COLORADO
Higher Education Competitive Research Authority

March 1, 2025

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 2024. This includes multi-year projects that received continued funding in 2024, and new initiatives funded for the first time in 2024.

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 2024, CHECRA spent $2,622,484 in 2024 to support 14 research grants. Those 14 grants total over $111 million in research awards to Colorado. The Authority received a single distribution of Limited Gaming Funds of $2.1 million. Interest earnings on the Authority's funds totaled $67.821 in 2024.

Following is a list of the multi-year research grants that received CHECRA funding in 2024.

University of Colorado (CU)

- In 2016, with CU Boulder as the lead awardee, the NSF awarded a $24 million, 5-year grant for the Science and Technology Center on Real-Time Functional Imaging (STROBE). STROBE brings together universities, national laboratories, industry, and international partners to create a powerful new set of real-time imaging modalities. STROBE was renewed after the initial 5-year period and CHECRA pledged $400,000 per year for another five years; 2024 was the fifth and final year of funding for this project.

- 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 has pledged $400,000 annually for five years plus a one-year extension. 2024 was the fifth year of funding.
- The NSF-funded Center for Integration of Modern Optoelectronics Materials on Demand STC, funded by the National Science Foundation, will 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 fourth of five payments in 2023.
- 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 will be able to design and build incredibly small devices that tap into the world of atoms and photons—the tiny packets of energy that make up light. CHECRA made the first of five payments of $175,000 in 2024.

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 everyone 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 4th of five payments of $325,000 to CU and 3rd of 5 payments of $75,000 to CSU in 2024.

Colorado State University (CSU)

- The CSU ROOTS project funded by the Department of Energy Advanced Research Projects Agency–Energy is exploring the commercial use of soil sampling technologies and technologies in farm-scale soil carbon and greenhouse gas quantification. CHECRA provided the final of three payments of $133,000 in 2024.
- The NSF-funded Colorado-Wyoming Climate Resilience Engine (CO-WY Engine) is a collaborative initiative focused on driving innovation in climate resiliency across the Colorado-Wyoming region. The CO-WY Engine 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 first of 10 payments of $500,000 in 2024.

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.

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 provided the following cost shares for NAWI projects in 2024:

- In collaboration with Denver Metro Water Recovery, the University of Colorado Boulder’s Mobile Demonstration DPR project is researching technologies that will reuse wastewater and create purified water toward meeting water sustainability objectives in Colorado. CHECRA provided a one-time cost share of $81,000 for this project.
- CSU’s Optimizing Electric and Water Grid Coordination under Technical, Operational, and Environmental Considerations project is examining strategies to manage and coordinate water system operations and the electric grid such that water treatment processes can be compatible with electrification efforts. By understanding how water utilities operate and treat water, Colorado water utilities can reduce operational costs, improve energy efficiency, and contribute to grid reliability. CHECRA made the second of two payments of $30,611 in 2024.
- CHECRA supported four NAWI projects at the School of Mines. These projects focus on process controls for water treatment systems and on decontaminating water supplies. CHECRA provided one payment on each of the four projects for a total of $168,540.

Appendices to this report include detailed information on each of the projects listed above. 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.

- CU Boulder’s STROBE mentored 30 undergraduate students for research experiences in the summer of 2024. In addition, multiple outreach activities were implemented, including K-12 school visits locally and in the four corners region, where every year STROBE has collaborated with CU Science Discovery and local teachers to develop hands on activities for middle school students. STROBE also presented at a Girls in Science Night at the WOW! Children's Museum.

- CHECRA funding directly contributed to securing a $200,000 Phase I grant in to launch a Colorado-based startup, Optimized Kinetics LLC. The company specializes in developing innovative electrified fleet transition plans for government bodies, public fleets, and private entities, focusing on cost, reliability, and emissions implications.
- The Colorado-Wyoming Climate Resilience Engine is a collaborative initiative focused on driving innovation in climate resiliency to reshape the landscape of reliable climate technologies and economic development in Colorado and Wyoming – two states that have grappled with two decades of environmental challenges such as aridification and extreme weather events. As part of the project, the startup program offers a suite of customized services and resources to empower climate resilience startups – advancing the startup ecosystem in Colorado.

