COLORADO
Higher Education Competitive Research Authority

March 1, 2026

Honorable Members of the House and Senate Education Committees
State Capitol
200 East Colfax
Denver, Colorado 80203

Re: Annual Report of the Colorado Higher Education Competitive Research Authority (CHECRA)

Dear Representatives and Senators:

Colorado Revised Statutes §23-19.7-103(3) requires the Colorado Higher Education Competitive Research Authority (CHECRA), housed at the Colorado Department of Higher Education, to report annually to the Education Committees of the Colorado House of Representatives and Senate on research projects funded by CHECRA in the previous calendar year. This letter reports on activities and projects funded in the calendar year 2025. This includes multi-year projects that received continued funding in 2025, and new initiatives funded for the first time in 2025.

CHECRA was created to provide a source of matching funds for National Science Foundation (NSF), U.S. Department of Energy, and other competitive federal grants that require or are more competitive with a state match. CHECRA funding has helped to bring significant research dollars to Colorado. Funding is used both to support large, multi-year research center initiatives, including Engineering Research Centers (ERCs) and Science and Technology Centers (STCs), and for single year research projects that are part of larger, multi-institution initiatives.

In 2025, CHECRA spent $2,105,950 to support eight research projects. Those 8 projects show a 1:10 direct economic benefit for Colorado. That is, the total funding received from federal agencies over the projects' lifetime is ten times the amount provided by CHECRA over the same period. Additional administrative costs totaled $19,600. The Authority received a single distribution of Limited Gaming Funds of $2.1 million and interest earnings on the Authority's funds totaled $42,826 in 2025.

Following is a list of the multi-year research grants that received CHECRA funding in 2024. Appendices to this report include detailed information on each of the projects.

University of Colorado (CU)

- Quantum Systems Through Entangled Science and Engineering (Q-SEnSE) is one of several NSF Quantum Leap Challenge Institutes, which are multi-organizational interdisciplinary collaborations designed to ensure the United States retains global leadership in quantum information science. Q-SEnSE includes extensive collaborations with leaders from other academic institutions in the US and Europe, NIST, National Laboratories, and industry to make broad, fundamental advances in quantum science and engineering. CHECRA initially pledged $400,000 annually for five years and then pledged funding for a one-year extension. 2025 was the final year of funding for Q-SEnSE.

- The NSF-funded Center for Integration of Modern Optoelectronics Materials on Demand STC, funded by the National Science Foundation, is helping to develop new classes of optoelectronic materials, devices, and systems. These devices underpin the modern information technology era and society is increasingly reliant on them for efficient lighting, information display, and optical data transmission. CHECRA made the final of five annual payments of $200,000 in 2025.
- The University of Colorado Boulder received a grant from NSF in 2024 to launch a facility known as the National Quantum Nanofab (NQN). In this facility, Colorado researchers and quantum specialists from around the country are designing and building incredibly small devices that tap into the world of atoms and photons—the tiny packets of energy that make up light. CHECRA made the second of five payments of $175,000 in 2025.

Colorado State University (CSU) and University of Colorado

- The NSF-funded ASPIRE ERC is a collaborative venture between CU and CSU (and other universities). The mission of ASPIRE is to improve the health and quality of life for Coloradans by catalyzing sustainable and equitable electrification across the transportation industries, using a holistic approach to eliminate range and charging as barriers to electric vehicle use. CHECRA made the final of five payments of $325,000 to CU and 4th of 5 payments of $75,000 to CSU in 2025.

Colorado State University (CSU)

- Formally known as the Colorado-Wyoming Climate Resilience Engine (CO-WY Engine), this program is now called the NSF Advanced Sensing and Computation for Environmental Decision-Making (ASCEND) Engine in Colorado and Wyoming. ASCEND is a collaborative initiative focused on driving innovation in climate resiliency across the Colorado-Wyoming region. ASCEND brings together a diverse network of partners to develop and commercialize technologies that address critical community resiliency challenges, foster economic growth, and enhance community well-being. CHECRA provided the second of 10 payments of $500,000 in 2025.

Colorado School of Mines

- The DOE-funded Flexible Hybrid SOFC CHP System using Low Carbon Fuels project is aimed at reducing greenhouse gas (GHG) emissions and accelerating the development of innovative decarbonization technologies. The project has included engagement with underrepresented groups through partnership with the Society of Hispanic Professional Engineers and other minority-serving structures. CHECRA provided the second of three payments of $133,000 in 2025.

The National Alliance for Water Innovation (NAWI)

NAWI brings together numerous federal laboratories, institutions, and others focused on reducing the cost, greenhouse gas emissions, and energy associated with desalinization. Colorado institutions participate in NAWI with specific research projects. CHECRA supported two NAWI projects at the School of Mines, both of which were in their second and final year. These projects focus on potable reuse of reclaimed water and improved desalinization. CHECRA provided payments of $38,050 and $59,900 on the two projects for a total of $ 97,950.

Benefits to Colorado

In addition to the millions of dollars in federal funding coming into the institutions and the state—and the impressive scientific results achieved under the projects—the research funded by CHECRA has many benefits to Colorado. These benefits include support for graduate and undergraduate students, outreach to K-12 students and teachers, and economic development benefits from spin-off technologies and companies.

Following are some highlights of these benefits from the research funded in 2024.

- Tools developed in the School of Mines' demonstration system will be adopted by Colorado utilities (both water and wastewater treatment facilities) and can be adapted to many other industries.
- Q-SEnSE is contributing to making Colorado a quantum leader. The high level of scholarly output and accessibility accelerates innovation, supports workforce training, and reinforces Colorado and U.S. leadership in quantum science by enabling rapid knowledge transfer across the broader research and technology community. The program also expanded K–12 and public engagement through the widely accessible PhET Quantum Measurement simulations, enabling high school students and the science-curious public to conduct interactive, math-free quantum experiments online.
- The ASCEND Engine brings many benefits to Colorado, including the following:
    - ASCEND focuses on developing and deploying technologies that help Colorado communities anticipate and reduce environmental risks, such as wildfire damage, water system disruptions, and air quality impacts. The goal is to shift from reacting to disasters toward earlier, smarter, and more cost-effective planning and prevention.
    - A major objective of ASCEND is to grow Colorado's clean-tech and environmental technology economy. The Engine supports startups and expanding companies, helps attract private investment, and connects entrepreneurs with customers and partners – resulting in new Colorado-based jobs and business growth.
    - ASCEND invests in workforce development and training programs so that

Colorado students, workers, and career-changers can access jobs in environmental technology, data, engineering, and related fields. These efforts are designed to ensure that Colorado employers can find skilled talent locally and that residents benefit directly from the growing innovation economy.

Thank you for your support of this ongoing research. We welcome any questions.

Sincerely,

Inta Morris
CHECRA Secretary, on behalf of the CHECRA Board

Appendices

Appendix A:	Q-SEnSE (University of Colorado Boulder)
Appendix B:	Optoelectronics Science and Technology Center (University of Colorado Boulder)
Appendix C:	National Quantum Nanofab (University of Colorado Boulder)
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Appendix A: Q-SEnSE (University of Colorado Boulder)

Principal Investigator: Jun Ye
Period of Performance: 09/01/2024 – 08/31/2025
Funding from Federal Agency: National Science Foundation
CHECRA Funding (total/total in 2025): $2,600,000/ $600,000

Project Summary

As an NSF-sponsored Quantum Leap Challenge Institute, Q-SEnSE has a primary mission of advancing and realizing true quantum advantage in sensing and measurement through collaboration among experts in fundamental physics and applied engineering. Established in 2020 with the leadership of JILA, a joint institute of NIST and the University of Colorado, Q-SEnSE currently comprises 44 senior investigators at 11 universities, 2 National Labs, one National Institute, and one FFRDC. Overall strategy and direction are coordinated through a representative Executive Committee led by Principal Investigator Jun Ye and including a Deputy for Science and Research Convergence, a Director for Education and Workforce Development, and a Director for Operations.

Research projects are organized around three Grand Challenges.

Grand Challenge 1: Develop Quantum Advantage in Sensing and Measurement. A unique design feature of our Center is exploitation of the fundamental connection between emerging quantum technology and frontiers of physical sciences, with Center investigators performing pioneering theory and experimental studies on entangled quantum states to demonstrate genuine quantum advantage in quantum sensing and measurement systems. We broadly explore, engineer, and apply many-body quantum states to protect quantum coherence and accuracy, optimize entanglement for measurement, and build inter-system connections for distributed sensing.

Grand Challenge 2: Develop Field-Deployable and Distributed Sensing and Measurement Systems. To facilitate and hasten new quantum technologies for practical applications, we are developing systems with advanced integration, measurement, and interconnectivity capabilities robust enough to be deployed in the field. Examples include integrated systems such as optical atomic clocks, matter-wave interferometers, magnetometers, chip-scale-nonlinear-photonics, optical frequency combs, and distributed sensing networks.

Grand Challenge 3: Create a National Quantum Infrastructure for Sensing and Measurement: Case Study – Strontium. To provide a lasting impact for a quantum ecosystem, a unique Center goal is development of robust, cost-effective, and standardized tools that provide synergy across multiple practical implementations. With multiple leading research groups working with alkaline earth atoms such as Sr, we exchange information to allow rapid tool development, technology maturation, and dissemination. We aim to develop and distribute these tools to a broad user community through coordinated partnerships among universities, National Laboratories, NIST, and industry partners.

Spanning those Grand Challenges is a fourth major goal: Design and establish mechanisms to introduce undergraduate and master's level students to the principles and practices of quantum science and engineering in a team setting and prepare those individuals for productive entry into an economy that has begun to recognize, pursue, and take advantage of, the promise of those fields. This ambitious research program has the potential for transformative extensions of quantum sensing for new basic physics (detection and characterization of dark matter, dark energy, and matter-antimatter asymmetry); for applications of quantum technologies to areas of practical importance (quantum communications and networking); and for establishing, and hastening use of, standards for quantum tools for academia and industry. We also seek strong impact of quantum technology on many different scientific fields, including some of which are yet to be imagined.

We are implementing concrete ideas to train the next generation of the quantum workforce, spanning new undergraduate and postgraduate degrees, new educational modules for two-year colleges, and internships or summer schools with emphasis on introducing underserved minorities to the educational and professional opportunities in quantum science and engineering.

