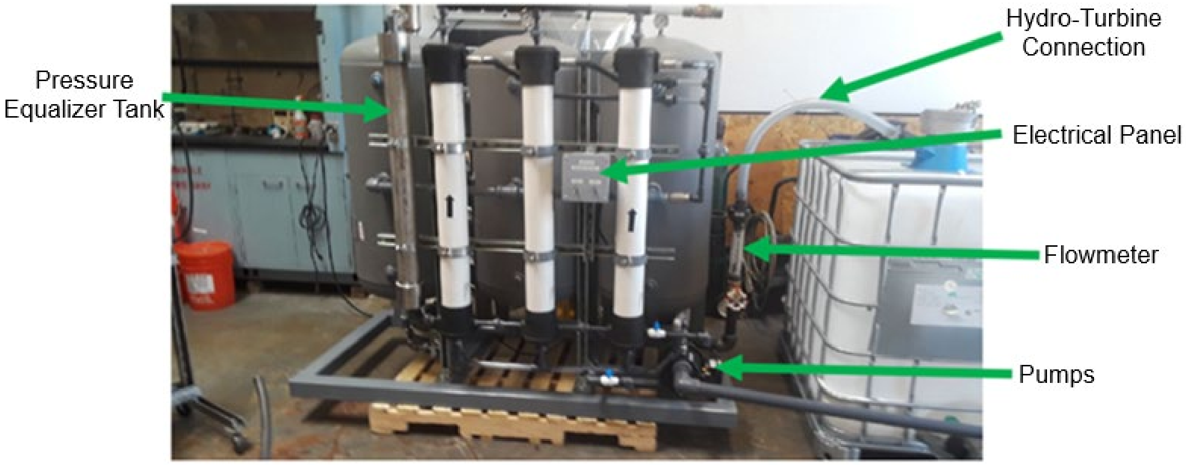
The overview of the system with the fabricated components, three membrane modules and their corresponding pressure vessels are shown in Figure 9. Their connections to the hydro-electric (hydro)-turbine are illustrated in Figure 10. The initial baseline design used pressurized equalizer tanks as shown in Figure 10. The size of the pressurized tanks and regeneration system is specific to the output power requirement. The setup was evaluated to validate operation up to a hydraulic pressure of 400 pounds per square inch (psi). The system operated satisfactorily, and the desired flow rate of the draw solution was achieved, but the team quickly realized that the pressurized buffer tanks were not scalable for larger scale WHOP Engines. In addition, the pressure capability of the membrane module is crucial to reach the WHOP Engine power production targets. To resolve the issue, the team assessed different membrane modules to ascertain the feasibility of using pressurized membrane modules to generate the pressure needed to drive the turbine instead of using pressurized storage tanks.

Figure 9: Connections between the Baseline WHOP System Components

Baseline WHOP system successfully validated 600 W of power production.

Source: T2M Global

Figure 10: Membrane Modules and Pressure Vessels Connected to the Turbine



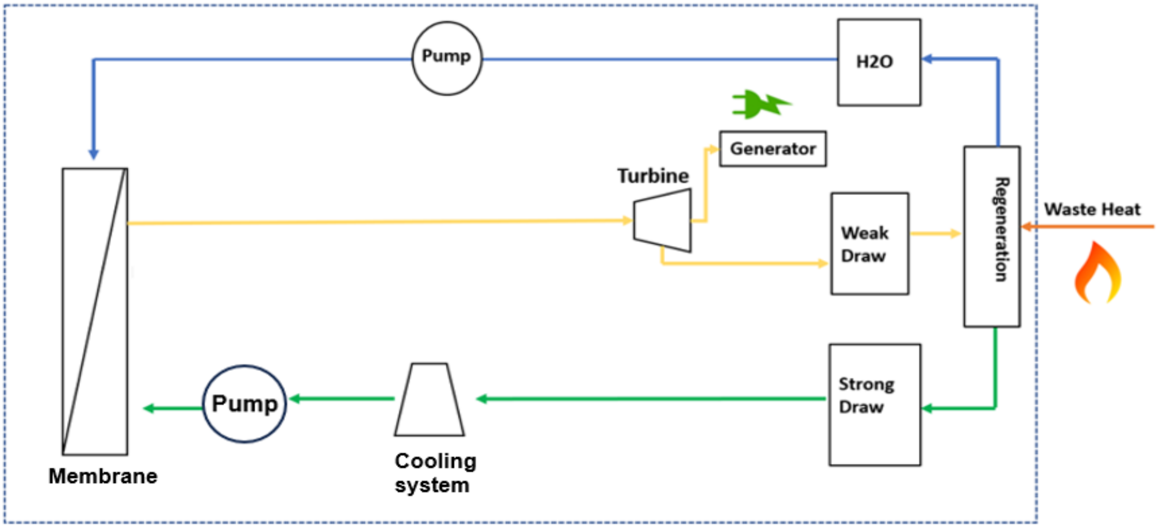
Stable operation up to a hydraulic pressure of 400 psi was achieved.

Source: T2M Global

WHOP Engine for Proof-of-Concept Validation

Given the limitations in the existing supply chain, a new system had to be considered for the proof-of-concept testing that made use of different osmotic agents and components. Figure 11 below represents the updated process flow diagram for the current design of the WHOP Engine. The updated design no longer has a need for gas desorption, and gas-liquid mixing, so the result is a less complicated system. This was accomplished by the use of higher performance osmotic agents with a lower temperature regeneration. It is also a closed loop system that does not require any inputs other than the low-level waste heat. For the proof-of-concept demonstration, an electric heater was used to simulate an on-demand waste heat source.

Figure 11: Process Flow Diagram of the WHOP Engine



The closed-loop system does not require ANY make-up of working fluids.

Source: T2M Global

Figure 12 depicts the membrane modules, pumps, and hydroturbine with the generator. Outside of the illustration are three storage tanks for the working fluids and osmotic agent. The WHOP Engine used for this proof-of-concept demonstration was not packaged tightly to leave room for maintenance and adjustments to the layout. In a scaled-up design for commercialization, the WHOP components will be much more tightly packaged to occupy a small footprint and be readily truck-transportable.

Figure 12: The WHOP Engine Integrated and in Action

The system is designed with reliability, accessibility, and maintainability in mind.

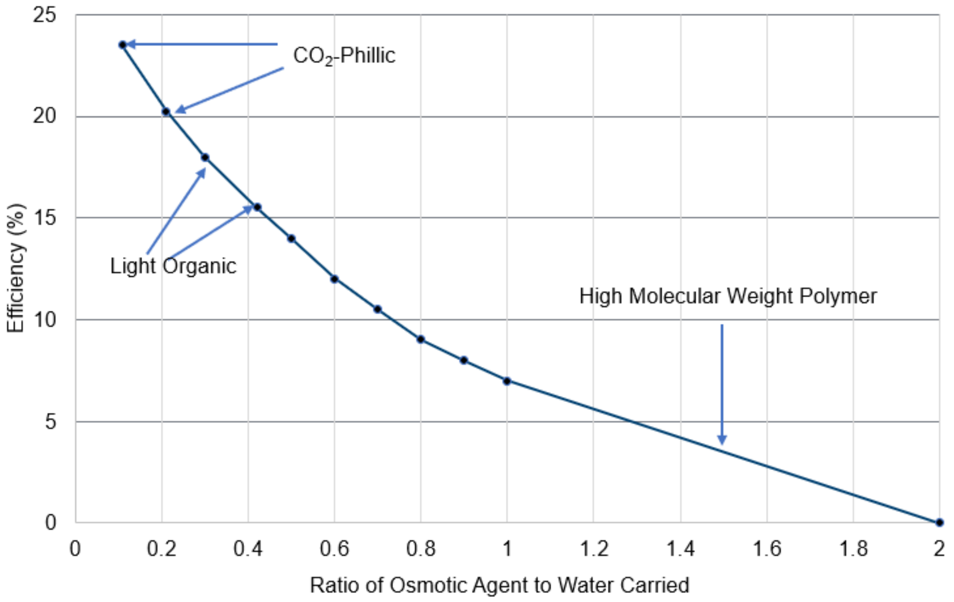
Source: T2M Global

Working Fluid Development

Throughout the course of this project, dozens of different osmotic agents were investigated to meet WHOP Engine operating requirements at respectable electrical efficiency. As stated, original working fluids made use of a CO_2-phillic osmotic agent. These osmotic agents operate by switching from hydrophilic to hydrophobic properties after exposure to CO_2 for efficient regeneration. The osmotic agent initially absorbs water due to its hydrophilic segments, creating the hydraulic pressure that drives a water turbine. After producing power in the water turbine, the dilute working fluid is then regenerated by using CO_2 gas to release the absorbed water. The CO_2 is then removed from the osmotic agent using low-level waste heat. Over a dozen CO_2-phillic osmotic agents were tested. They had reasonable performance, but poor regeneration cycle life. This is caused by the thermal degradation of the osmotic agent over the course of multiple regeneration cycles. The entire system was consequently reworked to accommodate operation on osmotic agents that are not reliant upon the CO_2 cycle for regeneration. These new working fluids included organic and inorganic compounds with lower regeneration temperature and hence greater suitability to benefit from low-level heat. They have proven to be far more stable upon regeneration cycles.

Several different thermolytic osmotic agents were evaluated for their water carrying capacity. First a traditional, high molecular weight osmotic agent was used with a 1.5 carrying capacity ratio to benchmark the low end of the efficiency curve, as depicted in Figure 13. Then two lower molecular weight osmotic agents with higher carrying capacity were examined, over the same pressure range.