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

Dr. Angie Paccione

Angie Paccione
Chair of the Board of CHECRA

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Appendix A: University of Colorado STROBE

NSF award to University of Colorado, Boulder (UCB)
NSF Award: 1548924
Title: *Science and Technology Center on Real-Time Functional Imaging (STROBE)*
Period of Performance: 10/01/2016 – 09/30/2026 (~$48M over 10 years, renewed)
Total 2024 CHECRA Funding: $400,000
Award PI's: Margaret Murnane (Director), Jianwei Miao, Markus Raschke, Naomi Ginsberg

Abstract
Microscopy is critical for discovery and innovation in science and technology, accelerating advances in materials, bio, nano and energy sciences, as well as nanoelectronics, data storage and medicine. Although electron, X-ray and optical nano imaging methods are all undergoing revolutionary advances, no single imaging modality can address critical questions underlying much of science and technology in the 21st century. These grand challenges include: How to capture high-resolution images of functioning nano, energy and quantum systems to guide energy efficient designs? How to rapidly image viruses and vaccines, with molecular-scale information? How to image nanoscale living matter without freezing or labeling? Addressing these major scientific challenges requires the development of the microscopes of tomorrow by integrating state-of-the-art microscopes, new methods, novel sample preparation, fast detectors, big data, advanced algorithms and machine learning - which could not be accomplished without a center.

Progress made over the last year
STROBE brings together academia (CU Boulder, UCLA, UC Berkeley, UC Irvine, Florida International University and Fort Lewis College), national laboratories (NIST, LBNL, ORNL) and several US industries to develop and advance microscopy tools and techniques. Major achievements in 2024 include enhanced collaborations with partners who come to STROBE as a resource – institutions such as NIST, 3M, Moderna, Moore Foundation, MRS, DOE LBNL, PPNL, Imec, NSF IPAM, the Penn State NSF MRSEC and elsewhere. STROBE curricula, training and best practices being adopted broadly, within CU Boulder and more broadly by the international Materials Research Society (MRS). A diverse group of >175 graduate student and postdoctoral scientist alumni are impacting the US workforce, and are now working in the US at KLA Tencor, NIST, ASML San Jose, Zoom, Intel, Mitre, the American Physical Society, Applied Materials, HRL, SLAC, Sandia and elsewhere. STROBE has an additional >235 undergraduate alumni. Most notably, STROBE technologies are now either used, are impacting, or will be soon adopted by several national laboratory facilities at NIST (Boulder and Gaithersburg), Lawrence Berkeley Lab, Argonne National Lab, Los Alamos National Lab, industry and elsewhere.

Outcomes/benefits of this project over the past year (2024)
1. STROBE is attracting new collaborations from national labs, academe and industry.
2. >175 STROBE diverse Ph.D. and postdoctoral graduates are impacting the US workforce. Of these, ~33% were women and 12% URM, well above the national

averages (20% & 4%). STROBE has an additional >235 undergraduate alumni in multiple career tracks.

3. STROBE partners with Dr. Jeff Jessing at Fort Lewis College (FLC) on a collaborative NSF grant called PEAQS, that is partnering to build research capacity at FLC in Durango, and at Norfolk State University (an HBCU). STROBE's role is to arrange multiple exchange visits for training and research; help with writing grants and grant reports; broaden the research and collaboration network; provide technical and professional training on topics such as resumes, interviewing, software, financial planning, mentoring, tutoring for classes, writing and presentation training; advice on renewed in 2024. PEAQS leadership submitted a successful recompete proposal to continue this partnership between FLC, NSU, STROBE, and a new Science and Technology Center called IMOD. STROBE is passing on best practices and lessons learned to IMOD.
4. UCLA STROBE scientist Hong Zhou continued to provide images of their vaccine to Moderna, as a service spanning ~5 years. For bio-materials, sub-2Å resolution is required to obtain the chemical structure. Only the best electron imaging labs, like Zhou's, have the specialized setups to manage the immense amounts of data required to reach this resolution.
5. STROBE research advances have resulted in >383 papers that are highly cited (please see https://strobe.colorado.edu/ for Publications, News and Awards). The large majority of the papers are collaborative, involving joint university/national lab/industry work.
6. Trainees received multiple awards, including Postdoctoral Fellowships to work at NIST Boulder Labs, graduate fellowships, best papers (see https://strobe.colorado.edu/news-events/awards/)
7. Every year, STROBE collaborates with CU Science Discovery and the teachers in the Four Corners region to develop hands on activities for middle school students. In spring 2024, STROBE continued its "Water in the West" theme. STROBE, Science Discovery, and PEAQS undergraduates from Fort Lewis College implemented these workshops in May 2024 for students from middle schools around the Four Corners region, including Tse BitTai Middle School on the Navajo Nation and Bayfield Middle School. Students learned about how the water they drink goes from rain/ snow to their tap, including the water purification process. The students measured the pH and dissolved solids content of the water before and after every step in the process which started with them building their own water filters to filter out large particles from local river water, sending the water through a carbon filter, and looking for living organisms in the water under 3D printed microscopes. The teachers were given the pH and dissolved solids meters along with a classroom set of digital microscopes to continue the actives after the workshop. Please see page 12 of the STROBE Newsletter (attached).
8. Each year, NSF supports a symposium at the Materials Research Society (MRS) conference to welcome undergraduate students from NSF PREM MSIs (Partnership for Research and Education in Materials) programs to the materials science community. Dr. Sarah Schreiner collaborated with a team of NSF and PREM faculty