Results Achieved:

Representative Milestones for 2025 - Research

Ye & Safronova, "*Frequency ratio of the ^{229m}Th nuclear isomeric transition and the ^{87}Sr atomic clock* ", Nature 633, 63-70 (2024). DOI: 10.1038/s41586-024-07839-6; "*$^{229}ThF_4$ thin films for solid-state nuclear clocks* ", Nature 633, 63-70 (2024). DOI: 10.1038/s41586-024-08256-5; "*Temperature Sensitivity of a Thorium-229 Solid-State Nuclear Clock* ", Phys. Rev. Lett. 134, 113801, DOI: 10.1103/PhysRevLett.134.113801; "*Fine-structure constant sensitivity of the Th-229 nuclear clock transition*," arXiv:2407.17300 (2024), DOI: 10.48550/arXiv.2407.17300

Science:

- Nuclear quadrupole-state-resolved optical transition in Th-229
- 12-digit frequency ratio of 229mTh nuclear isomeric transition and 87Sr atomic clock
- Ground and excited state nuclear volume difference determined for 1st time
- Measured temperature sensitivity of Th solid-state nuclear clock

Impact:

- "Dawn of the nuclear clock"
- Sensitivity of Th-229 nuclear clock transition to fine-structure constant allows dark matter search via nuclear transition

Sinclair & Newbury, "Application of Quantum-limited Optical Time Transfer to Space-Based Optical Clock Comparisons and Coherent Networks", APL Photonics 9, 016112 (2024), DOI: 10.1063/5.0170107; "Compact dual comb time-transfer and ranging for future space-based distributed sensing", Applied Optics, in Press (2025), DOI: 10.1364/AO.559584.

Science:

- State-of-the-art optical time transfer and phase-coherent network for distributed sensing
- Quantum-limited optical time transfer tolerates losses from long ground-to-space links
- Compact dual-frequency comb system for both optical ranging and time transfer

Impact:

- Free-space time transfer; intercontinental clock comparisons for time dissemination and coherence transfer
- Implementation on mobile platforms and future space systems

Diddams, Combes & Rieker, "Squeezed dual-comb spectroscopy", Science 387, 653-658 (2025), DOI: 10.1126/science.ads6292; "GHz repetition rate mid-infrared frequency comb spectroscopy of fast chemical reactions", Optica 11, 876-882 (2024), DOI: 10.1364/OPTICA.521

Science:

- 1-GHz repetition rate frequency comb centered at 1560 nm amplitude-squeezed by > 3dB over 2.5-terahertz bandwidth achieved mode-resolved spectroscopy of H_2S gas with S/N ratio surpassing shot-noise limit
- High-speed, broadband, mid-infrared dual frequency comb absorption spectrometer to quantify abundances and temperatures of chemical species throughout rection cycle

Impact:

- Wide applicability of broadband, high-resolution spectroscopy
- Sense multiple species in dynamic chemical environments

Thompson, Rey & Ye, "Two-axis twisting using Floquet-engineered XYZ spin models with polar molecules", Nature 633, 332-337 (2024), DOI: 10.1038/s41586-024-07883-2;

"Hamiltonian engineering of collective XYZ spin models in an optical cavity", Nature Phys, April 15 (2025), DOI: 10.1038/s41567-025-02866-0.

Science:

- First-time observation of mean-field dynamics under two-axis twisting Hamiltonian
- Floquet engineering techniques to tune interactions between ultracold molecules trapped in optical lattice
- Cavity QED-mediated two-axis twisting model realized for spin-squeezed states aiming for Heisenberg limit on phase estimation

Impact:

- Enhance sensitivity of precision measurement experiments

Regal & Knappe, " Investigating the hyperfine systematic error and relative phase in low-spin-polarization alkali-metal free-induction-decay magnetometers", Phys. Rev. A 111, 033106 (2025), DOI: 10.1103/PhysRevA.111.033106

Science:

- Vapor cell-based alkali-metal optically pumped magnetometers
- Two complementary methods to mitigate systematic error from overlaps of ground-state hyperfine Zeeman resonances
- 3.5-fold improvement across wide range of spin polarizations

Impact:

- Enhanced sensitivity for lab-based magnetometry

Lewandowski, "Student reasoning about quantum mechanics while working with physical experiments", Phys. Rev. Phys. Edu. Res. 20, 020135 (2024), DOI: 10.1103/PhysRevPhysEducRes.20.020135

Science:

- Novel methods to research effectiveness of quantum education
- Physical apparatus demonstrating quantum phenomena to overcome student aversion to abstract mathematics
- Analyzed in-the-moment thinking to identify how students reason through experimental evidence of single-photon interference

Impact:

- Improved quantum education based on rigorous research
- Help teachers guide students to understand quantum topics through their own ideas and lab activities.

Hume, Leibrandt & Ye, " High-Stability Single-Ion Clock with 5.5×10^{-19} Systematic Uncertainty", Phys. Rev. Lett., submitted; arXiv:2504.13071, DOI: 10.48550/arXiv.2504.13071.

Science:

- Best laser frequency stability by a cryogenic silicon cavity delivered over 2 km
- Single ion clock frequency stability of 3.5×10^{-16} at 1 s; systematic uncertainty of 5.5×10^{-19}
- Systematic uncertainties reduced by novel ion trap electrical design with lower excess micromotion, better vacuum with lower collisional shifts

Impact:

- Enables extended coherence time for the Al^{+} single ion clock
- Expands potential for transportable, ultra-precise clocks

Holland, Rey & Thompson, "Entangled matter waves for quantum enhanced sensing", Phys. Rev. A 110, L041301 (2024), DOI: 10.1103/PhysRevA.110.L041301

Science:

- New method to create and control entanglement between motional states of atoms in cavity without need for electronic interactions
- Cavity response leads to different squeezing interactions between atomic momentum states

Impact:

- Create and harness entanglement crucial to quantum sensing and simulation

Vuletić, "Error-detected quantum operations with neutral atoms mediated by an optical cavity", Science 387, 1301-1305 (2025), DOI: 10.1126/science.adr7075

Science:

- Coupled atoms in optical tweezers to high-quality Fabry-Perot fiber cavity
- Site-selective hyperfine-state cavity readout across 10-site array with > 99.9% fidelity
- Repeated rounds of classical error correction, exponential suppression of logical error

Impact:

- Advances in integrating two modular sensing systems: optical cavities and programmable arrays of atomic tweezers
- Fast, non-destructive readout of individual atomic qubits

Rey, Ye & Zoller, "Exploring the Dynamical Interplay between Mass-Energy Equivalence, Interactions, and Entanglement in an Optical Lattice Clock", Phys. Rev. Lett. 134, 093201 (2025), DOI: 10.1103/PhysRevLett.134.093201.

Science:

- Probe gravitational redshift via tiny variation of atomic transition frequency depending on position in gravitational field
- Expand understanding of relativistic effects to many-body quantum systems, where atoms can interact and become entangled

Impact:

- Probe interface of quantum physics and general relativity

Education and Workforce Development

Quantum Forge (Bennett)

- 15 physics and engineering students sponsored by Colorado companies, Maybell Quantum, Mesa Quantum Systems, and Xairos Systems LLC
- Maybell donated 4K dilution refrigerator to Quantum Forge
- U. Oregon began remote QForge pilot for masters students in applied physics

Quantum PhET Simulations for high-school students and science-curious public

- Web-based, user-driven "experiments" in Quantum Measurement
- No advanced math – "Run experiments, tweak controls, observe results, develop quantum intuition"
- https://phet.colorado.edu/en/simulations/quantum-measurement

QSEnSE Research Exchange (QRX) professional development program under Bennett

- Partnered with Colorado Community Colleges, Fort Lewis College, Worcester Polytechnic to recruit 20 students for online and in-person quantum professional development with lectures, workshops, industry events

The University of New Mexico (Deutsch)

- CQuIC Summer School, connecting 1st and 2nd year students to QIS education and preparing them for QSEnSE projects
- QU-REACH summer training program for undergraduates

CUBit quantum initiative, Quantum Engineering Initiative, QSEnSE

- Roadmap for developing quantum workforce
- Quantum Scholars program provided scholarships in partnership with SPIE

Other Benefits to Colorado:

With its international scientific profile in quantum sensing, locus of expertise in leading-edge quantum theory and experimental science, steady flow of quantum-savvy graduates into Colorado companies, and as a catalyst for Elevate Quantum, Q-SEnSE has established and maintained itself as a current and forward-looking resource for the Front Range and the state of Colorado.

Q-SEnSE researchers have produced more than 300 peer-reviewed publications, now organized and publicly accessible through a dedicated website (https://publications-qsense.colorado.edu/) to ensure transparency and ease of discovery. The majority of these papers are open access, significantly expanding the reach of groundbreaking research to scientists, students, industry partners, and policymakers. This high level of scholarly output and accessibility accelerates innovation, supports workforce training, and reinforces U.S. leadership in quantum science by enabling rapid knowledge transfer across the broader research and technology community.

The program expanded K–12 and public engagement through the widely accessible PhET Quantum Measurement simulations, enabling high school students and the science-curious public to conduct interactive, math-free quantum experiments online.

This program achieved major advances in quantum science and technology, including breakthroughs in quantum sensing, atomic clocks, and fundamental physics. Researchers developed new methods to enhance measurement precision beyond classical limits using entanglement and spin squeezing, demonstrated record-setting optical clock accuracy and stability, and advanced portable and space-ready quantum sensors. The team also pioneered integrated photonics, novel laser systems, and microscopic control of atoms and ions, enabling scalable and high-fidelity quantum platforms. These accomplishments strengthen U.S. leadership in precision measurement, support applications ranging from navigation and secure timing to space exploration and dark matter searches and lay the foundation for next-generation quantum technologies.

The success of Q-SEnSE in both Science and Education & Workforce Development is recognized at the national level, particularly at the National Science Foundation, which has invited our center to the final selection round for an additional six years of funding. This funding extension would sustain research momentum, expand workforce development programs, and deepen industry partnerships. Phase II support would also enable scaling of emerging quantum sensing technologies toward real-world deployment, strengthening U.S. competitiveness and accelerating economic impact in the rapidly growing quantum sector.