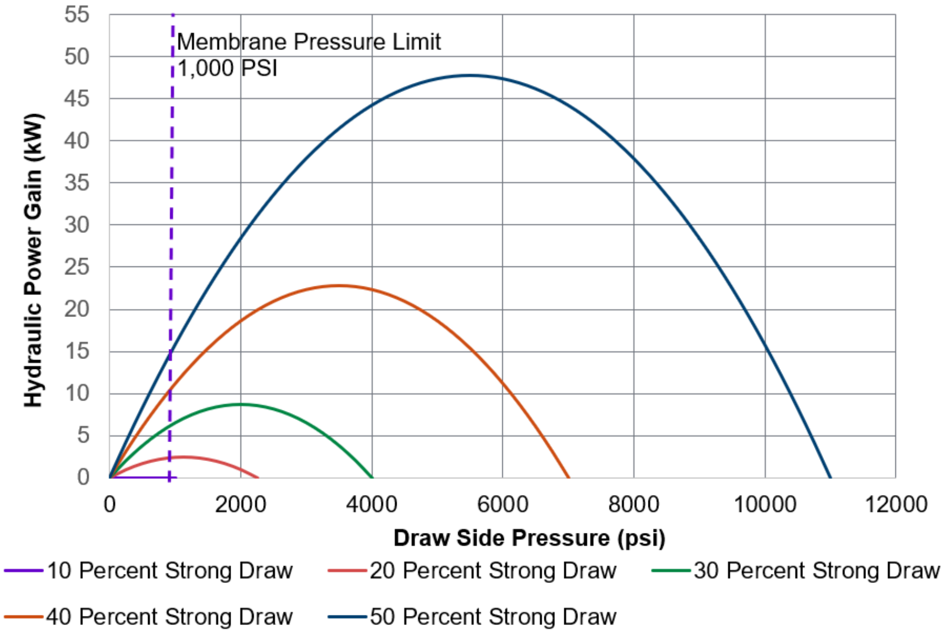
Figure 13: WHOP Efficiency vs. Osmotic Agent's Water Carrying Capacity: Lower Osmotic Agent to Water Ratio Yields Greater Efficiency



Source: T2M Global

Upon the discovery of an acceptable osmotic agent, a parametric analysis was conducted to understand the maximum power output possible from the WHOP Engine at different strong draw (SD) concentrations as shown in Figure 14 below. The membrane modules used in testing were limited to a shell side pressure maximum of 1,000 psi (shown as the vertical line in Figure 14). Hence the housing/membrane limitation of 1,000 psi imposes an output hydraulic power restriction of around 7 kW for 30 precent SD. Therefore, the testing conducted could not fully exploit the draw solution osmotic potential. Figure 14 also points out that, subject to the 1,000 psi operating condition limitation, the WHOP Engine should be able to generate around 17 kW with a 50 percent SD solution.

Figure 14: WHOP Cycle Performance Estimates – Theoretical Limit



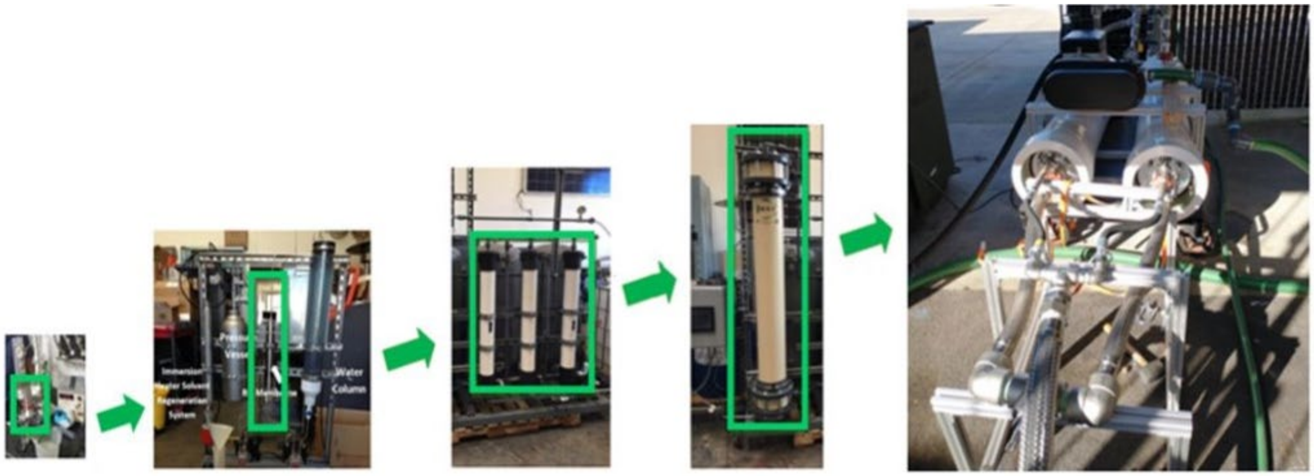
A more concentrated draw solution leads to greater power output.

Source: T2M Global

High Flux and Pressure Tolerant Membrane Module Development

Figure 15 illustrates the substantial increase in membrane surface area over the project's duration. The first membrane module used in the project had a surface area of 0.008 square meters, before increasing 43,000 times throughout the project's duration to 350 square meters. This improvement can be attributed to a sheer increase in size, as well as a more intelligent use of the membrane's internal space.

Figure 15: Increase in Membrane Surface Area Over the Project Duration



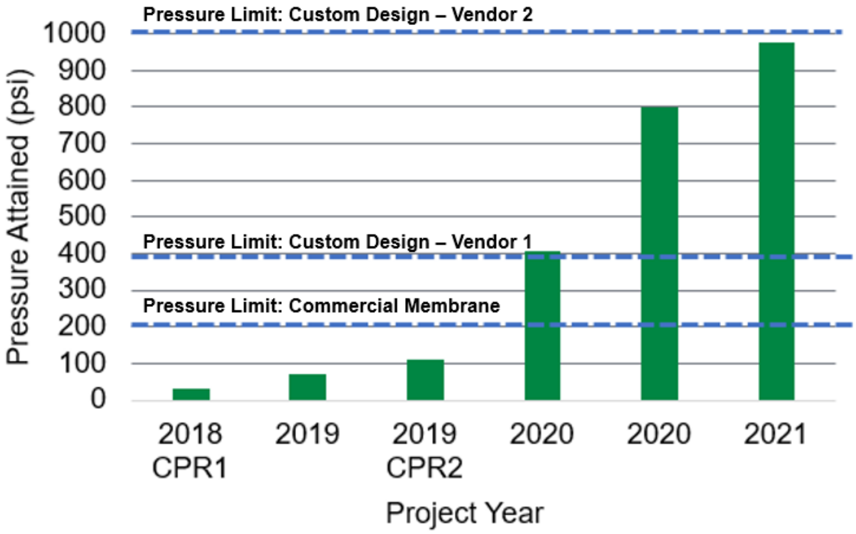
(A: 0.008 m^2) (A: 1.041 m^2) (A: 3 x 3.6 m^2 each) (A: 43 m^2) (A: 2 x 350 m^2 each)

High-pressure capable, large-area membrane module validated.

Source: T2M Global

Figure 16 shows the improvement in the maximum operating pressure of the membrane modules as the project proceeded. The membrane pressure capability was progressively increased from 30 → 200 → 400 → 1,000 psi. Commercial membranes do not exceed 200 psi, so the team worked extensively with two different vendors to increase the pressure capability. The first vendor that the team worked with was able to double the pressure capability to 400 psi. Upon attempting to push this membrane to higher pressures, it resulted in a membrane failure. Analysis conducted with the vendor showed inherent limitations of the design and materials of construction of the membrane. Upon further research into membrane developers, a second vendor was identified that was willing to custom produce a membrane module with a pressure target of 1,000 psi. The first iteration could withstand up to 800 psi. The test data was reviewed with the vendor, and the lessons learned were implemented to produce a second generation of this new membrane module. It was successfully tested with pressures up to 1,000 psi in the team's test facility (as shown in the technical barriers section, Figure 39). The membrane was subsequently integrated into the WHOP Engine set up at the project host site, located at the Trevi Systems Inc. facility in Rohnert Park, California, and successfully operated in the presence of the California Energy Commission (CEC) Commission Agreement Managers (CAM).

Figure 16: Supply Chain Development for High-performance Membrane

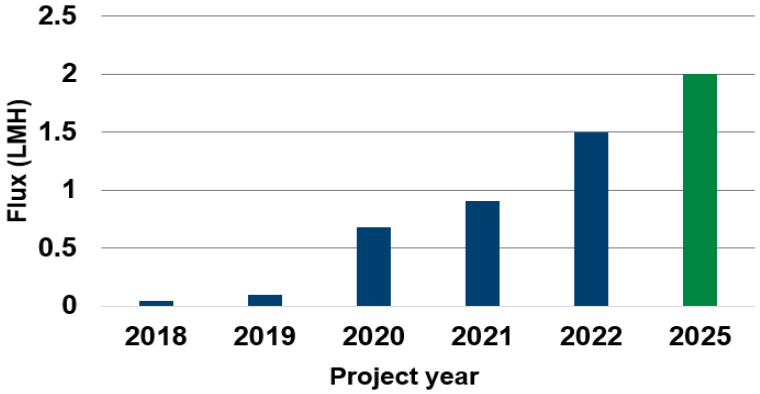


Pressure capability increased 30 times and validated.

Source: T2M Global

Figure 17 illustrates the progress made in membrane flux capacity. Flux can be described as the quantity of water crossing the membrane over a period of time and is measured in liters per square meter per hour (LMH). This increase is a result of developments in membrane geometry and material chemistry as previously explained, as well as changes to the osmotic agent. The increase in flux contributed greatly to the power output increase from 6 W to 6 kW, as more water was pressurized to spin the hydroturbine. Figure 17 also shows the target flux in the 100 kW-class membrane modules to achieve the 30 percent long-term efficiency goal.

Figure 17: Membrane Development to Increase Flux



Membrane optimization requires a complex tradeoff between flux, pressure, and capacity.

Source: T2M Global

Turbines Considered for kW-class WHOP Engine

T2M investigated all types of hydroturbines and ranked them according to their suitability for the specific operating requirements of the WHOP Engine. Only a few of the investigated turbine types met the pressure and flow requirements of the project. Many commercial turbines are optimized for high flow rates and relatively low pressures, while this project requires turbines that work with a low flow rate and high pressure. Turbine vendors were contacted to discuss the feasibility of customizing a traditional hydroturbine; however, price estimations were prohibitively large due to the costs of producing a highly durable casing and rotor, with no guarantees on the efficiency on this small scale. A lower cost novel design appropriate for the kW-class WHOP Engine was identified. It met the pressure, flux and power output requirements of the project at a reasonable price but resulted in a lower efficiency of approximately 65 percent (results section, Figure 37). There is an opportunity for further development of this design to reach the high efficiency, high reliability, and low capital cost customary for hydroturbines.