members to develop and organize the MRS PREM Research Scholars Symposium at the 2024 MRS Spring Meeting in San Francisco. This symposium hosted almost 100 undergraduate PREM Research Scholars from around the United States for two days (see photo on page 13 of the STROBE Newsletter). Scholars participated in professional development and networking activities, and the symposium ended with a poster session for all participants to share their materials research projects with the community. Dr. Schreiner offered two workshops at the symposium on *Networking at Conferences* and *Turning Your Science into a Story*. The STROBEPREM partnership supported 10 students from Fort Lewis College and NSU at the symposium.

9. STROBE technologies have been integral to ~13 joint university-industry grants with small and large businesses, and several other industry fellowships/grants in the first 8 years.
10. STROBE-enhanced IR sources are now available to a broad user community at the Department of Energy Synchrotron Source at UC Berkeley.
11. STROBE-enhanced advanced algorithms for X-ray imaging are now available to a broad user community at the Department of Energy Synchrotron Source at UC Berkeley.
12. STROBE-enhanced tabletop X-ray sources are used by NIST Boulder for advanced materials research, and will soon be adopted at NIST Gaithersburg.
13. STROBE mentored ~30 undergraduate students for research experiences in the summer of 2024.
14. Multiple outreach activities were implemented, including K-12 school visits locally and in the four corners region, as well as presenting at a Girls in Science Night at the WOW! Children's Museum.

Additional documentation: Please see STROBE's Fall 2024 Newsletter. *Thank you so much for this CHECRA support!*

Appendix B: CU Q-SEnSE

NSF Q-SEnSE Year 4 Report to CHECRA
JILA and University of Colorado Boulder
Submitted January 27, 2025
Full name of the funded project: Quantum Leap Challenge Institute for Enhanced Sensing and Distribution Using Correlated Quantum States
First and last name of the primary investigator (PI) for this project:
Jun Ye (JILA, NIST and the University of Colorado Boulder)

Short description of the project:
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, 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 in a cyclically reinforcing Relationship.

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.

Progress made over the last year

Representative Milestones over Year 4 -- Research

Ye & Zoller, "*Essay: quantum sensing with AMO platforms for fundamental physics*", Phys. Rev. Lett. 132, 190001 (2024). DOI: 10.1103/PhysRevLett.132.190001
Invited by the Editors of Phys. Rev. Lett., two senior Q-SEnSE investigators collaborate on their vision for potential key breakthroughs in physical sciences enabled by growing capabilities of quantum information science and engineering. An important question is raised: what critical impact will the second quantum revolution with ubiquitous applications of entanglement bring to bear on fundamental physics? Ye and Zoller argue that a compelling vision is to harness the rapid development of quantum information science to define and advance the frontiers of measurement physics, with strong potential for fundamental discoveries. Some of the most challenging problems, such as quantum aspects of gravity, fundamental symmetries, or new physics beyond the minimal standard model, can be tackled at the emerging quantum measurement frontier, defined by fault-tolerant quantum computing and entangled quantum sensor networks.