Appendix B: Optoelectronics Science and Technology Center (University of Colorado Boulder)

PI: Seth Marder (PI at CU Boulder)
Period of Performance: 10/01/2025-09/30/2026
Funding from Federal Agency: $24,500,000
CHECRA Funding (total/total in 2025): $1,000,000 total / $200,000 in 2025

Project Summary

The National Science Foundation (NSF) Center for Integration of Modern Optoelectronic Materials on Demand (IMOD, imod-stc.org) is one of six Science and Technology Center (STC) funded in 2021. The NSF STC program supports exceptionally innovative and complex research and education projects that necessitate substantial, long-term funding. The primary objectives of NSF STCs are to conduct world-class research through collaborative partnerships among academic institutions, national laboratories, industrial organizations, and other entities. Additionally, STCs support research advances at disciplinary interfaces and often apply novel approaches within disciplines. Specifically, IMOD is guided by the vision of integrating colloidal quantum dot technology into both conventional (e.g., quantum light sources) and unconventional (e.g., quantum light-emitting diodes) applications. In this context, our Center is primarily focused on quantum materials rather than quantum compilers.

IMOD consists of 24 core faculty-led research groups based across 14 US academic institutions, and includes over 100 graduate students, postdoctoral research fellows, and research scientists. The University of Washington serves as the primary institution, which subcontracts to the other academic institutions in the network that includes:

- The City University of New York
- Columbia University
- Georgia Institute of Technology
- Lehigh University
- Northwestern University
- University of Berkeley, California
- University of Chicago
- University of Colorado Boulder
- University of Maryland
- University of Maryland, Baltimore County
- University of Pennsylvania
- Arizona State University (evaluation lead)
- University of California-Berkeley (seed awardee)
- Rice University (seed awardee)

Results Achieved:

In Year 5, IMOD distributed three new seed awards and one renewal seed award. One of the four seed awards was issued to CU Boulder. Furthermore, previous seed awardees from CU Boulder, Gordana Dukovic and David Jonas, were fully integrated such that four CU Boulder faculty received funding in Year 5 – Marder (PI), Dukovic (core-faculty), Jonas (core-faculty), and Yazdi (YR5 seed awardee).

Highlighted activities funded by CHECRA that support IMOD's progress on its intellectual merit and broader impact goals are provided below. Two technical slides are include at the end of the report.

- Staff to support operation and research
- Instrumentation access and services for a microscopy facility
- Supplementing seed grant funding in a manner that increased the number of seed awards granted to CU Boulder through IMOD
- Increased access to IMOD events to facilitate collaboration by supporting student travel to the annual meeting held in Seattle
- Providing travel support for a workshop held in Durango for our PREM partnership

Other Benefits to Colorado:

- IMOD Fellows based at CU Boulder have organized and participated in regional science outreach, including an IMOD Teacher's Workshop held at CU Boulder on Nov. 17, 2025
- IMOD underwent a successful program review associated with a renewal proposal based on our accomplishments and new research directions that was submitted last year.
- Through IMOD, CU-Boulder supports two successful NSF Partnerships for Research and Education on Materials (PREM) awards that provide research funding for the following institutions: Fort Lewis College, Norfolk State University, and the University of California, Merced.
- CU Boulder hosted IMOD Research Experience for Undergraduates (REU) students in the summer of 2025, providing them with the opportunity to engage in CU Boulder research.
- Marder and Ginger (at the University of Washington) have made a technological advancement that may serve as the basis for a provisional patent application.

Appendix C: National Quantum Nanofab (University of Colorado Boulder)

PI: Professor Scott Diddams (scott.diddams@colorado.edu)
Period of Performance: 2025
CHECRA Funding 2025: 175,000

This funding is allocated for activities and personnel in support of the new state-of-the-art National Quantum Nanofab (NQN) that is being established at CU Boulder. This facility will be an open-access facility for academic, government, and industrial users and will allow co-design and development of atomic-photonic quantum devices. It will enable quantum device fabrication, characterization, and packaging capabilities essential for basic research and tech transfer, including quantum networks, atomic clocks, and advanced quantum sensors. The NQN facility will feature advanced instrumentation to address challenges in quantum device construction, including high vacuum and cryogenic temperatures. NQN will also serve as an educational hub and workforce development center to train an emerging workforce in quantum science and engineering.

We have used the CHECRA funds to hire a staff member, Chuang Qu, who supports the NQN technical operations including support and training of users on the recently acquired Electron Beam Lithography system (NSF MRI award) for nanoscale device fabrication. This state of the art instrument directly enables and strengthens the NQN mission. Dr. Qu is earned his Ph.D. in Mechanical Engineering from Missouri University of Science and Technology in 2019. Prior to joining CU, he worked as a senior research engineer at the J.B. Speed School of Engineering at the University of Louisville, where he specialized in advanced nanofabrication and characterization techniques. Chuang's research focused on the development of novel nanomanufacturing processes, including microsphere photolithography (MPL) and glancing angle deposition (GLAD), to engineer functional surfaces with applications across optical, biological, and mechanical domains. He is a strong addition to our team and is already providing excellent support to users of the Electron Beam Lithography system and other nanofabrication tools. His work also benefits the other quantum initiatives at the state level such as the Quantum Incubator and Elevate Quantum via open access to the NQN and the available key expertise of the staff member to the Colorado quantum ecosystem, including local quantum companies.

Appendix D: ASPIRE (Part I: Colorado State University; Part II: University of Colorado)

Part I: Colorado State University
PI: Jason Quinn, PhD. Professor, Department of Mechanical Engineering, Walter Scott, Jr. College of Engineering
Period of Performance: 2025
Funding from Federal Agency: $400,000 total with $80,000 in 2025
CHECRA Funding (total/total in 2025): $300,000 total with $75,000 in 2025

Project Summary

ASPIRE is a National Science Foundation Engineering Research Center focused on making electric transportation practical, affordable, and reliable at scale. Since its launch in 2020, ASPIRE has secured more than $174 million in committed funding to develop infrastructure and system-level solutions that reduce electric vehicle charging costs, improve grid reliability, lower air pollution, and expand access to advanced transportation technologies. The Center is leading a coordinated national effort to modernize the transportation system through scalable electrification, with a long-term vision of seamless, ubiquitous charging that integrates wireless and wired technologies directly into transportation networks and electric utility systems.

ASPIRE has achieved several world-leading milestones, including deployment of a 1 MW wireless charging system for heavy-duty trucks and a 200 kW in-road dynamic wireless charging system installed on a state highway. These demonstrations are designed to reduce battery size requirements, lower total system costs, and improve fleet operational efficiency.

Within this national effort, the Colorado State University (CSU) research team leads development of integrated evaluation and planning tools that support cost-effective infrastructure deployment. In Year 5, the CSU team developed and launched ASPIRE's Dynamic Wireless Power Transfer Costing Tool, enabling researchers and industry partners to evaluate total cost of ownership and greenhouse gas impacts under various deployment scenarios. The team is actively working with CU Boulder to integrate air quality modeling into CSU's systems framework to better quantify public health impacts. The CSU team is a core partner across the center supporting teams in terms of understanding technological advancements in terms of economic and environmental impact.

Results Achieved:

Funding from CHECRA has been instrumental in sustaining CSU's leadership role within ASPIRE and has served as catalytic seed support enabling the team to compete successfully across multiple research, commercialization, and technology transfer initiatives. This year, major accomplishments by the CSU team include:

- Serving as lead authors on a high-impact interdisciplinary publication integrating ASPIRE's research portfolio with pilot-scale demonstrations and national deployment strategies.
- Successfully completing a U.S. Department of Energy (DOE) Small Business Technology Transfer (STTR) Phase I award led by our Colorado-based startup, Optimized Kinetics LLC, in partnership with CSU.
- Filing an invention disclosure for electrified transportation energy modeling through CSU STRATA, the CSU System's intellectual property management and technology transfer office.
- Securing an Advanced Industries Proof-of-Concept grant from the Colorado Office of Economic Development and International Trade (OEDIT) to develop and pilot our planning model with Via Mobility Services in Boulder, Colorado.

Interdisciplinary Publication with ASPIRE
Published in *IEEE Electrification Magazine*, "The Future of Electrified Transportation in the United States: Unlocking the Opportunities of Electrification Through Innovation" provides a comprehensive, interdisciplinary assessment of how electrified transportation can deliver large-scale economic, environmental, and grid benefits. This publication builds upon our two 2024 articles in prestigious *Nature Portfolio* journals, extending prior cost, climate, and systems-level analyses into a broader national framework for infrastructure deployment and grid integration. The article synthesizes ASPIRE's research portfolio, including total cost of ownership modeling of electric vehicles across light-, medium-, and heavy-duty sectors; pilot deployments of electrified roadways in Utah, Indiana, and Florida; development of multi-megawatt charging hubs; and intelligent system modeling to coordinate transportation and electric grid planning. By integrating engineering innovation, economic modeling, pilot-scale validation, and workforce development strategies, the publication demonstrates scalable pathways to reduce costs, improve reliability, accelerate heavy-duty electrification, and strengthen U.S. competitiveness in electrified transportation.

Small Business Technology Transfer Award
Optimized Kinetics LLC is our Colorado-based spinout emerging from the ASPIRE Engineering Research Center, focused on developing fleet management tools for electrified transportation systems. Building on foundational research developed at CSU through ASPIRE, Optimized Kinetics completed a $200,000 project from the U.S. Department of Energy under the Small Business Technology Transfer (STTR) program in partnership with Colorado State University. This award supported the development of an advanced modeling and optimization platform designed to plan cost-effective transit electrification at the system level. Case study results demonstrate the potential for up to a 79% reduction in required capital infrastructure investment and a 66% reduction in grid impact relative to conventional heuristic planning approaches. In the near term, Optimized Kinetics will provide planning services to transit agencies and commercial fleets transitioning to electrification, with a roadmap to deliver a scalable software-as-a-service platform for real-time operational management.

Invention Disclosure at Colorado State University
Through our research within ASPIRE and in conjunction with CSU's role in the DOE STTR award, our team has filed an invention disclosure for electrified transportation energy modeling with CSU STRATA. The technology addresses a critical gap in fleet electrification planning by providing accurate route-specific energy consumption estimates to guide vehicle selection, battery sizing, charging infrastructure deployment, and cost planning. Unlike existing tools that are either overly simplified or too complex for practical use, this framework combines physics-based rigor with computational efficiency suitable for real-world agency decision-making. It leverages commonly available operational and geographic data, can be calibrated using limited fleet energy consumption logs, and produces time-resolved outputs that integrate directly with an optimization solver to support infrastructure and operational planning decisions. Designed to scale across vehicle types, route networks, and climate conditions, the invention strengthens CSU's intellectual property portfolio while enabling the development of practical tools to improve the cost-effectiveness and reliability of electrified fleet deployment across Colorado.