Regeneration System Development

The regeneration of the working fluid is important for long-term stable operation of the WHOP Engine. The spent working fluid (diluted by freshwater flux in the membrane module) needs to be regenerated to its original chemical potential. Factors affecting the regeneration system performance and cost include:

- Heat transfer efficiency affects the rate of regeneration.
- Stability of the working fluid during cycling between high and low chemical potential states.
- Regeneration temperature for the working fluid: must be compatible with the temperature of available waste heat.

- Strong draw solution: The working fluid concentration has a significant impact on WHOP efficiency. With a higher concentration, there is a greater power output (as shown previously in Figure 14), but also a need for more waste heat in the regeneration loop.

The WHOP regeneration system is designed to operate over a wide range of temperatures to make the approach versatile. To regenerate the draw solution, an atomizer capable of generating small droplets was selected. The required droplet size was calculated based on desiccant regeneration equipment used for commercial applications. The regeneration system with a heat source is shown in Figure 18.

Figure 18: Ultrasonic Regeneration Equipment

Includes the Atomizer, Draw Tanks and Heat Source.

Source: T2M Global

The current WHOP Engine uses a closed-loop system that maintains the working fluid and only inputs waste heat. The closed-loop system requires very little in terms of operation and maintenance costs, while showing respectable efficiency. Future iterations of the WHOP Engine may further improve upon the efficiency by using an open-loop system that can assist in the host site operations.

Demonstration Site Preparation for kW-class WHOP Engine

The team considered half a dozen host sites for the demonstration, in northern as well as southern California. The host site in Rohnert Park, California was selected in agreement with the CEC CAM, and the team successfully secured the demo site including a lease agreement for the anticipated testing period. A layout of the WHOP Engine's major components and interconnections was drafted and refined to facilitate its installation with the least number of modifications needed. All the permits and approvals needed for the test were obtained before installing the equipment. Major activities include:

- **Electrical Supply:** Two full-size electrical panels were installed at the demonstration site to provide both the single-phase and three-phase power needed to power the various components of the WHOP Engine. A dedicated WHOP control system with Velico Programmable Logic Controller (PLC) was fabricated and installed (Figure 19). This includes:
    - Variable Frequency Drives to support WHOP operation at different power levels.
    - Power outlets for pumps, motors, and other electrical equipment.
    - Power distribution boxes with circuit breakers for safe operation.
    - Associated control equipment to communicate with the PLC.

  The installation and factory testing were performed by a licensed electrician as per the permits obtained from local authorities. Appropriate conduits were used to minimize interferences and protect electrical lines from degradation by the elements as well as accidental damage. Where possible, power lines were routed overhead for safety, and to minimize trip hazards on the ground.

Figure 19: Electric Supply and Dedicated Control System

All necessary electricity supply and control components properly installed.

Source: T2M Global

- **Electrical Load Bank:** The kW-class power production from the WHOP Engine was consumed in a resistive load bank. A three-phase electric load cell sub-system was procured and delivered to the site (Figure 20).

Figure 20: Military Grade Electrical Load Bank

Three-phase electric load cell meets all performance and safety requirements.

Source: T2M Global

- **Draw Solution Storage:** The high-pressure tolerant membrane module design has allowed the team to use significantly larger draw solution storage tanks. Three 4,500-gallon storage tanks were successfully secured, installed, and plumbed at the test site as shown in Figure 21. The increased storage capacity provided a buffer for the regeneration system, making the overall WHOP Engine system design significantly more flexible and cost-effective.

Figure 21: 4,500-Gallon Storage Tanks for the Draw Solutions and Working Fluid

There is no net consumption or emissions of any fluids in the WHOP Engine.

Source: T2M Global

- **Component Installation:** The WHOP skid was moved and rearranged for reliability, accessibility, and maintainability. This rearrangement provided easier access for repair, troubleshooting, and upgrades that were needed to meet validation test objectives. The following major systems were installed (Figure 22):
    - Membranes for pressurization system of the working fluid.
    - Water turbine for conversion of pressure energy to rotational energy.
    - 240V AC generator for production of electricity synchronized with the local grid.
    - Safety sub-system for protection of personnel, host site, and test equipment.
    - Outside plumbing to the large 4,500-gallon storage tanks (Figure 23).

Figure 22: WHOP Engine Components for Check-Out Testing

Integration of two membrane modules completed.

Source: T2M Global

Figure 23: Installation and Plumbing of Storage Tanks for Process Fluids

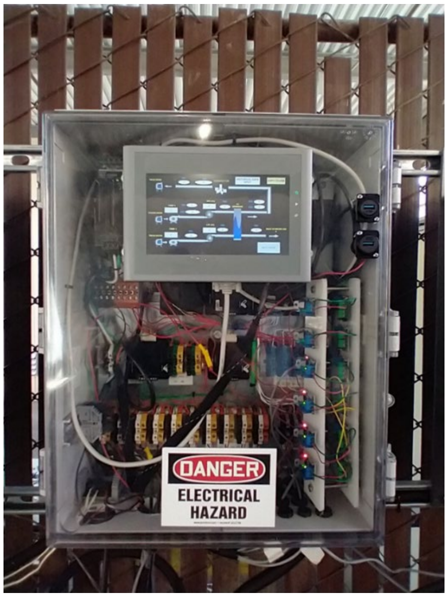
The working fluid storage tanks represent the energy storage capacity.

Source: T2M Global

PLC Software Integration for Test Data Collection

The purpose of the PLC software was to log operational data to assess stable operation and gather performance data for overall system performance evaluation. Integration of the software with the motors on the WHOP skid enabled continuous control for safe operation. The data generated from the integration process was continuously monitored and compiled. Figure 24 below shows the PLC screen of the WHOP Engine.

Figure 24: Motors in the WHOP Engine Integrated with the PLC Software



Allowed for continuous operation and data logging for later analysis.

Source: T2M Global

kW-class WHOP Testing

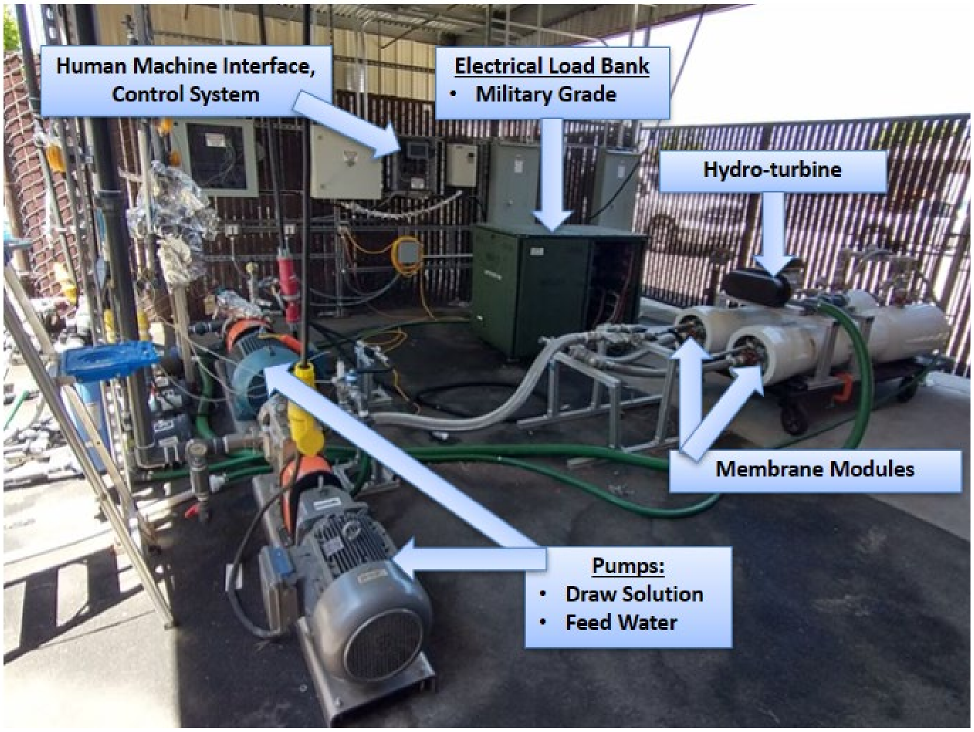
Demonstration testing of the kW-class WHOP Engine was conducted at the host site. The system setup is shown in Figures 25 and 26. The membrane modules were fed draw solution at two target concentrations (18 percent and 30 percent) from the SD shell side pump at pressures of 400 to 1,000 psi as well as at two different draw solution temperatures (20˚C and 30˚C). The objective was to determine the peak power production possible from the engine. Pure water was fed to the bore of the membranes using a second pump with feed pressures up to 200 psi. The membranes used were the 10-inch membrane elements specially designed for this application. The membrane array was connected to the hydroturbine and alternating current (AC) generator which was in turn connected to the three-phase resistive load bank. The power produced was calculated from voltage and current readings taken on the three-phase load bank. Process parameters such as membrane flux, membrane pressure capability, water gain, and osmotic pressure of the draw solution were evaluated against the net power output from the WHOP Engine to ascertain the performance of the membrane modules and identify areas of improvement.

Figure 25: HMI, Load Bank, Membrane Modules and Storage Tanks

Supply chain developed for membrane modules – commissioned and achieved 1,000 psi.

Source: T2M Global

Figure 26: kW-class WHOP Engine System in Operation



WHOP Engine power production validated.