Wineland & Allcock, "*Two-mode squeezing and SU(1,1) interferometry with trapped ions*", DOI: 10.48550/arXiv.2312.10847
Investigators at University of Oregon are collaborating on experimental implementation of quantum circuits on two motional modes of a single trapped ion. They realized the required displacement, squeezing, two-mode squeezing, and beamsplitter operations using oscillating electric trapping potentials in both one and two modes. The trap electric fields drive the modes resonantly or parametrically without the need for optical forces. They demonstrated a maximum sensitivity of a SU(2) interferometer within 0.67(5)dB of the standard quantum limit (SQL) as well as a single and two-mode SU(1,1) sensitivity of 5.9(2)dB and 4.5(2)dB below the SQL respectively, thus showing phase sensitivities near the Cramer-Rao bound.

Lewandowski, "*Seeing quantum effects in experiments*", Physical Review Physics Education Research 19, 020144 (2023), DOI: 10.1103/PhysRevPhysEducRes.19.020144

On the important front of quantum education, Q-SEnSE's research-based approach is exploring new directions while improving traditional instruction-oriented labs. This paper describes an interview study about the values of seeing quantum effects in experiments for both instructors and students involved in undergraduate instructional labs, and connecting abstract, mathematical theory with more intimate pictures of quantum phenomena through observing experimental results, sometimes in conjunction with interacting with or understanding part of the experiment. By focusing on a popular set of quantum optics experiments and find that students believe they are observing quantum effects and achieving related learning goals by working with these experiments, the study presents important findings on how to best utilize quantum experiments in the curriculum and make explicit related learning goals.

Knappe & Regal, "*Correcting heading errors in optically pumped magnetometers through microwave interrogation*", DOI: 10.48550/arXiv.2310.11017
Quantum engineering requires close collaboration between physicists and engineers. In this recent study, two Q-SEnSE investigators implemented microwave-driven Rabi oscillations and Ramsey interferometry on hyperfine transitions as two independent methods to detect scalar systematics of free induction decay signals to measure *in-situ* heading errors of optically pumped magnetometers in geomagnetic fields. The technique is shown to have wide applicability in challenging regimes of compact vapor cells, imperfect optical pumping, and high buffer gas pressure, achieving suppression of large inaccuracies to levels below 0.6 nT, even in arbitrary magnetic field directions.

Newbury & Sinclair, "*Quantum-limited optical time transfer for future geosynchronous links*", Nature 618, 721 (2023), DOI: 10.1038/s41586-023-06032-5
Q-SEnSE has been the world leader in developing science and technology for optical atomic clocks and optical time transfer, opening the possibility of large-scale free-space networks that connect both ground-based optical clocks and future space-based optical

clocks. Such networks can enable space-based long baseline interferometry, advanced satellite navigation, clock-based geodesy and thousandfold improvements in intercontinental time dissemination, thus promising better tests of general relativity, dark-matter searches, and gravitational-wave detection. In this new work the Q-SEnSE team demonstrate time transfer with near quantum-limited acquisition and timing at 10,000 times lower received power than previous approaches. Over 300 km between mountaintops in Hawaii with launched powers as low as 40 μW, distant sites are synchronized to 320 attoseconds.

Ye & Kaufman, "*Multi-qubit gates and 'Schrödinger cat' states in an optical clock*", Nature, submitted (2024), DOI: 10.48550/arXiv.2402.16289
Optical atomic clocks, the current state-of-the-art in frequency precision, are a rapidly emerging area of focus for entanglement-enhanced metrology. Tweezer-based clocks feature microscopic control and detection with high-fidelity entangling gates developed for atom-array information processing offers a promising route towards leveraging highly entangled quantum states for improved optical clocks. In this strong team effort of Q-SEnSE, a family of multi-qubit Rydberg gates to generate "Schrodinger cat" states of the Greenberger-Horne-Zeilinger (GHZ) type with up to 9 optical clock qubits in a programmable atom array has been developed and employed. To overcome the reduced dynamic range of GHZ states, a cascade of varying-size GHZ states is simultaneously prepared to perform unambiguous phase estimation over an extended interval. These are key building blocks for Heisenberg-limited scaling of optical atomic clock precision.