Advanced Industries Proof-of-Concept Grant
As a continuation of our commercialization efforts, we secured a $63,000, two-year Advanced Industries Proof-of-Concept grant through the Colorado Office of Economic Development and International Trade (OEDIT). This project will advance development of a digital twin platform for electric buses and strengthen the resiliency of our optimized electrification planning framework. The resulting intellectual property is intended to be licensed to Optimized Kinetics for commercial deployment. The integrated planning platform will be piloted with Via Mobility Services in Boulder, Colorado, which operates 17 fixed-route buses and 163 demand-response vehicles. This real-world deployment provides an opportunity to validate system performance, quantify cost savings, and demonstrate operational reliability in a Colorado transit setting.

NSF and CHECRA support for ASPIRE enabled the foundational research and tool development that made this pilot possible. This state-funded proof-of-concept project represents a critical transition from research to in-field validation, strengthening commercialization readiness and positioning the technology for broader adoption. Continued NSF and CHECRA investment remains essential to sustain the CSU research team and advance this Colorado-developed innovation through deployment and market entry.

Other Benefits to Colorado:

Combined NSF and CHECRA support have enabled our team at Colorado State University to advance cutting-edge research beyond the laboratory and toward measurable economic and workforce impact for the State of Colorado. This sustained investment has provided the continuity necessary to translate foundational research into commercially viable solutions with the potential to reduce public costs associated with achieving Colorado's 2050 zero-emission vehicle goals.

Colorado-Based Commercialization
Building on this foundation, our team has launched a Colorado-based startup, Optimized Kinetics LLC, embedded within the state's growing electrification ecosystem to bring this technology to market.

- The joint Optimized Kinetics and CSU team completed a U.S. Department of Energy (DOE) Small Business Technology Transfer (STTR) Phase I award in 2025.
- We are in the process of applying for a $1.1 million Phase II award to scale development of the real-time operational management software and prepare the technology for market launch.
- By 2035, we estimate our serviceable addressable market will reach $30 million per year for transit and $960 million per year for commercial fleets.
- CHECRA funding has provided critical continuity between federal funding phases, significantly reducing commercialization risk.

This progression positions Optimized Kinetics as a Colorado-based clean technology company with strong growth potential.

Direct Fiscal and Operational Benefits to Colorado Transit
Our team is developing a system-level software platform to optimize the planning and real-time operation of electrified transit and fleet vehicles. Using advanced optimization tools and AI-driven decision support, the platform directly addresses cost inefficiencies that currently inflate electrification expenditures.

Through structured customer discovery interviews with transit agencies, we identified recurring implementation challenges:

- Heuristic planning practices (e.g., one charger per bus) that increase capital costs and reduce system efficiency.
- Uncertainty in electric vehicle range during winter weather conditions, limiting deployment and reducing emissions benefits.
- Limited operational tools to maintain reliability during disruptions, often requiring fallback to diesel vehicles.

Our technical solutions directly address these barriers.

Preliminary analysis indicates that statewide deployment of our tools could reduce electrification-related capital costs by more than $100 million for the Colorado Clean Transit Enterprise. These savings are driven by optimized charger-to-bus ratios and targeted grid upgrades, preventing costly overbuilding of electrical infrastructure.

In addition to capital cost reductions, our platform improves reliability and resiliency by:

- Accurately modeling vehicle range under Colorado-specific weather conditions.

- Providing operational decision-support tools that reduce service disruptions and diesel fallback.

Through a 2025 Colorado Office of Economic Development and International Trade (OEDIT) proof-of-concept grant, our team will pilot this technology with Via Mobility Services in Boulder, Colorado. This pilot ensures immediate in-state impact while providing validation prior to scaling the platform nationally as a software-as-a-service offering.

In summary, CHECRA funding has enabled our research team to catalyze economic development in Colorado, leverage federal investment, support workforce growth, and position the State to realize substantial public cost savings in the transition to zero-emission vehicle fleets.

Part II: University of Colorado Boulder

PI: Qin Lv
Period of Performance: 01/01/2025 – 12/31/2025
Funding from Federal Agency: NSF
CHECRA Funding (total/total in 2025): $1,625K / $325K

Project Summary

ASPIRE is the first Gen 4 National Science Foundation (NSF) Engineering Research Center (ERC) dedicated to infrastructure for electrified transportation. It is the first of its kind in the world to take a holistic approach to eliminate range and charging as barriers to electrifying all vehicle classes, from passenger cars to heavy duty trucks. The center is pursuing innovative wireless and plug-in charging and infrastructure technology solutions that bring the power to the vehicles—where they drive and park. The result will be smaller and longer lasting batteries on vehicles, effectively unlimited range, and a seamless charging experience. Users will no longer be concerned with when, where, or how they will charge, and electric vehicles will be less expensive to purchase and operate than their gasoline and diesel counterparts. Electric vehicles will become a resource to decarbonize the electric grid and an ideal companion to connected and autonomous vehicles. The ASPIRE team will serve as a trusted guide for society and as a champion for engineering workforce specially trained to support the ensuing cross-industry transformations. Since its initial NSF award in 2020, ASPIRE has grown to over 450 participants across 10 partner universities, 70 industry and innovation members, and has received commitments for more than $174M in fundamental research and pilot demonstration projects.

Supported by the CHECRA fund in 2025, our project has two major research efforts: (1) modeling the air quality implications of vehicle electrification and (2) analyzing neighborhood-scale air quality concentrations and their sources. In addition, we have focused on student engagement and regional partnership building activities to develop the electrified transportation ecosystem.

Results Achieved:

For our modeling work, we have modeled the impacts of 100% vehicle electrification for the Wasatch Front on fine particulate matter air pollution ($PM_{2.5}$) and nitrogen dioxide (NO_2) and assessed how that would play out for health impacts with two scenarios, one in which all of the added electric power load for the electrified vehicles (EVs) were powered by renewable energy and the other in which the added electricity came from fossil fuels in proportion to the current grid mix.

We presented a poster on this analysis at the 2025 ASPIRE Annual Meeting. The findings demonstrate that the health benefits of vehicle electrification fall along the heavily trafficked I-15 corridor through the Wasatch Front, whereas the health harms of the added load under current grid mix is predominantly in less populated areas near coal-fired power plants. We are modeling more scenarios of vehicle electrification to help analyze where we should electrify roadways to optimize air pollution (PM2.5 and NO2) and health benefits.

This is in collaboration with ASPIRE colleagues at Colorado State University and aligns with ASPIRE's National Initiatives to electrify 10,000 miles of roadway for in-road EV charging.

For our monitoring work, we have completed our project studying carbon monoxide and $PM_{2.5}$ and are in the process of publishing the results. We found that anthropogenic activity and changes in local meteorology and transport both result in greater heterogeneity of air pollutant concentrations from neighborhood to neighborhood. We have now deployed a fleet of twelve low-cost PM sensors and gas-phase sensor systems at residential addresses to study the impacts of roadway coarse PM on local air quality.

Traeic-related coarse PM is a result of tire, brake, and road wear, which is directly related to the weight of the vehicles on the road. Because EVs often weigh more than their internal combustion engine vehicle counterparts, we expect an increase in coarse PM near roadways. To understand how this shift could impact nearby communities, we are working towards establishing an understanding of the current impacts.

During this deployment, best practices are being developed for the calibration of low-cost optical particle counters. Proper calibration of the sensors will allow for more accurate analysis of the sensor data collected and in any future projects done by us or others in the field of low-cost monitoring. Additionally, we are exploring methodologies for separating background concentrations from local enhancements, which is essential for capturing roadway impacts on air pollution.

Other Benefits to Colorado:

There are trade-offs to decisions to electrify vehicles, whether light-duty or heavy-duty, in terms of costs, infrastructure investments, and impacts to the environment and health. While only part of those trade-offs, better understanding of the air pollution and health implications of vehicle electrification can help with decisions about where and how to promote this change. Our work on modeling the air quality and health implications of various possible future scenarios of infrastructure development for vehicle electrification, including implications for which places and people are affected, can help in providing decision-makers with information that can inform those decisions. Our monitoring work also offers insight into the current impact of roadways on the air quality of nearby communities, and how these impacts are expected to change with vehicle electrification. The findings from this work can be informative for different locations in Colorado.

We have organized and participated in several student and community engagement events, including ASPIRE Student Association recruitment events, ASPIRE Research Expo, NSF STEM Day, Sustainable Transportation Summit, as well as in-person meetings between ASPIRE center directors and CU Boulder campus leadership. These activities help increase public awareness of electrified transportation, train future workforce, and develop regional partnerships that can lead to local pilot projects in Colorado.

Appendix E: NSF ASCEND Engine in Colorado & Wyoming (Colorado State University)

PI: Cassandra Moseley, PhD. Vice President for Research
Period of Performance: Initial Period: 03/01/2024 – 02/28/2026

- Follow-on Period: 03/01/2026 – 02/28/2034

Funding from Federal Agency:

- NSF via Innosphere Ventures funding to CSU: $300,000 per year
- NSF funding to the Engine lead: $7,500,000 per year; $15,000,000 total

CHECRA Funding in 2025: $500,000

Project Summary:

Formally known as the Colorado-Wyoming Climate Resilience Engine (CO-WY Engine), this program is now called the NSF ASCEND Engine in Colorado and Wyoming (ASCEND Engine). ASCEND stands for Advanced Sensing and Computation for Environmental Decision-Making.

In short, the ASCEND Engine helps Colorado protect communities, grow talent, strengthen the economy, and reduce long-term costs by turning research into real-world solutions. Please see more information and impact stories at https://www.innosphere.org/impact.

The NSF ASCEND Engine in Colorado and Wyoming is an unprecedented initiative to establish the region as the nation's leading provider of environmental intelligence. ASCEND accelerates innovation in advanced sensing and applied AI to deliver practical solutions in our core focus areas of wildfire, water, soil, and air quality challenges. By bringing together researchers, startups, industry, utilities, and communities across the region, ASCEND translates technologies from lab to real-world use, strengthening environmental resilience, creating high-quality jobs, and creating enduring economic impact.

The ASCEND Engine is aligning use-inspired research and development, translation of innovation to practice, and workforce development to build a nationally and globally significant ecosystem. This ecosystem includes Colorado and Wyoming partners across multiple sectors and organizational types, including institutions of higher education, federal research laboratories, small businesses, industry leaders, community groups, and public sector agencies. The Engine is funded by the U.S. National Science Foundation (NSF), with the Colorado-based non-profit Innosphere, as the lead recipient.