Source: T2M Global

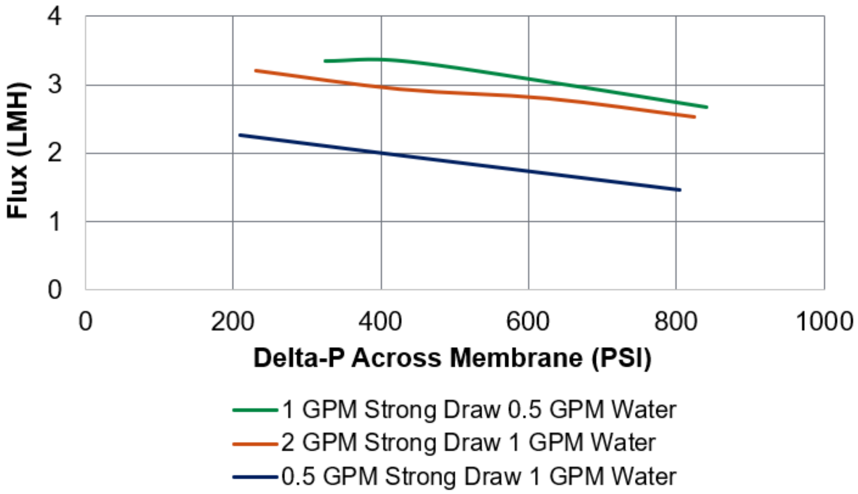
CHAPTER 3: Results

Test Results from kW-class WHOP Engine

Membrane Flux

At 18 percent draw solution, the tests conducted on the 5-inch membrane module demonstrated a membrane flux difference of about 0.5 liter/meter2/hour (LMH) over a wide applied hydraulic pressure range of 400 to 900 psi as shown in Figure 27, below. This indicates that variations in the drawing hydraulic pressure had a minimal influence on the membrane flux compared to the flow rates of the draw solution and water. The same membrane flux measurements were conducted on the large 10-inch membrane module for comparison shown in Figure 28, below. The membrane flux achieved on the large 10-inch membrane module was 1.5 LMH. From Figure 27 and Figure 28, the membrane flux of the 10-inch membrane module is somewhat reduced, indicating that there are some flow path restrictions in the larger membrane. This can be attributed to the longer bore path (the 10-inch membrane has a bore length of 1.2 meters as compared to 0.4 meter for the 5 inch membrane), creating difficulty in feeding sufficient fluid into the bore for the given bore diameter. The 10-inch membrane was selected for further testing due to its substantially larger surface area, which effectively offset the reduced membrane flux.

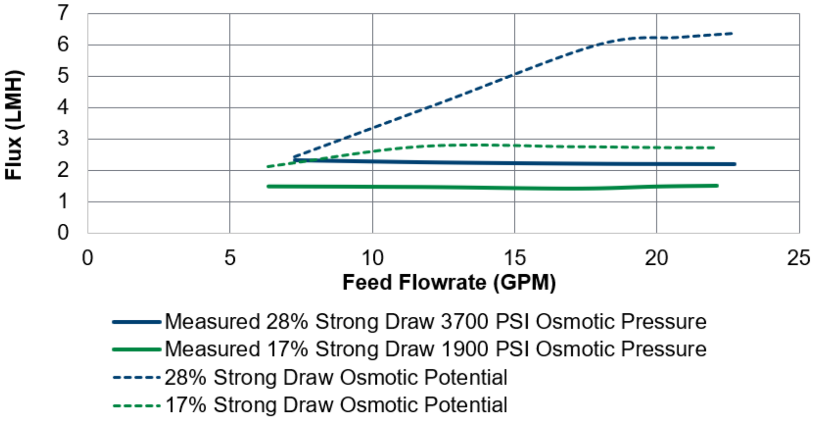
Figure 27: 5” Membrane Flux with Hydraulic Pressure



Favorable outcome: membrane flux dependence on hydraulic pressure has been reduced.

Source: T2M Global

Figure 28: 10” Membrane Test Results - Flux vs. Feed Flowrate

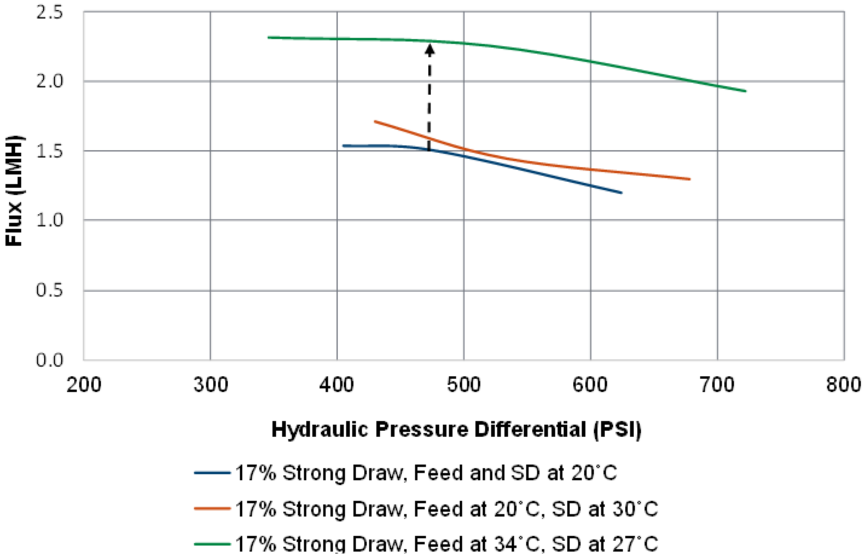


Target membrane flux of 1.5 LMH was achieved.

Source: T2M Global

The effect of temperature on the membrane flux, using the 10-inch membrane, was then investigated. The temperature of the feed and the strong draw solution varied between 20°C to 35°C to gauge its impact on flux. An increase in the vicinity of 2 percent flux increase per 1°C temperature rise was expected, as determined from experience. Figure 29 shows that the increased temperature did influence the flux across the membrane. Keeping the feed at 20°C and increasing the strong draw temperature to 30°C did not have a significant impact on the flux (orange curve in Figure 29). But increasing the feed temperature to 34°C and the strong draw temperature to 27°C resulted in a noticeable increase in flux (green curve in Figure 29). A flux increase to over 2.2 LMH from 1.5 LMH is shown through the dashed arrow. The increased flux is a very promising result as theoretically the flux should directly relate to the WHOP Engine power output.

Figure 29: Variation of Membrane Flux with Feed and Draw Stream Temperatures



A 40 percent increase in flux was achieved using higher operating temperatures.

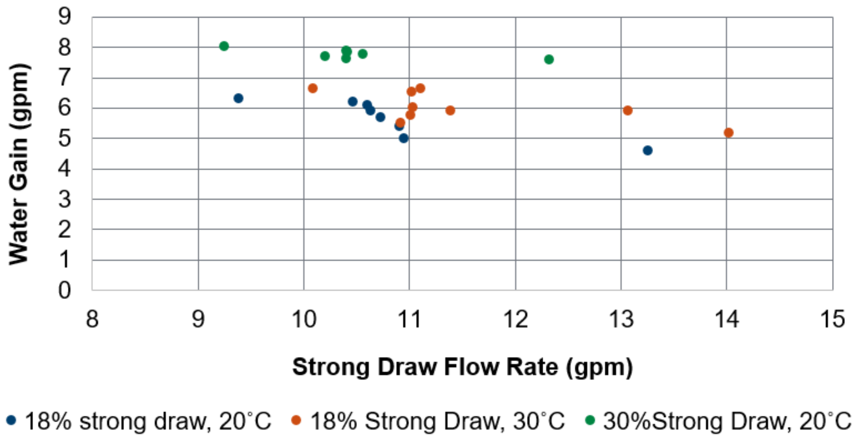
Source: T2M Global

Water Gain in Membrane Module

One of the key factors affecting WHOP Engine performance is the dilution rate, or the amount of water that crosses the membrane versus the amount sent to the membrane. The results obtained from osmotic dilution experiments are shown in Figure 30. For 18 percent draw solution, the data points at 20˚C are marked in blue while the ones at 30˚C are marked in orange; for 30 percent draw solution, the data points at 20oC are marked in green. The figure shows that with an 18 percent SD solution and a flow rate between 10 and 14 gallons per minute (gpm), there is insufficient water gain with an average water pickup of 5.9 gpm. The tests were then repeated with the 30 percent draw solution to allow for higher osmotic draw strength, and therefore, allow more water to cross the membrane. The green data points show that the membrane does indeed produce more water, but not at twice the level, instead producing on average 7.8 gpm. Per the draw solutions' osmotic potential, the water gain should have been much higher, as shown in the Figure 31 graph below. The solid blue and green curves represent the measured water gain while the dashed blue and green curves represent the theoretical curves.

Although slightly lower, the membrane flux is not substantially lower to account for the drop-off in performance. Membrane polarization is likely the culprit in this loss of flux at higher concentrations, but this theory is also not sufficient to explain the relatively poor water gain. Further analysis and testing will be required to understand this difference between expected and measured water gain. For this reason, there is a great opportunity to continue development of these advanced membranes.

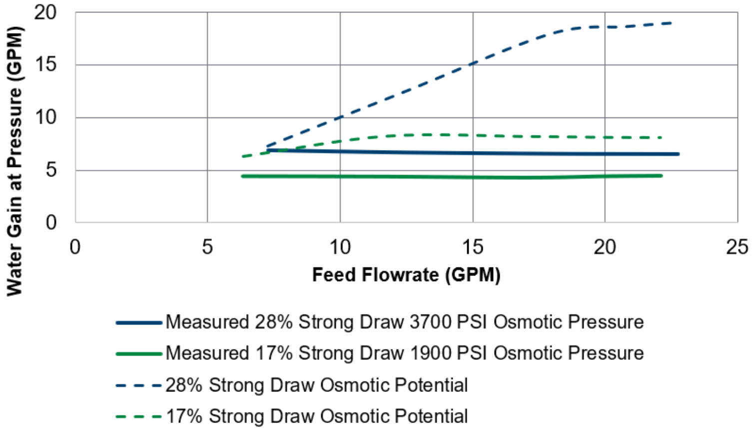
Figure 30: Membrane Performance - Measured Water Gain



Lower pumping power is beneficial for WHOP Engine efficiency.