Diddams & **Rieker**, "*Complete reactants-to-products observation of a gas-phase chemical reaction with broad, fast mid-infrared frequency comb*s", DOI: 10.48550/arXiv.2307.07029
Q-SEnSE researchers use a range of quantum-enabling technologies for broad impact. In this new effort of Q-SEnSE, two leading researchers on frequency combs use a high-speed and broadband, mid-infrared dual frequency comb absorption spectrometer to quantify the abundances and temperatures of chemical species in the complete reactants-to-products breakdown of 1,3,5-trioxane, which exhibits a formaldehyde decomposition pathway that is critical to modern low temperature combustion systems. The advances in understanding of chemical reaction pathways and rates open the door for novel developments such as combining high-speed chemistry with machine learning.

Chiaverini & **Stick**, "*Integrated photonic structures for photon-mediated entanglement of trapped ions*", DOI: 10.48550/arXiv.2401.06850
This cross Q-SEnSE collaboration addresses a challenging quantum engineering problem facing everyone using trapped atomic ions for quantum computing, sensing, and networking. These applications often require the collection of individual photons emitted from ions into guided optical modes, in some cases for generating entanglement between ions. In contrast to proof-of principle demonstrations of photon collection based pm high-numerical-aperture lenses and single-mode fibers, integrated photonic elements in ion-trap structures offer advantages in scalability and manufacturabilty. By analyzing structures monolithically fabricated with an ion trap for collecting single photons from

ions, coupling them into integrated waveguides, and manipulating them via interference, practical considerations for realizing photon-mediated entanglement between trapped ions using these waveguide-based devices are presented.

Jau & **Deutsch**, "*Entangling quantum logic gates in neutral atoms via the microwave-driven spin-flip blockade*", Phys. Rev. A 109, 012615 (2024), DOI: 10.1103/PhysRevA.109.012615
This collaboration between university and national lab introduces a new protocol for entangling gates between neutral atoms via Rydberg dressing and a microwave-field-driven spin-flip blockade. An auxiliary hyperfine state is optically dressed to acquire a partial Rydberg character. A microwave field coupling a qubit state to this dressed auxiliary state can be modulated to implement entangling gates. In contrast to strong dipole-blockade regimes usually employed in Rydberg experiments, using a moderate-spin-flip-blockade regime results in faster gates and smaller Rydberg decay, with the goal for high-fidelity, more robust two-qubit entangling gates.

Safronova & Ye, "*Clock with 8×10−19 systematic uncertainty*", Phys. Rev. Lett. June 17 (2024). DOI: 10.48550/arXiv.2403.10664
Building on the leading platform for optical atomic clocks, a theory-experiment collaboration across Q-SEnSE has demonstrated a clock with total systematic uncertainty of 8.1 × 10-19 in fractional frequency units, representing the lowest uncertainty of any clock to date. With 105 atoms in Wannier-Stark eigenstates of a shallow optical lattice, record atomic coherence time and measurement precision are achieved, providing precise and efficient control of systematic effects. Except for the dynamic blackbody radiation shift uncertainty at 7 × 10-19, all other systematic effects have uncertainties near or below 1 × 10-19.

Monteleoni, *Smith & Albash*, "*Hamiltonian learning using machine learning models trained with continuous measurements*", DOI: 10.48550/arXiv.2404.05526
Within Q-SEnSE, strong collaboration has been established between U. Colorado and New Mexico with investigators from computer science, applied math, and quantum information. Employing machine learning models to estimate Hamiltonian parameters using continuous weak measurement of qubits, this new work considers two settings for the training of the model: supervised learning where the weak measurement training record can be labeled with known Hamiltonian parameters versus unsupervised learning where no labels are available. This construction is tested on a system of two qubits, achieving accurate prediction of multiple physical parameters in both the supervised and unsupervised context. The fact of “learning” is established through the demonstrated benefits from larger training sets.