The ASCEND Engine in Colorado and Wyoming exists to help communities, businesses, and workers better prepare for and respond to environmental challenges – especially wildfire, water shortages, air quality issues, and land and soil health – while creating good jobs and economic growth. Objectives include:

- Turning research into real-world solutions
- Supporting companies and job creation

- Improving resilience to wildfire, water, and climate impacts
- Building a strong workforce
- Connect partners into one coordinated ecosystem

As we seek to catalyze the NSF funding to draw additional investments into the overall region, it's important to note that Engines who demonstrate progress toward well-defined milestones could receive up to $160 million from NSF over 10 years. CHECRA funding unlocks the full potential of the NSF Engine award, enabling the ASCEND Engine to expand the frontiers of technology and innovation, spur economic growth, and transform Colorado into a world-leading hub of innovation.

Results Achieved:

**The past year's funds were allocated into three areas, with specific summaries, achievements, and benefits to Colorado described, below.

Other Benefits to Colorado:

- **Turn Colorado research into real-world solutions:** ASCEND helps move cutting-edge research developed at Colorado universities, national labs, and startups out of the lab and into practical use. This includes new tools that help communities and businesses better understand environmental risks and make smarter decisions before disasters happen. The ASCEND Engine aligns with public safety, infrastructure protection, and fiscal responsibility, because this work helps Colorado reduce the cost and impact of natural disasters by improving early warning, preparedness, and decision-making tools for wildfire, water, and climate risks. Through this work, Colorado is being positioned as a national leader and a national testbed for solving real-world environmental challenges, allowing solutions developed here to be adopted by other states.
- **Support Colorado companies and job creation**: A major objective of ASCEND is to grow Colorado's clean-tech and environmental technology economy. The Engine supports startups and expanding companies, helps attract private investment, and connects entrepreneurs with customers and partners – resulting in new Colorado-based jobs and business growth.
- **Improve Colorado's resilience to wildfire, water, and climate impacts**: ASCEND focuses on developing and deploying technologies that help Colorado communities anticipate and reduce environmental risks, such as wildfire damage, water system disruptions, and air quality impacts. The goal is to shift from reacting to disasters toward earlier, smarter, and more cost-effective planning and prevention.
- **Build a strong Colorado workforce**: ASCEND invests in workforce development and training programs so that Colorado students, workers, and career-changers can

access jobs in environmental technology, data, engineering, and related fields. These efforts are designed to ensure that Colorado employers can find skilled talent locally and that residents benefit directly from the growing innovation economy. ASCEND is a training ground for Colorado's next generation of data scientists, engineers, and climate resilience professionals. Key points: Fellows gain hands-on experience, not just academic training; Skills are directly relevant to Colorado employers; Talent is trained in Colorado, on Colorado problems. This connects ASCEND to workforce shortages, retention of high-skill talent in the state, and long-term economic resilience.

- **Connect Colorado partners into one coordinated ecosystem**: Rather than working in silos, ASCEND brings together Colorado universities, local governments, industry leaders, nonprofits, and community organizations. By coordinating efforts across these groups, the Engine helps ensure that investments, research, and workforce programs are aligned with Colorado's economic and environmental priorities. The project directly supports rural and urban communities alike, because ASCEND connects research institutions with the real needs of Colorado's rural, urban, and agricultural communities, ensuring public investments benefit the entire state. While ASCEND works with front-range universities and labs, it applies outcomes to rural, wildfire-prone, and agricultural communities, while engaging with utilities, local governments, and land managers.

Colorado-based winners of the Translation grant RFP included:

The Engine awarded $1,015,000 of Round 1 and Round 2 Translation grants to Colorado-based startup companies and $550,000 to Wyoming-based startup companies. Therefore, 65% of Translation grant funding went to Colorado.

- **Page Technologies.** *Complex Earth Sensing/Soil Carbon Capture Data & Analytics*: Next-Gen Soil Monitoring: Wireless Printed Sensors for Agriculture. *Key partners*: Syngenta Group, University of Wyoming, 3 Rocks Ranch, Colorado State University, Growing Gardens, Meshcomm Engineering. *Amount*: $330,000
- **Aquanta Vision Technologies Inc.** *Methane Emissions Analysis*: Commercialization of an enhanced methane leak detection platform. *Key partners*: CSU METEC, SeekOps, CSU Strata, Chevron Studio, Rose Rock Bridge. *Amount*: $385,000
- **Cquester Analytics.** *Soil Health*: Translating advanced infrared spectroscopy sensing and data analytics for the commercialization of innovative, high throughput and low-cost soil health monitoring. *Key partners*: Colorado Department of Agriculture, Nature Based Solutions in Shell. *Amount*: $300,000

Colorado-based winners of the Use-Inspired/R&D grant RFP included:

1st and 2nd round of R&D grants awarded $2,600,000 to Colorado-based teams and awarded $300,000 to Wyoming-based projects. Therefore, 80% of R&D grant funding went to Colorado.

- **Colorado State University.** *Soil Carbon Capture Data & Analytics*: Developing soil pyrogenic carbon monitoring and modeling capabilities to improve prediction of wildfire impacts and biochar management on ecosystem resilience and C sequestration. *Partner*: National Ecological Observatory Network (NEON). *Amount*: $299,731
- **Colorado State University.** *Methane Emissions Analysis*: Evaluation of monitoring, reporting, and verification (MRV) technology for cattle feedlots. *Partner*: National Institute of Standards and Technology (NIST). *Amount*: $299,911
- **University of Colorado Boulder.** *Wildfire Risk and Prediction*: Mapping Vulnerability: Assessing the Built Environment's Susceptibility to Wildfires through AI and Big Data. *Key partners*: CoreLogic, CyVerse. *Amount*: $300,000
- **Colorado School of Mines.** *Wildfire Risk and Prediction*: Predicting Regional Wildfire Risk through Climate-Wildfire-Power-System Interactions. *Key partners*: Xcel Energy, Tri-State Generation and Transmission, Fire Adapted Colorado. *Amount*: $300,000
- **Colorado State University.** *Wildfire Preparedness and Response/Air Quality*: Rapid Analytics & Deployment of Sensor Networks for Emergencies. *Key partners*: Colorado Department of Public Health and Environment (CDPHE), OEDIT. *Amount*: $275,000
- **Colorado State University and University of Wyoming.** *Water Quality & Availability*: Scalable, data-driven water quality forecasting for municipal water supply. *Key partners*: Upper Cache La Poudre Research, Northern Water, Cities of Fort Collins, Greely, and Thornton. *Amount*: $260,000
- **Virridy (Evan Thomas).** *Water Quality & Availability*: Rapid Development of In-Situ Water Quality Sensors & Geospatial Analytics for Watershed Management. *Key partners*: In-Situ Inc., Mortenson Construction, Denver Water, National Ecological Observatory Network (NEON). *Amount*: $275,000
- **National Ecological Observatory Network (NEON) operated by Battelle Memorial Institute.** *Cross-Cutting R&D and Translation Infrastructure*: Experimental Digital Twin for Ecosystems: Water, Soil, Drought. *Key partners*: National Renewable Energy Laboratory (NREL), NVIDIA, PAGE Technologies. *Amount*: $300,000
- **Rallypoint (Joshua Day).** *Cross-Cutting R&D and Translation Infrastructure*: Accelerating Digital Twins with Surrogates and Scientific Machine Learning. *Key partners*: JuliaHub Inc., National Ecological Observatory Network (NEON), CU Boulder's Earth Lab. *Amount*: $286,000

Project – "RADSENSE: Rapid Analytics and Deployment of Sensor Networks for Emergencies"; John Volckens ($275,000)

The project had the following objectives. Objective 1 will advance the technology readiness of a patented CSU air sensor technology (the “AirPen”) to support wildland fire smoke monitoring. Objective 2 sought to develop machine-learning models to forecast wildfire smoke concentrations and exposures using historical data. Objective 3 sought to develop a decision support tool for real-time smoke forecasting and communication, including the development and demonstration of a digital dashboard oriented towards public-health stakeholders. All objectives were successfully completed.

We constructed 25 prototype units and verified their functionality in the lab (e.g., sensor data logging, wireless communications, pump flow, solar battery charging). Field demonstration of the technology was successful in partnership with the Environmental Defense Fund. A Phase I commercialization award was secured from the National Institutes of Health.

We developed machine-learning and artificial intelligence models to forecast wildfire smoke events across the continental United States. We also developed and demonstrated a web-based platform to relay smoke forecast information in an easily-digestible format for public health officials and the public.

Results Achieved:

- Doctoral Dissertation: "A Versatile Low-Cost Platform for Particulate Matter, Volatile Organic Compound, and Noise Monitoring." by Emilio Molina-Rueda. CSU Department of Mechanical Engineering. July 2025.
- Publication: Development of a manuscript describing AirPen field deployment in Houston, TX: "A Low-Cost, Community-Based Platform for Monitoring Ambient Concentrations of Hazardous Air Pollutants" by Molina-Rueda et al. This manuscript will be submitted for publication (target: Environmental Science and Technology Letters) in Q1 2026.
- SBIR Phase I Awarded: Initial commercialization of the AirPen technology was achieved through an NIH Phase I award to Access Sensor Technologies in 2025. (NIH R43ES037202). A Phase II application has been prepared for submission but is awaiting reauthorization of the SBIR program by Congress.

Other Benefits to Colorado:

- The Phase I award to Access Sensor Technologies led to the creation of 1 FTE position at the company, located in Fort Collins, CO. Approximately 80% of the Phase I award funds ($305,260) were spent on parts, labor, and vendor services sourced from Colorado.
- The AirPen technology was patented by CSU STRATA (US Patent 11,474,005). In October 2025, CSU STRATA initiated the pursuit of a trademark designation for the term "AirPen".
- Future implementation of the wildfire smoke forecasting system will have economic

benefits to the State of Colorado in the form of avoided health outcomes, and improved public health planning and risk communication.