Source: T2M Global

Figure 31: Membrane Performance - Water Gain Data



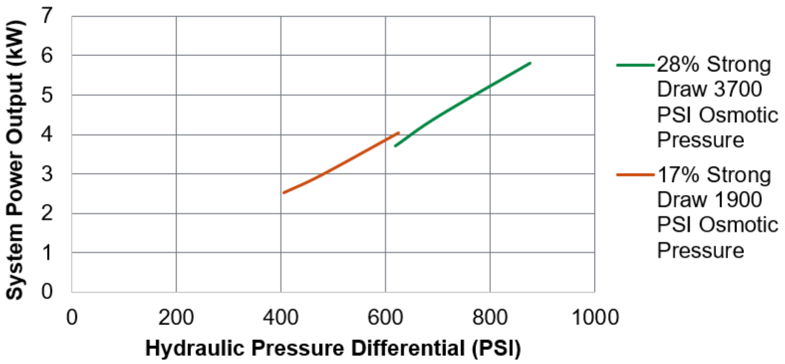
Expected vs. measured water gain across the WHOP membrane.

Source: T2M Global

Power Output

The measured power produced by the two-element 10-inch membrane module is shown in Figure 32 below. The higher osmotic pressure draw solution clearly shows an increase in output power, with a peak of 6 kW versus 4 kW for the lower osmotic pressure draw solution. It should be noted that based on the tests conducted on the 5-inch membrane element, the power output was projected to be 7 kW from the 10-inch membrane module based on power density and surface area. The slight decrease in power output (6 kW vs. 7 kW) can be attributed to the slightly lower flux as mentioned previously. The lower osmotic pressure draw solution was also not able to run at the 1,000 psi level for peak output power; whereas, the 30 percent was. To understand why water gain was less than expected, the feed parameters were varied (i.e., hydraulic pressure and draw solution temperature as shown in Figure 33 below). The graphs show that the total output power (for the two membranes) is linearly dependent on applied hydraulic pressure, so pressure retardation of the osmotic draw solution was clearly not a factor.

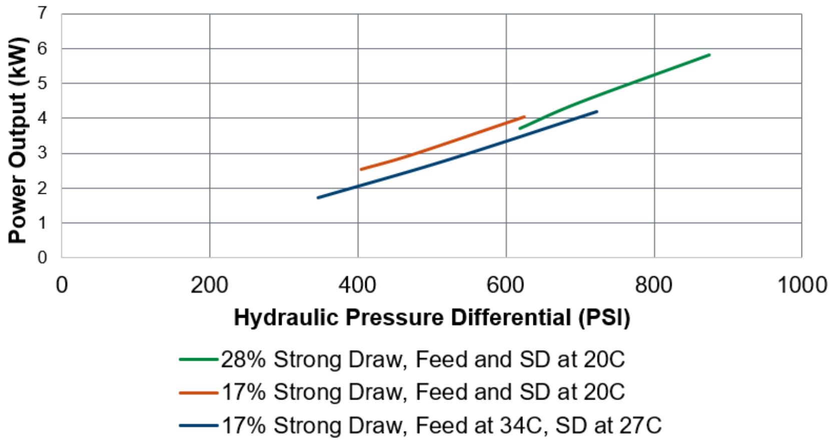
Figure 32: Measured WHOP Engine Power Output



As expected, an increase in hydraulic pressure leads to an increase in power output.

Source: T2M Global

Figure 33: Parametric Evaluation: WHOP Power Output vs. Operating Conditions

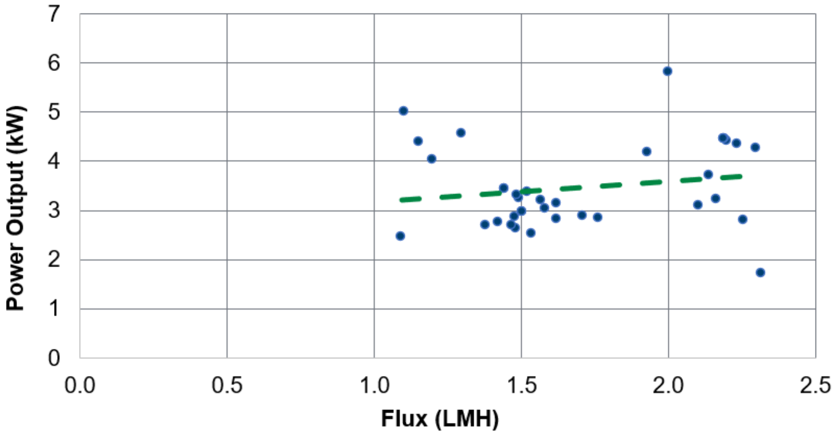


Increased temperature translates to an increase in WHOP power output.

Source: T2M Global

Figure 34 shows the relationship between flux and WHOP Engine power output. From Figure 34, as shown by the green dashed trendline, an increased flux translated to a slight increase in power output. In the WHOP Engine, fluid power generates the electrical power output via the hydroturbine and electric generator. This fluid power is gained via the flux across the membrane. The fluid power is a product of the flow and the hydraulic pressure increase. As the pressure goes up, the flux decreases since the pressure differential between osmotic pressure versus hydraulic pressure decreases, meaning less osmotic driving force with increases in hydraulic pressure. When calculating the ratio of pressure to flux, the ratio increases with pressure, so the product also increases with pressure (the pressure increases at a higher rate than the flux decreases), as shown through the blue dotted trendline in Figure 35. Conversely, the pressure decreases faster than the flux increases, so a higher flux does not translate to higher power for these test conditions. This phenomenon is currently under investigation to better understand the results and presents an opportunity for future research.

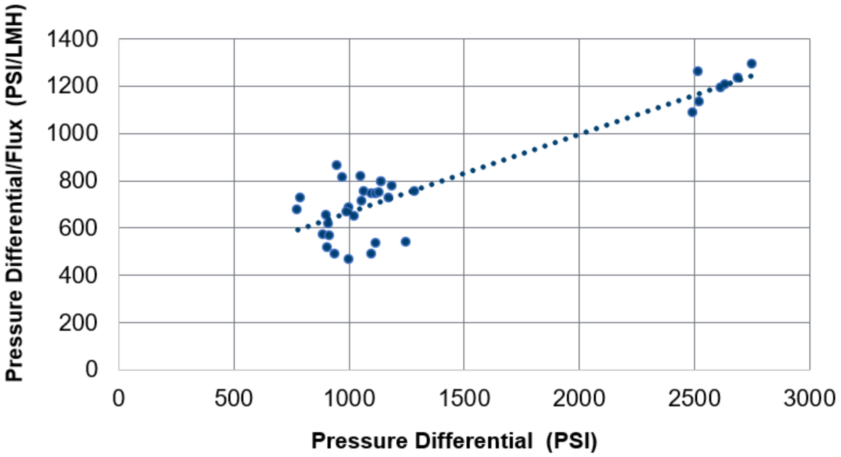
Figure 34: Variation of Power Output with Membrane Flux



Increased flux did translate to an increase in power output.

Source: T2M Global

Figure 35: Pressure Differential/Flux Ratio vs. Pressure Differential



The pressure differential to flux ratio increases with osmotic pressure.

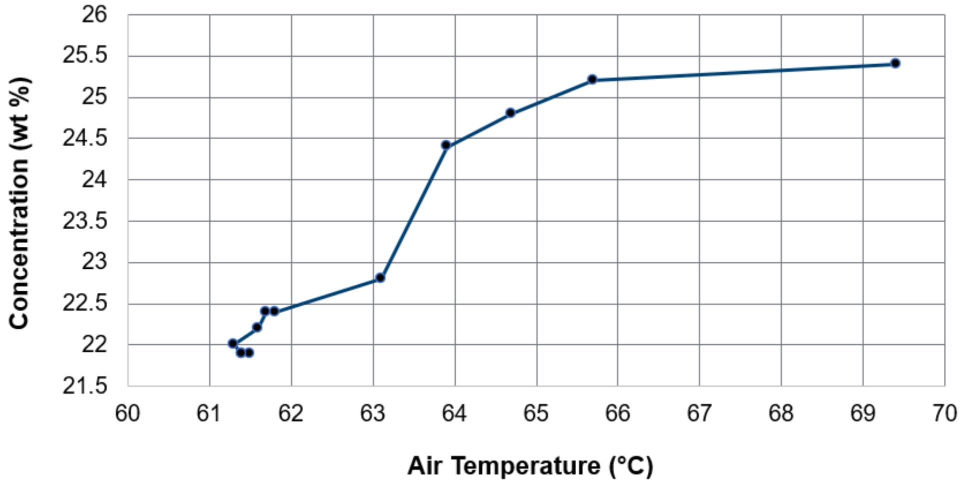
Source: T2M Global

Regeneration System

Development and testing efforts to optimize the working fluid for cost-effective regeneration were performed. The working fluid in this scenario is the solution formed by the diffusion of water across the membrane into the osmotic agent. This optimization effort included testing of the thermal regeneration system of the low-pressure spent working fluid. The heat supply to the thermal regeneration system and its physical interaction with the draw solution were systematically varied to study the impact of airflow direction and temperature on regeneration efficiency. Dilute draw solution at 20 percent weight concentration was fed to the regenerator and the concentration of the output was monitored.

The variation of draw solution concentration with the heat supply is shown in Figure 36. It shows an interesting trend with temperature, where below approximately 60˚C there is no material improvement in the concentration. However, there is a significant improvement between 63 to 66˚C, indicating that the source of waste heat needs to be in this temperature range to affect concentration. The test results also reveal a plateau at around 66˚C, indicating that there is no significant improvement to be gained at higher temperatures for the regeneration of the selected working fluid. The regeneration energy for the working fluid was measured for an ultrasonic low-temperature spray regeneration process. As anticipated, the energy requirement is slightly higher than other regeneration technologies. However, this system offers the unique advantage of operating at much lower temperature ranges (40 to 60˚C), where the waste heat is more abundant. The efficiency of the low-level waste heat is expected to be increased significantly at lower operating pressures.