Outcomes/benefits of this project over the past year

Representative Milestones over Year 4 – Education and Workforce

Convergence and Communications: Q-SEnSE incorporates activities to foster convergence and coordination in its geographically dispersed team of 44 senior investigators, including:

- **Q-SEnSE Research Exchange (QRX)** internship program under **Bennett** recruited 9 students from 4 minority serving institutions for yearlong professional development in industry enculturation and preparation for internships. QRX partnered with SRI International, Infleqtion, LANL, and Atom Computing for resume-building, direct networking with industry, cohort-style community-building, and access to internships. In Year 4, QRX will expand content and partnerships in Colorado and explore nationalizing the model.
- **Quantum Forge**, under **Bennett**, ran its 1st project, sponsored and mentored by Maybell Quantum. Eight upper division undergraduates teamed to research designs for a heat exchange component of Maybell's dilution refrigerator. After project completion, some team members continued as summer interns at Maybell. In Year 4, Quantum Forge will expand both professional development and technical training.
- **Quantum Scholars Program** (CU Boulder) The Department of Physics and College of Engineering & Applied Sciences collaborated to establish this program. A cohort of about 20 undergraduates receive stipends to pursue a quantum-focused degree coordinated between Physics and Engineering and engage in learning opportunities linking them with local quantum companies.

Catalysis of Related Quantum Initiatives

Q-SEnSE is the original core, and remains one of the primary foci of CUbit, an umbrella administrative unit at the University of Colorado Boulder that seeks to coordinate quantum research and education across departments and colleges. https://www.colorado.edu/initiative/cubit/ Q-SEnSE was a spark for the formation of the Quantum Engineering Initiative (QEI), a new unit in the CU College of Engineering, jointly staffed by Engineering faculty and accomplished quantum scientists and engineers from NIST Boulder Labs.

Additional Documentation

Fourteen-Minute Q-SEnSE Highlights Video, remains available on the home page of our comprehensive website, describing the goals, impact, and public benefit of our Center and, by implication, of the QLCI program generally. See https://www.colorado.edu/research/qsense.

Appendix C: CU Optoelectronics STC

Full name of the funded project: STC: Center for Integration of Modern Optoelectronic Materials on Demand (IMOD). NSF Award No. DMR-2019444

First and last name of the primary investigator (PI) for this project (or PI's): Seth Marder (PI at CU Boulder)

Short description or abstract of the project

The National Science Foundation (NSF) Center for Integration of Modern Optoelectronic Materials on Demand (IMOD) was established in September 2021. IMOD is a Science and Technology Center (STC), one of six such centers 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, both domestically and internationally. Additionally, STCs undertake significant investigations at the intersections of disciplines or employ 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 11 US academic institutions, and includes over 100 graduate students, postdoctoral research fellows, and research scientists. The lead institute is the University of Washington, 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 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)

In Year 4, IMOD distributed three new seed awards and two renewal seed awards. One renewal of the five seed awards was awarded to CU Boulder. One renewal was awarded to Rice University. Additionally, the University of California-Berkeley received a new award, increasing IMOD's representation of US academic institutions to fourteen. Furthermore, previous seed awardees from CU Boulder, Gordana Dukovic and David Jonas, were fully integrated as core faculty members into IMOD.

Progress made over the last year

In the past three years, IMOD has achieved numerous accomplishments. In Year 1, we developed a Strategic Plan that outlines our 10-year vision and goals, along with performance indicators and metrics for achieving our 5-year milestones. IMOD has written and submitted its renewal proposal to secure funding for the second five-year period of performance (Phase 2). IMOD has made significant progress on its intellectual merit and broader impact goals. We have established a strong center culture and identity that has been recognized through the evaluation of our programs. Highlights of these activities, including a summary of the activities funded by CHECRA support, are provided below.

- IMOD has submitted a renewal proposal based on our recent accomplishments.
- IMOD has developed intellectual property and has published numerous high-profile publications, including those in Science Magazine.
- IMOD, in collaboration with CU researchers, has developed a system that generates ultra-bright light-emitting diodes based on quantum dots.

Outcomes/benefits of this project over the past year

- IMOD submitted a renewal proposal based on our accomplishments and new research directions.
- CU Boulder faculty and staff led a workshop held at Fort Lewis College to facilitate interactions among faculty from IMOD, a DOE Energy Frontier Research Center led by NREL, and colleagues at Fort Lewis College.
- CU-Boulder was involved in two successful NSF Partnerships for Research and Education on Materials (PREM) proposals that provided research support for the following institutions: Fort Lewis College, Norfolk State University, and the University of California, Merced.
- CU-Boulder hosted NSF Research Experience for Undergraduates (REU) students in the summer of 2024, 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.
- Marder nominated IMOD faculty member Juan-Pablo Correa-Beana for a prestigious Sloan Fellowship, which he was awarded.