Project – "Regional Hail project in Northern Colorado and Southern Wyoming, a combination of Sensor Observations, modeling and prediction"; Chandra Venkatachalam ($100,000)

Project Summary:

AI-Based Short-Term Hail Forecasting for Colorado. Hail is one of the most destructive severe weather hazards in the United States, causing more than $10 billion in annual losses over the past 14 years (Faust et al., 2022 [1]). According to Verisk's 2021 report [2], Colorado ranks among the most hail-prone states in the nation. In 2024, a major hailstorm in the Denver metropolitan area caused nearly $2 billion in damage, highlighting the significant economic risk to Front Range communities. Hailstorms result in property and crop damage, vehicle losses, rising insurance costs, and threats to public safety. While storms cannot be prevented, their impacts can be reduced through earlier and more accurate warnings.

The goal of this project was to develop an AI–based, real-time hail forecasting system capable of predicting hailstorm severity with a 2–3 hour in future across Colorado. This type of reliable short-term forecast (nowcasting) is critical for use by emergency managers, local governments, businesses, and residents to prepare for severe weather. We collaborated with NVIDIA and adopted their AI storm forecasting model (StormScope [3]) to modify and generate high-resolution hail predictions over the Colorado–Wyoming region. Their standard model is not sufficient for hailstorm applications. The system uses modern DL techniques, including diffusion and transformer architectures, to realistically model storm evolution. The hail short term forecasting system operates at 3 km spatial resolution and 10-minute temporal resolution. Forecasts are updated hourly and provide short-term predictions with up to 3 hours of lead time. Each forecast cycle generates eight ensemble members to quantify uncertainty and improve reliability. We also developed a new radar compositing and data integration framework that incorporates operational NEXRAD radar observations and CSU CHIVO radar observations. Model forecasts are verified using dual-polarization radar systems deployed by Colorado State University.

Results Achieved:

- Generated high-resolution storm predictions that closely match radar-observed storm structure and intensity.
- Demonstrated improved short-term forecast skill compared to the traditional numerical weather prediction model, the High-Resolution Rapid Refresh (HRRR), for up to approximately 2 hours.
- Successfully integrated multiple radar data sources to enhance forecast accuracy.

Other Benefits to Colorado:

This project directly addresses one of Colorado's most costly natural hazards by using artificial intelligence to improve hailstorm prediction.

- **Public Safety**
  - Potential hailstorm warning to be shared with NWS
  - Increased preparation time for emergency managers
- **Economic Impact**
  - Potential reduction in losses due to hailstorms
  - Potential benefit to insurance industry
  - Potential benefit for farmers and other businesses
- **Workforce and Innovation**
  - Training students and staff in AI
  - Strengthening Colorado's leadership in AI-driven solutions.
  - Supporting future technology partnerships

References:

[1] Faust, E., M. Bove, and A. Radler, 2021: Thundestorms, hail and tornadoes: Localized but extremelydestructive.Munich,RE,accessed10January2021, https://www.munichre.com/en/risks/natural-disasters-losses-are-trending upwards/thunderstorms-hailand-tornados.html.

[2]https://www.verisk.com/solutions/catastrophe-risk-solutions/natural-hazard-risk-response/hail-severe-thunderstorm/

[3] Pathak, J., Abbas, M. S., Harrington, P., Hu, Z., Brenowitz, N., Ravuri, S., Carpentieri, A., Leinonen, J., Adams, C., Hennigh, O., Geneva, N., Durran, D., & Pritchard, M. (2026). *Learning accurate storm-scale evolution from observations*. arXiv preprint arXiv:2601.17268. https://arxiv.org/abs/2601.17268.

Program – "Embedded Data Science Fellowship Program"; Subrecipient – Innosphere Ventures (ASCEND Engine) – Mike Freemen
($125,000 in Year 2)

Project Summary

Rather than funding isolated projects, CHECRA dollars were used to support shared technical capacity – a proven ASCEND Engine model that accelerates multiple research efforts simultaneously and increases the return on investment for each funded project. The investment was strategically applied to support embedded data science expertise within Colorado-based research teams, ensuring that publicly funded research translated into usable tools, stronger models, and workforce development outcomes aligned with Colorado's environmental and economic priorities. This embedded fellowship model ensures that research teams have access to high-level data science expertise they could not otherwise afford individually, while maintaining scientific rigor and accelerating progress across the Engine's entire R&D portfolio. Technical fellows supported with these funds act as the "connective tissue" across projects – standardizing workflows, improving data quality, and enabling research teams to scale their work more efficiently.

Results Achieved:

- Mikkel Quam, who serves as a Data Science Fellow embedded directly within ASCEND Engine R&D teams, providing advanced data science support across multiple Colorado institutions. Mikkel's role is intentionally cross-cutting. Instead of supporting a single research group, he works alongside Colorado State University, Colorado School of Mines, the University of Colorado-Boulder, and the Colorado School of Public Health, helping teams transform complex environmental data into decision-ready insights.
- Bridger Huhn, a Data Science Fellow who provides hands-on analytical and machine-learning support to ASCEND Engine research teams across three higher-education institutions. Bridger's work focuses on applied AI and data engineering challenges that directly support Colorado's wildfire and climate resilience goals, including:
    - Wildfire Risk & Built Environment Analysis (University of Colorado-Boulder). Working with Dr. Virginia Iglesias, Bridger developed machine-learning workflows using aerial imagery to identify homes destroyed in past wildfire events. This work produces high-quality training data that allows researchers to better understand how building materials and landscaping contribute to wildfire loss—critical inputs for improving future risk modeling and mitigation strategies.
    - Localized Climate Intelligence (Colorado State University). In collaboration with Dr. Kristen Rasmussen, Bridger supports efforts to downscale large climate datasets using AI techniques, enabling climate information to be used at local and community scales rather than only regional or global levels. This makes climate data more actionable for Colorado decision-makers, utilities, and planners.

Other Benefits to Colorado:

- Improved integration of large environmental and public health datasets relevant to wildfire, climate, and land-use decision-making
- Faster progress from research concepts to deployable tools
- Increased effectiveness of state and federally funded research already underway at Colorado institutions
- Advanced wildfire research that informs safer building and land-use practices
- Improved access to locally relevant climate data
- Stronger AI and data infrastructure across Colorado research institutions

CHECRA's investment did not fund isolated activities—it multiplied the impact of existing Colorado research dollars by embedding specialized data science talent where it was most needed. This approach has helped research teams accelerate technical progress, improve model performance, and increase the likelihood that research results translate into real-world impact. In short, this means that CHECRA funds strengthened Colorado's research capacity, improved wildfire and climate resilience science, supported high-value workforce development, and increased the return on public research investments.

CHECRA funding enabled Bridger Huhn to support climate research that makes large, complex climate datasets usable at local scales, a long-standing challenge in climate science. Results achieved this year include: Application of AI techniques to downscale large climate datasets for more localized use; Direct support to Colorado State University research teams working on regional and community-scale climate analysis; and Increased usability of climate data for researchers focused on weather extremes, wildfire conditions, and environmental risk.

With Data Science Fellows being the "connective tissue" across the Engine's research portfolio, outcomes are seen through the increase of overall effectiveness of NSF-funded research already underway at Colorado institutions. Those outcomes include: Faster scaling of scientific machine-learning workflows; Improved performance and efficiency of data-intensive research tasks; and Better integration of computing, analytics, and domain science across projects.

Appendix F: Flexible Hybrid SOFC CHP System (Colorado School of Mines)

Mines PI: Robert Braun
Period of Performance: 08/01/24 – 01/30/26 – 1st Budget Period
Mines Funding from Sponsor: $4.5M over three years (two budget periods)
Total CHECRA Funding: $400,000

Summary of Project:
This DOE sponsored project aims to combine advances in robust, low-temperature metal-supported solid oxide fuel cell (SOFC) stack technology with innovative, high-efficiency, low-cost balance-of-plant equipment to achieve significant CAPEX reductions in an ultra-high efficiency, low-emission combined heat-and-power (CHP) system for 1-10 MW industrial applications. The project will demonstrate a full-scale (100 kW) integrated hybrid system capable of being fueled from a range of low-carbon fuels, including 100% hydrogen, hydrogen-pipeline-natural-gas blends, and biogas while offering grid services options for industrial customers.

The original Community Benefits Plan (CBP) featured DEIA engagement with underrepresented groups through partnership with the Society of Hispanic Professional Engineers and other minority-serving structures, leading to appointment of SHPE students to the project's research positions. Energy Equity is central to the proposed techno-socio-economic, environmental and adoption research. The industrial partner was supposed to cross-train unionized manufacturing associates to facilitate domestic supply chains. *However, the CBP component of the project was terminated through Executive Orders*.

The technical project effort will develop and validate an integrated metal-supported SOFC power module-IC engine hybrid CHP system to enable a dynamically responsive, high efficiency, low-cost distributed power solution. The effort moves from component development work by the proposing team (TRL4+) to development and validation of a full-scale, pressurized, flexible hybrid CHP system (TRL6) that ultimately serves as a building block for industrial- and commercial-scale applications.

Project Objectives:
The primary objectives of the proposed project include:

- Characterization of pressurized, 30-kW multi-stack SOFC module operating from several low-carbon fuel blends, including 100% hydrogen, 50-50 H_2-natural gas, and biogas with measured power densities $\geq$175 W/cm^2 or greater.
- Demonstration of robust, stable-operation fuel-flexible 30-kW tail-gas IC engine operating from a range of fuel gas blends – from anode tail-gas steady-state operation to 100% hydrogen, natural gas during startup and necessary load-following mixtures.
- Demonstration of medium-voltage (4160 V), high-efficiency 100-kW industrial inverter building block with an efficiency of $\geq$98%.

- Verification of real-time model-predictive controls and SOFC stack/IC engine integration strategy via demonstration of three steady-state, stable operating points at 100%, 75%, and 50% of rated load in test facility.
- Verification of SOFC heat-recovery steam-generation equipment requirements to achieve CHP performance targets via testing of gas-to-gas heat recovery heat exchangers.
- Life cycle assessment (LCA) and techno-economic analysis (TEA) of the hybrid CHP system to establish capital cost ($\leq$1250 $/kW), life cycle CO_2 emissions, and application-market analysis using bottom-up costing and OpenLCA and NREL REopt software tools to quantify value proposition in industrial CHP applications, and environmental impacts.

Outcomes of Project over Past Year:
The project officially began in August of 2024 and completed its first budget period (BP1) 18-months later, on January 30, 2026. Actual funds for the award were not received until middle September and project subcontracting and kick-off did not occur until middle October. There were 20 milestones across seven project task activities that were scheduled. The team fully completed 18 of the milestones within BP1; the remaining two milestones were not completed due to vendor delays in hardware delivery. There were three Go/No-go milestones and two of the three were successfully completed, with the third being only 50% complete. Significant progress has been made towards advancing the technology readiness level of the high efficiency hybrid system.