Figure 36: Increased Draw Solution Concentration through Waste Heat



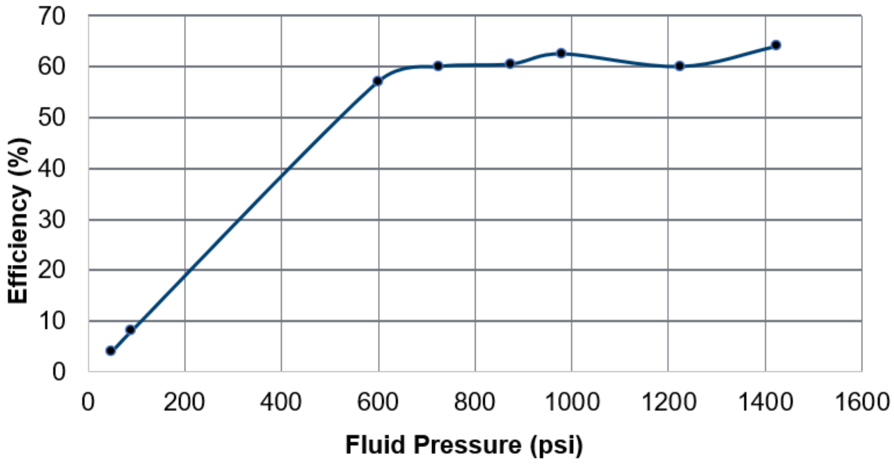
Highest improvement in concentration was observed at a waste heat temperature of ≥66˚C.

Source: T2M Global

Turbine Efficiency

Figure 37 indicates that the overall efficiency of the turbine and generator subassembly in the target operating range is around 60 percent. The stated efficiency for the turbine is 85 percent, and the alternator efficiency is 83 percent. Theoretically, this should result in a combined efficiency of 70 percent. Therefore, there is a 10 percent deviation between the expected and measured efficiency of the subsystem. This 10 percent deviation is currently under further investigation to determine the source. Because of supply chain constraints, the turbine's design has not been adapted to the specific requirements of the WHOP Engine. The team believes that with a custom-designed turbine, the overall efficiency of the subsystem can be increased considerably.

Figure 37: Water Turbine and Generator Subassembly Efficiency vs Pressure



The overall efficiency of the subassembly is around 60 percent.

Source: T2M Global

Technical Barriers and Challenges Faced in the Project

The WHOP Engine was a proof-of-concept project that explored unique concepts, and as such, there was little prior knowledge to build upon. The use of osmotic pressure across a semi-permeable membrane to generate power has been long understood; however, there has never been an attempt to take advantage of this knowledge in the way that the WHOP Engine does. To achieve the desired results, dozens of osmotic agents failed evaluation before the team discovered one that was not only capable of producing the required osmotic pressure, but also capable of being regenerated through many heating cycles. The development of a membrane that can withstand 1,000 psi is another new frontier. Where original commercial membranes could only withstand 200 psi, improvements in the membrane geometry and material chemistry as well as development of the supply chain allowed for the pressure capacity to be increased to 1,000 psi. This enabled successful demonstration of the kW-class WHOP Engine. Additional increases in membrane pressure capability could help to further improve WHOP Engine performance and efficiency.

The development of a suitable regeneration system represented a challenge due to its inherent interconnection with the chosen osmotic agent. Different approaches to regeneration were investigated during this project. Scale-up of the regeneration system would be needed to meet the needs of a larger WHOP Engine.

The COVID pandemic-related supply chain challenges were also a major barrier during development, and in many cases normally non-issues became problems to be solved such as:

- Extremely limited availability of suppliers.
- Lack of guidance from qualified application engineers at supplier facilities.
- Prohibitively higher component costs for the proof-of-concept assembly.
- Uncertainty in projecting capital cost for volume production.
- Uncertainty in manufacturing equipment design and supply.
- Budget uncertainty for the proof-of-concept.
- Budget uncertainty for early production units and mass production units.

The WHOP Engine requires components that are currently unavailable in the existing supply chain. This is primarily due to a mismatch in the size and functionality that lead to higher parasitic losses at smaller scales, such as the kW-class level. The kW-class system components are significantly smaller than commercial systems, which typically are up to 1,000 times larger.

Several more challenges were then faced in the scale-up from 6 Watts to 6,000 Watts. Some of these challenges include non-reproducibility of data and rapid degradation in the quality of the working fluid. To overcome these challenges, a customized facility, as shown in Figure 38, was developed, and designed to simulate the WHOP system operating environment and prequalify system components.

Figure 38: Customized Facility for Membrane Module Quality Assurance

Up to 1000 psi pressure capability.

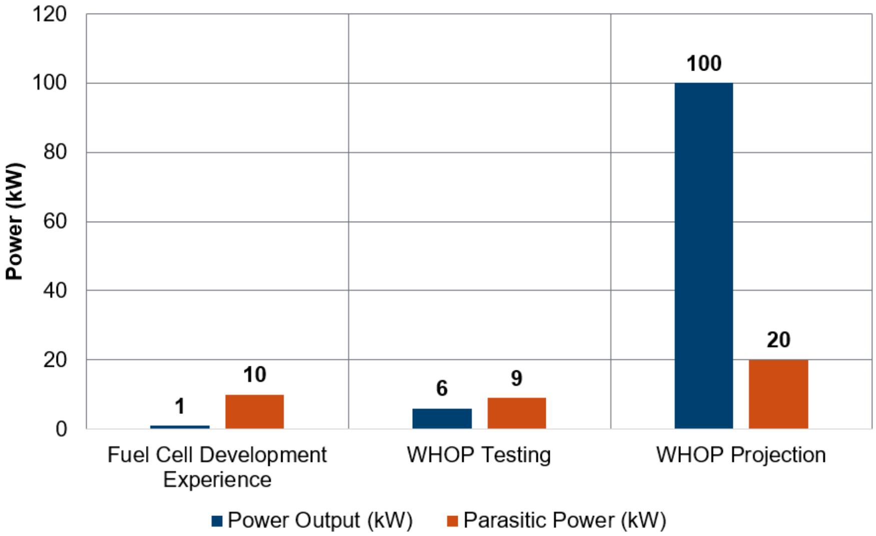
Source: T2M Global

Key Information Learned

For the larger system (6kW to 100 kW), once all the system parasitic losses are accounted for, the net electrical power output from the WHOP system increases significantly, as shown in Figure 39. Evaluation of the kW-class engine was critical in assessing sources of parasitic losses to account for them upon scale-up to the 100 kW-class WHOP Engine. Information learned regarding these parasitic losses includes:

- Un-optimized membrane operation with the selected working fluid resulted in reduced membrane flux at the elevated pressure in the 10-inch membranes.
- High-power consumption in off-the-shelf components that are operating at sub-optimal conditions (i.e., pumps, turbine, and generator) can be corrected when designing components for the 100 kW-class model.
- Heat transfer driving force for the low-level waste heat is an important factor for reaching WHOP efficiency targets. It can be improved by integrating the T2M team's Plastic Heat Exchanger (P-HEX), which is developing rapidly in a parallel CEC program.

Figure 39: WHOP Engine Power Output vs Parasitic Losses



Improvements in parasitic losses for larger WHOP Engines will lead to a higher efficiency.

Source: T2M Global

Future Research and Development Opportunities

There are many opportunities to optimize and improve upon the WHOP Engine's capabilities. The improvements include further optimization of the membrane design, additional research into the regenerative capabilities and stability of the working fluid, optimization of the hydroturbine to further improve efficiency, optimization of the draw solution, as well as the integration of more efficient plastic heat exchangers (P-HEX).

- **Membrane Optimization:** For further scaleup and commercialization of WHOP, membrane flux capacity of two LMH at the desired hydraulic pressure delivered to the inlet of the hydroturbine will be essential. To address this, membrane design will need to be optimized via factors such as pore size, differential pressure, various operational modes, membrane material chemistry and morphology, and the appropriate supply chains.
- **Working Fluid:** The physical, chemical, and osmotic cycle stability are critical for the long operating life of the osmotic engine. The retention of the osmotic potential in the concentrated working fluid and its ability to separate from water over thousands of repeated cycles will be the key to the techno-economic feasibility of the WHOP Engine. Long-term cycle testing must be conducted to assess the osmotic agents' stability.
- **Hydroturbine:** Due to the small scale of this WHOP Engine resulting in low turbine flow rates and a high hydraulic pressure, an off-the-shelf hydroturbine sized for this application was unavailable. This resulted in the selection of a turbine that was not operating near its ideal efficiency point. Future scale-up of the WHOP system will expand the supply chain options for suitably sized hydroturbines and lead to increased efficiency, system power output and performance.
- **P-HEX Integration for Greater Efficiency and Lower Cost Electricity:** The high capital cost of recovering low-level heat can be eliminated by integrating T2M's novel

P-HEX into the WHOP system. A key factor in cost-effective conversion of low-level waste heat to electricity is to capture the low-level heat economically. P-HEX has the potential to recover industrial low-level waste heat with up to 80 percent efficiency at approximately 1/10th the weight of an equivalent Metallic Heat Exchanger; thereby, reducing capital expenses by more than 80 percent. A baseline P-HEX has already been developed, and laboratory tested (Figure 40) that will need to be assessed and modified as necessary for material compatibility and heat transfer properties required for integration into the WHOP system design.

Figure 40: P-HEX developed and validated in parallel CEC and DOE Programs

P-HEX with up to 80 percent recovery ensures target WHOP Engine efficiency.