The following specific progress outcomes were achieved in 2025:

- Advanced fuel cell stack and multi-stack module modeling, validation, and performance prediction was completed to enable system model predictive control to be implemented for both single stack and full-scale integrated system testing. It also enabled commercial system concept generation and optimization, and technology scale-up efforts for 1 and 10 MW systems.
- Model-predictive control was implemented in both the Colorado Fuel Cell Center test stand and as a crucial controller for the integrated test facility at CSU
- Procurement of fuel pre-reformer, catalytic combustor, and Multi-stack SOFC module hardware was completed, of which CHECRA provided cost share for the fuel pre-reformer and catalytic combustor.
- Characterization of the 5 kW fuel cell stack test module which represents one small building block of system was done across a range of operating conditions and fuel compositions providing key test data and hardware performance verification data.
- A new tail-gas engine development effort was completed with a new 2.2L engine design and hardware delivered to CSU. This engine is to be tested in Budget Period 2. Critical test results that demonstrate that the 1L engine fueled by anode tail-gas meets the 10 kWe power target at the nominal hybrid system steady-state design condition.

Additionally, modifications for heat recovery in the Hybrid Integrated Test Facility at CSU is complete with a functional waste heat recovery steam generation system.

- Techno-economic analysis and Scale-up studies were completed for 100 kW, 1 MW, and 10 MW hybrid SOFC systems, and a preliminary life cycle assessment for the 100 kW commercial version of the system was completed.

Project Highlights:

System Design. System design & component requirements were defined for commercial versions of a full-scale CHP system with capacities ranging from 100 kW – 1 MW that enable >59% electric / 78% CHP efficiency at design rated power on high hydrogen-blended fuel for >85% CO_2 reduction. Flexible operation is a key aspect of the design and focuses on above design point power augmentation, and variable power-to-heat ratios. The design power-to-heat ratio can be flexed from 2.3:1 down to 1.1:1 at maximum thermal output by shutting off the engine and sending exhaust gas through the combustor. The power-to-heat ratio can be flexed up to 3.5:1 by sending all exhaust gases to the engine to generate power. This max electric efficiency scenario indicates that a hydrogen-rich fuel (~89% H2) can obtain an electric efficiency of 59.2% and 75% CHP efficiency while lowering carbon emissions by 85%.

Fuel cell stack testing (5 kW test module). In this effort, the Mines SOFC Characterization Team explored the electrochemical performance and thermal behavior of a 5-kWe Stack Test Module (STM, Fig. 2) provided by SOFC developer Ceres Power, Ltd. (Horsham, UK). Experiments are conducted across a wide range of operating pressures and fuel compositions, including H2 / natural-gas blends. Mines tested the 5-kW STM for a total fuel-cell run time of nearly 11000 hours. Total state points explored increased from 36 to 48, providing a wealth of data for computational model calibration and validation.

System Control. Model-predictive controller has been developed and tested on 5 kW SOFC stack test rig at Mines and implemented on the full integrated system at CSU, where it has be partially tested in certain operating modes. More work remains to be done on this. The full system model-predictive control strategy demonstrated via modeling for system startup, operation at system design point, and shut down is nearly completed.

Integrated Hybrid System Test Facility @CSU. The CSU team was tasked with installing the integrated compressor/expanders and the waste heat recovery heat exchangers. CSU has procured all the components and is 95% complete on these full facility modifications. The centrifugal compressors/expanders have been installed and tested to characterize performance. In addition, the waste heat recovery heat exchangers have been mounted in the facility, and the steam side piping has been completed as is shown in Fig. 3. The team has all the components to complete the final process side connections for the waste heat recovery heat exchangers but have been waiting to complete this final task until the go/no-go milestone is completed. Full system integrated testing was to begin this Spring but has halted due to challenges with DOE not funding any projects for their BP2 contracts.

Community Benefits to Colorado. While the Community Benefits Plan was officially terminated in early 2025, some elements were funded by Mines and CSU cost share or had progressed via synergistic activities such as course projects. Industrial energy sectors are significant energy consumers and often face unique challenges in adopting clean-energy solutions. By prioritizing high-efficiency DG-technology development for these sectors, we aimed to promote energy equity by reducing the environmental and health burdens on marginalized communities while fostering economic growth and job creation. The research seeks to identify and address barriers to the widespread adoption of high-efficiency DG technologies in industrial market sectors. It also aims to assess the techno-socio-economic feasibility and environmental life cycle assessment of deploying these technologies. Specific actions include:

- Quantifying the value of resilience and grid-services for flexible CHP, the lifecycle cost of energy, the social cost of carbon, and the economic output from the Justice, Equity, Diversity, and Inclusion (JEDI) job creation model roduct supply chain and environmental life cycle assessment.
- Perform life cycle assessment and techno-economic analysis.

DEI efforts. The 2025 SHPE National Convention occurred October 29th through Nov 1st and our low-carbon CHP program is provided full support for eight Mines SHPE students to attend the five-day conference. Two Mirror Mentoring Student Ambassador were appointed for Spring 2025. These students have been making weekly visits to Robert F. Smith STEAM Academy and CEC Early College, both schools are predominantly low-income students. The Mines students focus on examples of paths towards STEM careers and how to navigate those paths. These regular visits are growing rapport between the Student Ambassador and the high schoolers, allowing organic connections into STEM fields. We note that this Student Ambassador will be two of the eight Mines students to attend the SHPE National Convention as part of this DOE program.

Life Cycle Assessment. A life cycle assessment (LCA) to evaluate the environmental impact relative to competing technologies as it relates to technology adoption was developed. This LCA aimed to establish quantitative environmental impact (EI) data for the Flexible Hybrid SOFC-CHP system to quantify the potential value it could bring to industrial CHP applications like the datacenter application. Quantifying the environmental impacts over the system's life cycle in comparison with conventional co-generation technologies highlights the differences in the impacts produced by the system and where in the systems' life cycles these impacts occur. An energy justice perspective is applied to analyze the quantitative results of the life cycle assessment and through this perspective a conclusion is drawn about the adoptability of this technology.

Technology Licensing. In 2025, interest in licensing of the technology to a group out of Texas who is seeking to develop these systems for data center applications was first initiated in the Fall of 2025. Negotiations continue with a site visit planned in February 2026. The group is looking to license the Mines patent and further develop the technology for product release. Negotiations and discussions are still ongoing.

Appendix G: NAWI – Mines Potable Reuse (Colorado School of Mines)

Project and Mines PI: Tzahi Cath, PhD; Collaboration between Colorado School of Mines, Stanford University (Prof. Meagan Mauter and Prof. Bill Mitch), and CU Boulder (Prof. Karl Linden).
Period of Performance: 7/2024 – 12/2026
Reporting period: CY 2025
Mines Funding From NAWI: $487,928
Total CHECRA Funding: $116,800

Summary

Declines in volumes and quality of existing water resources resulted in rapid exploration of unconventional resources and new technologies for removal of conventional and emerging contaminants from impaired water, leading to intensification of water reuse. Non-potable reuse of reclaimed water has been practiced for many years for irrigation, cooling, and other industrial uses, but increased concentrations of recalcitrant contaminants in tertiary effluents led to examining of advanced processes to treat reclaimed water to higher quality, especially for irrigation of edible crops. In places that experience moderate and severe shortage of water supplies, some of which don't have access to the ocean, potable reuse is becoming a necessity and critical source of water.

Potable reuse of reclaimed or impaired water is divided into indirect potable reuse (IPR) in which the finished water (traditional + advanced treatment) is returned to an environmental buffer for additional treatment and blending with natural water (e.g., Aurora Water, Peter Binney water treatment plant). IPR requires that the water from the environmental buffer is re-treated in a water treatment plant (conventional and/or advanced), which increases the overall cost of the water when considering the additional pumping and treatment added to the process. In direct potable reuse (DPR), secondary or tertiary treated effluent is further treated by a train of advanced processes to ensure high log removal of microorganisms and micropollutants of emerging concern (e.g., pharmaceuticals, personal care products, industrial pollutants). The treated water is then sent to the distribution system, with or without blending with treated fresh source water.

In this awarded project we aim to improve the performance and the pipe-parity (cost of the next gallon of water…) of DPR through utilization of an existing demonstration-scale, mobile lab owned and operated by the Colorado School of Mines (Mines). We specifically test the unit in Colorado and California on reclaimed water in areas where water scarcity is significant. And we use the mobile lab to compare reverse osmosis (RO)-based and non-RO-based DPR in Colorado and California. We specifically focus on the removal of contaminants of emerging concern such as PFAS and viruses and the impact of traditional contaminants such as sulfate, calcium, and silica on RO and non-RO DPR operations. More importantly, we test the ability and the modification required of the DPR treatment train to reclaim water from anaerobic processes. As anaerobic processes are studied more

extensively and their implementation is predicted in the near future, it is important to know how the effluent of anaerobic processes will impact the DPR processes, in full strength or diluted with plant effluent.

Project Objectives

Our mobile demonstration system is a unique system that can in parallel and simultaneously compare different potable reuse approaches: RO-based and carbon-based (non-RO) direct potable reuse. DPR of reclaimed water is a major alternative to desalination of seawater or brackish water, especially when considering the energy demand of RO systems compared to carbon-based DPR systems. DPR is especially a viable solution for inland communities that don't have access to groundwater, their groundwater level dropped, or their water sources became contaminated. The new demonstration pilot project will be deployed at several sites in Colorado and California to not only demonstrate the differences between RO-based and carbon-based DPR, but also the two approaches with various reclaimed water streams, including effluents from aerobic and anaerobic (including SAF-MBR) biological processes. Special focus will be on comparing the performance of the two DPR approaches for removal of emerging contaminants of concern (CEC) and viruses.

While the technology readiness level (TRL) of the processes in the mobile lab are at the top level (9), the combination of processes is unique and the media used in adsorption columns is novel (TRL 4-5), with a special focus on PFAS removal while efficiently removing traditional CECs (pharmaceuticals, PCPs). In addition, demonstrating the prevention of scaling and fouling on membranes and adsorption media is another objective of the study. Overall, the DPR mobile demonstration lab is at a scale suitable to serve small communities of 150-250 people. With a unique synchronization of processes in a small footprint, it is important to demonstrate that the operating and capital costs of systems can be further reduced while water recovery is maximized and waste streams are minimized.