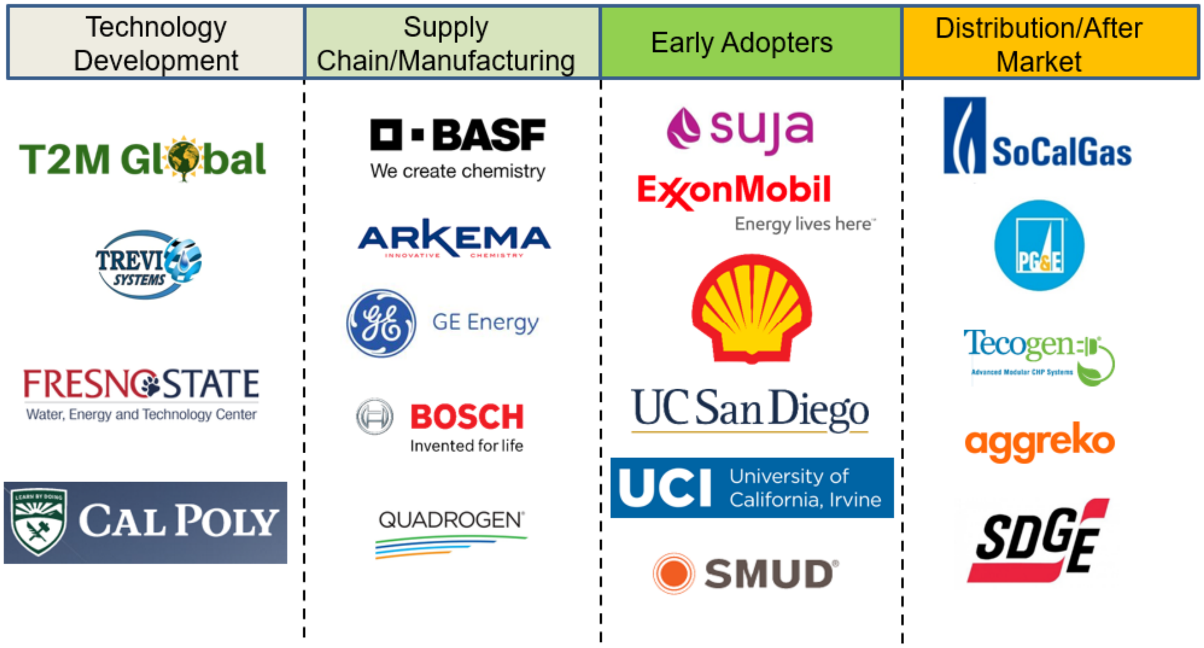
Source: T2M Global

- **Optimization of Draw Solution:** Although using a 50 percent SD solution increases the flux and water gain, and is practical in the WHOP front end, a higher concentration will require additional waste heat in the regeneration system. This is likely to affect the overall WHOP efficiency; however, most industrial sites have abundant low-level waste heat that can be used. This provides another avenue to further analyze and optimize the draw solution for WHOP development and scaleup in the future.
- **Open-Loop System:** The current iteration of the WHOP Engine is a closed loop system. Future iterations may include an open loop system that further reduces energy or waste heat needs for the host site to significantly increase efficiency.

Market Opportunities for the WHOP

T2M's outreach for collaboration with key industries, supply chain, and utilities has identified early deployment opportunities for WHOP Engines, Figure 41. One such opportunity is leveraging the synergy between WHOP technology and the hydrogen (H_2) production and fuel cell industries. This synergy is caused by the WHOP Engine's ability to improve H_2 production and fuel cell efficiency by up to 25 percent by converting wasted low-level heat to higher value, emission-free electricity. The T2M team has experience in working with many California utilities that have shown interest in the WHOP Engine. Among major hydrogen producers in California, T2M has working experience with Air Products and Chemicals, Air Liquide, and Linde-Praxair. Among refineries, T2M's collaborative experience includes Tesoro, Chevron, Exxon, and Shell. Among major fuel cell vehicle developers, T2M's interactions include hydrogen infrastructure solutions for GM in Hawaii, as well as Toyota and Honda in California.

Figure 41: Ecosystem for WHOP Engine Commercialization



Outreach to key players to meet highly customized supply chain needs.

Source: T2M Global

In addition, an Oak Ridge National Lab report assessing the waste heat to power market potential was especially useful in identifying market opportunities for low-level waste heat use in the manufacturing sector. Valuable insight was obtained such as the waste heat availability by industry in the United States as shown in Table 1. If all the available low-level waste heat (less than 300°F or about 150°C) were used by the WHOP Engine, the estimated cost savings would be greater than $5 billion per year.

Table 1: Manufacturing Sector Waste Heat by Industry

Industry	Energy Content (TBtu/yr) by temperature range (˚F)				
	<300	300-450	450-1200	>1200	**Total**
311: Food Manufacturing	3.7	28.3	19.2	-	**51.3**
312: Beverage and Tobacco Product Manufacturing	0.2	1.6	0.2	-	**2**
313: Textile Mills	10.3	1.9	0.4	-	**12.6**
315: Apparel Manufacturing	1.1	-	-	-	**1.1**
321: Wood Product Manufacturing	46.8	42.8	4.4	-	**94.0**
322: Paper Manufacturing	50.3	97.0	5.3	-	**152.6**
323: Printing and Related Support Activities	15.5	3.2	3.4	1.1	**23.2**
324: Petroleum and Coal Products Manufacturing	86.4	114.2	658.1	5.6	**864.3**
325: Chemical Manufacturing	112.8	80.4	108.3	22.9	**324.4**
326: Plastics and Rubber Products Manufacturing	7.9	2.4	0.6	0.5	**11.4**
327: Nonmetallic Mineral Product Manufacturing	19.5	48.1	105.7	18.9	**192.1**
331: Primary Metal Manufacturing	142.7	56.8	7.2	87.2	**293.9**
332: Fabricated Metal Product Manufacturing	49.5	114.8	9.8	-	**174.1**
333: Machinery Manufacturing	7.4	5.7	1.3	-	**14.4**
334: Computer & Electronic Product Manufacturing	3.1	2.2	-	-	**5.3**
335: Electrical Equipment Manufacturing	2	1.4	0.3	-	**3.6**
336: Transportation Equipment Manufacturing	6.2	7.4	1.1	-	**14.7**
337: Furniture & Related Product Manufacturing	2.1	1.9	0.5	0.1	**4.6**
339: Misc. Manufacturing	2.1	2	0.5	0.1	**4.8**
Total Energy Content (Tbtu/yr)	**570**	**612**	**926**	**136**	**2,245**

The market for waste heat beneficial use is large.

Source: Waste Heat to Power Market Assessment[4]

Table 2 depicts the potential market for the WHOP Engine in the United States, as well as its addressable market and the amount of 100 kW units required to fulfill these needs. Because there is currently no direct competition in this market, it can be assumed that the WHOP Engine has the potential to reach the entire addressable market.

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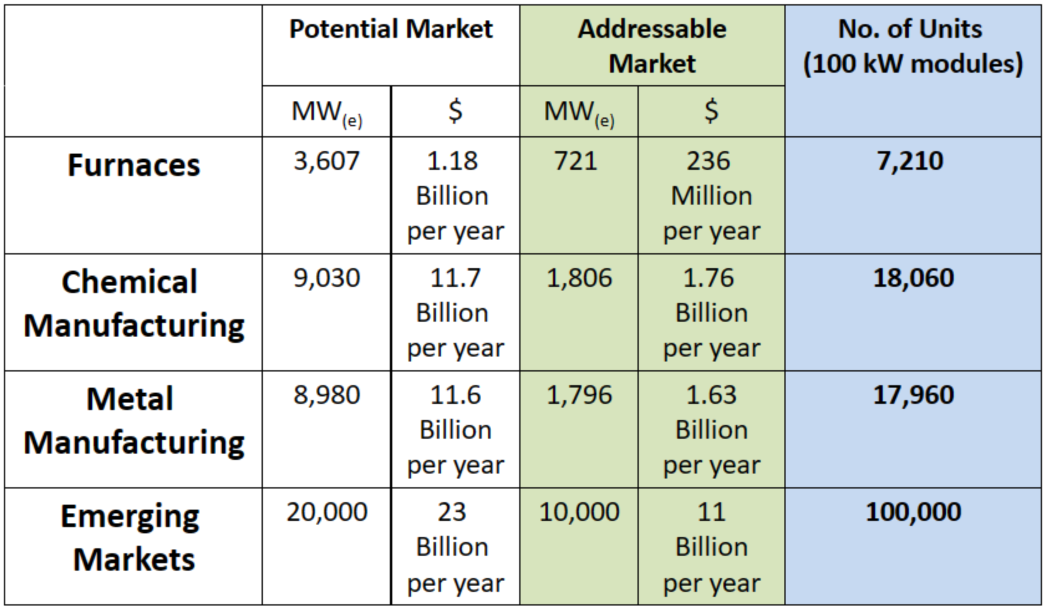
[4] "Waste Heat to Power Market Assessment". United States. https://doi.org/10.2172/1185773. U.S. DOE

Table 2: WHOP Market Opportunity and Growth



	Potential Market		Addressable Market		No. of Units (100 kW modules)
	MW$_{(e)}$	$	MW$_{(e)}$	$	
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**

WHOP technology will enable California to meet its 2045 100% renewable goal.

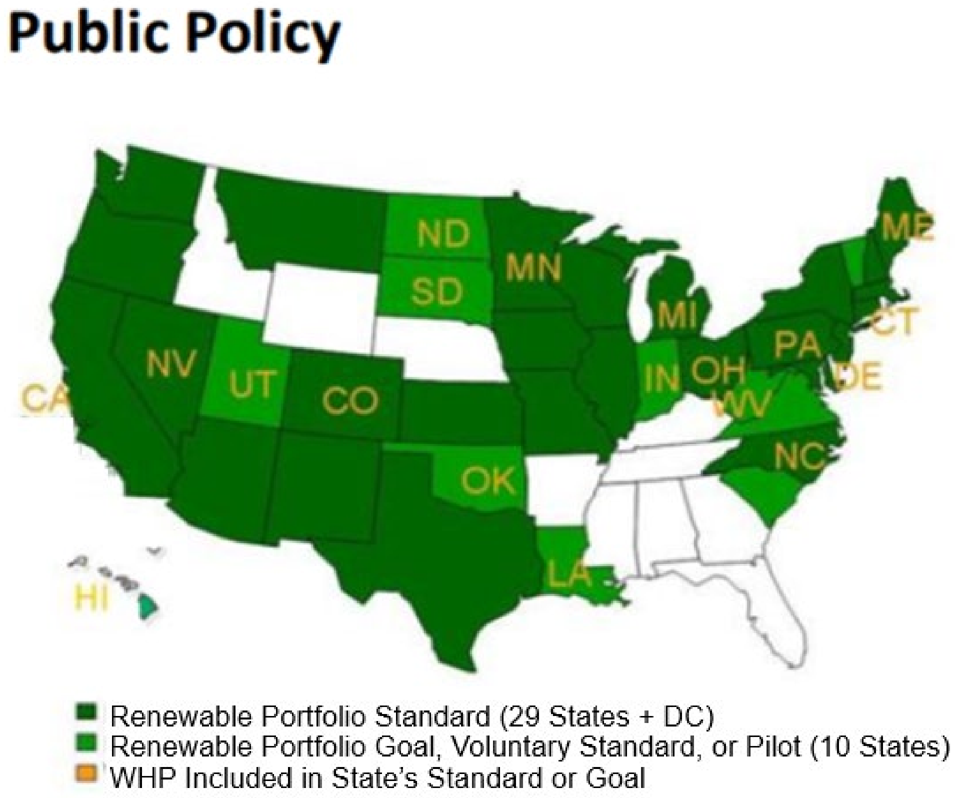
Source: T2M Global

Policy Barriers

Because the WHOP system produces no criteria pollutant emissions, the team expects to receive a blanket permit for rapid deployment following the CEC demonstration project. This demonstration entailed a California Environmental Quality Act document to be completed using data from the project and shared with California Air Resources Board (CARB) and the Air Quality Management District (AQMD) to verify no direct pollutant emissions.

While GHG and criteria pollutant emissions are not an issue for the WHOP Engine, currently, clean electricity derived from waste heat is not deemed as renewable. Additionally, carbon credits are not available for clean energy projects that make use of stranded resources produced through non-green methods. The WHOP Engine is such a case where wasted thermal energy may be recycled with no incremental CO_2 emission production. To this end, the team contacted CARB and it was to modify the policy to include electricity generated from wasted resources as renewable energy. Figure 42 depicts the progress that states nationwide have made towards a renewable portfolio standard (RPS). Of note is the fact that while California does include waste-heat to power (WHP) in the self-generation incentive program, it is not included in the RPS.

Figure 42: State Renewable Portfolio Standards that Emphasize WHP



Outreach to policymakers to support deployment of emission-free WHOP Engine is needed.

Importance of WHOP to California's Clean Energy and Climate Goals

The use of wasted resources such as low-level heat is a vital step in achieving California's clean energy goals, while providing the energy security needed to thrive. Several ways that the WHOP Engine can help California to achieve its goals include:

- **Carbon Footprint Reduction:** Reducing power purchased from the grid will significantly decrease the Host Site's carbon footprint – a crucial step toward carbon-neutral production. Assuming approximately 1 lb of CO_2 per kWh of conventional power generation,[5] the total GHG savings would be about 7 million metric tons of CO_2 per year in California. Nationwide there is a potential to reduce CO_2 emissions by over 100 million metric tons per year as depicted in Figure 43.
- **Energy Security:** Part of the Host Site's power needs can be met by the WHOP system, thereby reducing its drain on grid electricity. Electricity from WHOP can also be used to power a facilities' critical bus to maintain essential operations during a grid power outage. This has the potential to reduce or eliminate the need for highly polluting, noisy, and maintenance-intensive diesel backup generators.

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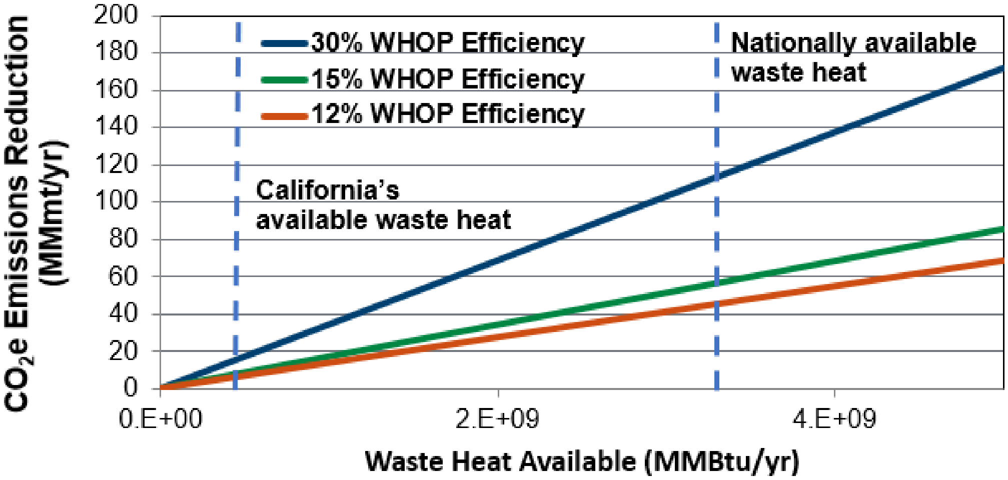
[5] U.S. Energy Information Administration (EIA) - https://www.eia.gov/tools/faqs/faq.php?id=74&t=11.

- **Supporting Intermittent Renewables:** The WHOP system has the potential to support the intermittency of solar and wind, as well as provide resiliency against natural disasters.

Figure 43: WHOP Engine CO_2 Equivalents Emission Reduction



Promises significant benefits toward climate change objectives upon wider deployment.

Source: T2M Global

CHAPTER 4: Conclusion

Currently, low-level heat is an expensive wasted resource at many industrial plants and commercial buildings. Approximately 7.5 quads/year of industrial processes and 5 quads/year of on-site steam production contribute to more than 300 million metric tons of on-site CO_2 emissions annually in the United States, with around 2.1 quads of that energy being lost as low-level waste heat. The WHOP Engine provides a means, at competitive costs, of efficiently converting this low-level waste heat to electricity with no additional GHG or harmful emissions, rendering greater sustainability to industrial operations, and relief to the utility grid.

This project has successfully shown that osmotic pressure can be converted into hydraulic pressure and energy before regenerating the osmotic potential of the working fluid. All of the necessary systems have been checked and proven effective including an innovative osmotic agent regeneration system. Upon commercialization, the WHOP Engine promises significantly lower electricity costs than conventional heat engines and existing solid-state generators such as piezo-electric.

The WHOP Engine exploits severely underused markets, harvesting solar-thermal, geothermal, and industrial waste-heat to synergistically support California's transition to a zero-emission economy. Successful implementation of this innovative technology will allow the production of clean energy that produces no GHGs, while removing strain from local grids and supporting the intermittent nature of other sources of clean energy such as solar and wind. Additionally, this technology will serve to provide benefits to surrounding communities, especially disadvantaged and environmental justice communities by reducing emissions of harmful pollutants. This will lead to lower hospitalization rates while creating new high-quality job opportunities.

Currently, incentives exist on the state and federal level for emission-free electricity. Low carbon fuel standard credits exist for the oil refineries and production facilities that can benefit from the WHOP Engine upon its successful scale-up and commercialization. Additionally, Renewable Identification Numbers are credits used for compliance with clean energy goals and are the currency of the EPA's renewable fuel standard program. Renewable energy certificates are also available upon the large-scale deployment of WHOP Engines where clean energy returned to the grid can become a source of profit.

While the WHOP Engine produces no incremental carbon emissions or criteria pollutants, the current carbon credits policy requires updating regarding recycled waste heat. At this point in time, carbon credits are not available for energy produced if natural gas or oil was used in its production, even if this energy repurposes an existing wasted resource. Additionally, California's current RPS do not include power from waste heat as renewable energy. T2M Global has worked extensively to raise awareness and challenge these policies to include electricity generated from wasted resources as renewable electricity.

Biogas and renewable natural gas (RNG) producers were identified as the initial Customer Segment. This is because of a combination of internal connections, a motivated research and development push to decrease the RNG production price in California, and the fact that the waste heat is in a range (less than 120°C) that is only usable by T2M's technology. Beyond biogas and RNG producers, there is also a vast market potential for low-level waste heat utilization in the manufacturing sector. Examples include industrial cement and asphalt producers, metal treatment and production facilities, as well as food processors and refrigeration companies. A strong demand for this technology is anticipated, with high availability of customer capital to purchase the systems, and minimal competition from other waste-to-power technologies.

While there were lessons learned along the way, the challenges opened paths for future innovation in many vital fields. The developments made in membrane technology have provided great opportunities in critical fields such as water purification and desalination. Out of the dozens of osmotic agents investigated, many different properties and applications have been uncovered. In particular, there is room for further investigation into the potential of CO_2-philics to capture and store atmospheric CO_2. Further work on WHOP technology may revisit some of these past challenges under a new light in order to improve the WHOP Engine capabilities.

There are many opportunities to optimize and improve upon the WHOP Engine's capabilities in the future. These improvements include further optimization of the membrane design, additional research into the regenerative capabilities and stability of the working fluid, optimization of the hydroturbine to further improve efficiency, an optimization of the draw solution, as well as the integration of more efficient plastic heat exchangers. In the short term, development is expected to focus on improvements to the working fluid to reduce the required heat of vaporization as well as further improvements upon the membrane technology to increase both flux and the pressure tolerance. Long term research will approach alternative osmotic agents and potentially reopen the investigation into CO_2-philic polymers, as they show great promise to further increase efficiency when an appropriately stable compound is discovered.

Investigation into the WHOP cycle is expected to continue as the module is scaled up to the 100 kW-class. The information gained and the progress made during this project were vital steps in learning how to harness an overlooked wasted resource in order to meet California's, and the nations, clean energy goals. When the WHOP Engine reaches full-scale production, it is expected to play a large role in revolutionizing the way energy is produced and waste heat is managed.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
¢	cents
AC	Alternating Current
AQMD	Air Quality Management District
BTU	British Thermal Unit (1 kWh = 3413 BTU)
CARB	California Air Resources Board
CEC	California Energy Commission
CO_2	Carbon Dioxide
DOE	Department of Energy
GHG	Greenhouse Gasses
GPM	Gallons per Minute (a measurement of flow rate)
kWh	Kilowatt Hour (a measurement of energy)
LMH	Liters per Hour per Meter Squared (a measurement of flux)
MM	Million
NOx	Nitrogen Oxides
P-HEX	Plastic Heat Exchanger
PLC	Programmable Logic Controller
psi	Pounds per Square Inch (a measurement of pressure)
Quad	One Quadrillion BTU
RNG	Renewable Natural Gas
RPS	Renewable Portfolio Standard
SD	Strong Draw
SOx	Sulfur Oxides
W / kW / MW	Watt / Kilowatt / Megawatt (1 MW = 1000 kW / 1 kW = 1000 W)
WHOP	Waste Heat to Osmotic Pressure

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Frequently Asked Questions (FAQs) - https://www.eia.gov/tools/faqs/faq.php?id=74&t=11. U.S. Energy Information Administration (EIA)