Project History

- The design and fabrication of the system was supported by a major grant from the Colorado Water Conservation Board and the National Science Foundation.
- First deployed in Colorado Springs in June 2021, then moved to Aurora Water (Sand Creek) in May 2022, South Platte Renew (Englewood) in June 2023, Metro Water Recovery (Commerce City) in August 2024, back to South Platte Renew in November 2024, and to Silicon Valley Clean Water (Redwood, CA) in May 2025. Thus, the system have been in continuous operation for more than 4.5 years(!)
- Substantial upgrade of the DPR trailer was conducted at the end of 2024 and beginning of 2025. The following upgrades were conducted:
    - Addition of power capacity into the trailer: 240V/100A was added for a total of 240V/200A
    - Installation of a new, split AC unit

- Incorporate an additional treatment train configuration: from existing adsorption→UV-AOP to the ability to operate UV-AOP→adsorption
- Improved plumbing for influent and effluent lines and installation of permanent winterization.
- Continue experiments for parallel project and move the trailer to Silicon Valley Clean Water.

Outcomes of Project over Past Year

- Published a major scientific article in collaboration with Colorado Springs Utilities and major consulting firm (Carollo Engineers)
- Upgraded internal RO system to enable testing under extreme condition (addition of chemicals dosing)
- Testing of the new RO system in the trailer demonstrated very low toxicity in the product water (at the level of deionized water…)
- Conducted a comparison study of water quality between the DPR system and drinking water in various cities in Colorado. Paper in final stages of preparation for publication
- Fabrication and deployment of a novel filtration system for the separation and removal of suspended organic matter and PFAS from influent to the trailer.
- Secured >$300,000 in 2026-2027 funding from DOD to test PFAS removal by the processes in the DPR trailer. Additional funding secured by others at Mines (>$6M, PFAS@Mines) will also use the DPR trailer for advanced testing of water treatment.

Examples of benefits to Colorado

- To be compliant with future regulations in Colorado, wastewater reclamation plants in Colorado will have to test, adopt, and implement new advanced technologies for the removal of nutrients (nitrogen and phosphorous) and carbon. Technologies tested in the mobile demonstration lab already show promising results
  - Important examples are Metro Water Recovery (the largest wastewater reclamation facility in Colorado) which this year utilized our demonstration system to address critical water quality problems in preparation for the implementation of Regulation 31 in Colorado.
- Tools developed in our demonstration system will be adopted by Colorado utilities (both water and wastewater treatment facilities) and can be adapted to many other industries.
- Hach is a Colorado-based, worldwide leading company in water quality sensors. The close collaboration between this project and Hach will undoubtedly bring more business to Hach and more tax money to Colorado. Companies such as Hach hire the next generation of engineers and scientists graduated in Colorado.
  - Mines and Hach are applying for 2027 congressional funding (>$1.5M)

Media resources

- PARC Innovation Flow Podcast S1E5: Pure Potential: Colorado's Path to Sustainable Water

- Innovations in Water Reuse with Iman Eldib & Dr. Tzahi Cath
- With new regulations, wastewater gains momentum as a defense against drought
- Mobile lab tour (clip)
- Direct Potable Reuse (DPR) podcast
- Recycling Water: Direct Potable Reuse Explained
- Mines' DPR mobile lab
- Mines' DPR mobile lab at Colorado Springs Utilities
- PureWater Colorado Mobile Demonstration Project
- First day of potable water production

Appendix H: NAWI – Mines Reciprocating Piston (Colorado School of Mines)

Mines PI: Tzahi Cath, PhD; Collaboration between Colorado School of Mines and Purdue University (Prof. David Warsinger, PI).
Period of Performance: 7/2024 – 7/2026
Reporting period: CY 2025
Mines Funding From NAWI: $306,318
Total CHECRA Funding: $76,560

Summary:

While reverse osmosis (RO) desalination is the most competitive and efficient desalination process today for low to moderate salinities impaired water (3 g/L to 70 g/L), its progress towards pipe parity (solutions and capabilities that make marginal water sources viable for end-use applications) has declined. Unlike conventional RO (RO membrane continuously splits impaired water into a product stream and a brine stream), batch and semi-batch RO process configurations are potentially the most efficient variants but they remain somewhat inefficient because of brine mixing and high downtime. There are also complexities associated with time-varying pressure, volumetric flow rates, and flow directions. While semi-batch processes like closed circuit reverse osmosis (CCRO) have had success at scale, the full-batch configuration with low downtime have not been commercialized yet. Furthermore, the current paradigm is that RO is limited to certain salinities and subsaturated conditions, and that significant energy improvements are unobtainable. We aim to change the paradigm with a best-in-class configuration of **batch reverse osmosis (BRO)**, that substantially reduces energy consumption, downtime, costs, membrane fouling potential, and improve other economic metrics. This process can extend viable water recovery across the feed salinity range (2 g/L to 120 g/L) and can be integrated with renewable energy.

Improvements to conventional RO are obtained with high-efficiency pumps, energy recovery devices, and membranes with high permeability. Today, this achieves diminishing returns. Despite great performance of these components, the energy efficiency improvement remains substantially limited by the excess overpressure above osmotic pressure during operation of conventional RO. Multi-staging has had some ability to address this; however, high-pressure booster pumps are often costly and inefficient. The current state of the art for low salinity, high recovery desalination is semi-batch CCRO. Continuous (conventional) RO with a pressure exchanger is the next best option. Yet, most RO plants use continuous RO without a pressure exchanger, which saves on hardware/capital costs, but reduces energy efficiency. BRO can substantially outperform the competing configurations because CCRO continuously mixes new feed with the recirculating brine, diluting the process water and increasing pumping requirements and time. BRO may also have superior membrane fouling resistance relative to CCRO because the RO membranes spend less time at high salinity. Finally, BRO with a reciprocating piston is expected to have reduced downtime (and thus

superior costs and water production) compared to previous configurations of BRO. The latter benefit is a result of the reciprocating nature, which reduces idle time. Indeed, previous designs piloted by the team and collaborators needed more time to empty and reset the process.

Project Objectives:

Our team aims to apply rigorous modeling, unique fabrication expertise at Mines, and realistic testing conditions to optimize BRO's energy efficiency, water recovery, and resilience with fouling-prone waters. To scale up this approach, we aim to better understand BRO supervision and control requirements in view of meeting pipe parity metrics, while ensuring safe and reliable performance. A nontraditional water source achieves pipe parity when a decision maker chooses it as their best option for extending its water supply.

The team has pioneered batch processes with piston-tanks, publishing and patenting the first configurations that can follow the osmotic pressure curve. The approach will attempt several firsts, including the first reciprocating-piston pilot, the highest salinity increases between feed and concentrate achieved by BRO, the first examination of valve and piston cycle timing via machine learning optimization to minimize salt retention and optimize the process.

The prototype is the first to scale up batch RO for achieving high energy efficiency, as past prototypes by team members (Purdue, MIT, Olin + Harmony Desalination) were too small to do so (i.e., the BRO lab-scale size was 2.8 L/min (less than 1 gallon per minute) – the current pilot system can treat water at a rate of 20 gallons/min (clean water).

Project History

- The project started in July 2024. The design of the new system was completed in late August 2024 and the team started the fabrication of the system at the Mines' Denver WE^2ST Water Technology Hub in late August 2024.
- The team was lucky to receive a donation from NGL-EP (midstream oil and gas company headquartered in Denver) that included a containerized (20' shipping container) RO system that was minimally used in the field. This RO system has been modified to multiple RO configurations and saved the project more than $150K in project costs, enable us to build a large and more sophisticated pilot RO system.
- The project also received more than $500K funding support from DOD to construct the system and enable advanced research in PFAS separation and concentration.

Outcomes of Project over Past Year:

- In 2025 we had six students/researchers and a staff member involved in the design and fabrication of the system:
  - Sofia Zook (a PhD student at Mines, supported by DOE grant and CHECRA, continue in 2026)
  - Adria Lau (PhD candidate at Mines, supported by a DOD grant, continue in 2026)

- Sandra Cordoba (Purdue University PhD student on long-term visiting status in Denver)
- Joel Aboderin (Purdue University PhD student on long-term visiting status in Denver)
- Louis Miyasaki (an MS student at Mines, supported by DOE and CHECRA, continue in 2026)
- Iman Eldib (graduated in 2025, MS student at Mines, supported by a DOE grant)
- Sultan Alnajdi (graduated in 2025, Purdue University PhD candidate on long-term visiting status in Denver)
- Wayne Loper (technician at Mines, supported by DOE grants and CHECRA, continue in 2026)
- Tani Cath (research associate at Mines and a graduate student at CSU, in charge of control systems and supported by DOD and CHECRA, continue in 2026)

Most importantly **(!)** when we started the design, we realized that we could build a much more sophisticated system that can be easily converted to operate under different reverse osmosis process configurations. Therefore, we have designed the system and constructed it with the ability to operate it in:

- Conventional RO configuration **(fully tested in 2025)**
- Closed circuit RO configuration (CCRO) **(fully tested in 2025)**
- Batch RO configuration with bladder pressure exchanger (BRO1) **(fully tested in 2025)**
- Batch RO configuration with piston pressure exchanger (BRO2) **(fully tested in 2025)**
- Pulse-flow RO (PFRO) **(will be tested in 2026)**

This creates a one-of-a-kind system (in the world) that enables us to compare different novel RO configurations for different sources of water, comparing and minimizing energy consumption, maximizing water recovery, and improving product water quality.

- As of mid February 2026, we have upgraded the system to enable operation at pressures of up to 1,000 psi (600 psi limit before). We have also completed the integration of a unique turbidity meter that can operate at ultra high pressure and provide early detection of membrane fouling and scaling. With the support from CHECRA we are completing the design of a pretreatment system that will enable us deployment in the field and testing of ground and surface water.

Lookout for 2026:

- Construction of a mobile pretreatment system (filtration, softening, pH control)
- Field deployment to test groundwater contaminated with PFAS
- Lab testing of desalination of pretreated produced water from the oil and gas industry

Examples of benefits to Colorado:

- Improve industrial water desalination and purification (O&G, food & beverage, power, mining)
- Removal of PFAS from contaminated ground water to improve the health of impacted communities and environments
- Reduce energy consumption and reduce CO_2 emissions associated with desalination of impaired water for advanced reuse applications.
- Long term visits of students from other states
- Support of native CO graduate and undergraduate students