Appendix D: CU National Quantum Nanofab

Professor Scott Diddams (scott.diddams@colorado.edu)

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 are still in the process of recruiting a staff member to support the NQN technical operations including the support on the recently acquired Electron Beam Lithography system (NSF MRI award) for nanoscale device fabrication. The latter state of the art instrument will directly enable the NQN mission. The finalist was interviewed on Feb 11 and an offer is in process. The potential start date would be April 2025, contingent on candidate's offer acceptance and when we expect the funds will start to be expensed. This position will also benefit 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 E: CU and CSU ASPIRE

University of Colorado

The ASPIRE NSF ERC 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 inclusive pathways from varied aspects of life into a diverse engineering workforce specially trained to support the ensuing cross-industry transformations. ASPIRE has grown to over 350 participants, recruited 31 industry and 21 innovation members, received commitments for more than $50M in pilot demonstration projects, formed and actively engaged its boards and councils, and significantly advanced engineering workforce development and diversity and culture of inclusion initiatives, including multiple workshops, training sessions, recruitment programs, and development of joint courses addressing convergent research across the center and diversity, equity and inclusion in transportation.

Progress made over the last year

We have continued work on better understanding the interdependencies between transportation and power infrastructure and how people from different communities use these systems. In 2024, we completed two studies. The first study established a methodology to determine how power disruptions influence travel behavior compared to weather events in the Denver Metropolitan area. The second study analyzed how EV adoption and sociodemographic factors relate to travel impacts from power disruptions in three regions (i.e., the Colorado Front Range, the San Francisco Bay Area, and the North Carolina Research Triangle. Overall, these studies explore the use of supervised machine learning algorithms to better understand the utilization of highway networks during power outage events and how EV adoption and area demographics impact an area's response to outlier weather and outage events. These findings can be extended to predict the impact of weather and power outages on other areas not included in the study and forecast impacts under hypothetical future situations.

We have made progress on two major research efforts: (1) modeling the air quality implications of vehicle electrification and (2) analyzing neighborhood-scale air quality concentrations and the sources they come from; we have also initiated efforts to expand our air quality sensing network to include more monitoring sites and new pollutants—like coarse particulate matter (PM)—that can help refine our understanding of the relationship between vehicle electrification and air quality. We continue to update our modeling framework to incorporate more nuance: assuming added electric load is powered by a realistic grid; differentiating between light- and heavy-duty vehicle emissions; enhancing our spatial allocation of where vehicle-related emissions reductions occur; and adding in multiple vehicle charging scenarios. We have completed analyses that furthers our understanding of the neighborhood-scale differences in air pollution from on-road sources using a combination of low-cost sensor measurements, source apportionment methodologies, and novel experimental techniques. Finally, we leveraged low-cost sensor measurements and coupled wind data to investigate the spatiotemporal heterogeneity of air pollution to identify air pollution source profiles.

Outcomes/benefits of this project over the past year

One PhD student supported by this fund successfully defended their dissertation in Fall 2024.

Results from these studies have been presented at a poster session during the Construction Research Conference, organized by the American Society in Civil Engineering in March 2024. We also have two scientific papers under review, one at Journal of Infrastructure Systems and the other at Transportation Research Part D. Our monitoring work over the last year has resulted in the completion of three scientific manuscripts -one of which has been published, one of which has been accepted, and one will be submitted at the end of February.

Our modeling achievements in 2024 reflect several scientific advancements: exploring changes in air quality at a finer spatial scale (1 x 1 km) than other studies and incorporating $PM_{2.5}$ and NO_2, the latter of which is an air pollutant that is less often considered in assessments of how air pollution affects health. Updates to the modeling framework that are underway represent additional scientific advancements, including distinguishing between light- and heavy-duty vehicles, spatially allocating vehicle emissions based on adoption trends, and considering the impacts of vehicle charging time—which has implications for grid cleanliness—on air pollution and health. Our work has the potential to have direct policy implications. We are currently exploring partnering with an initiative through the state of Utah to inform the state's strategic vehicle electrification efforts. Furthermore, over the last year we have shared our work at relevant scientific conferences such as the American Association of Aerosol Researchers annual conference and have communicated our scientific findings to community partners.

Colorado State University

PI: Jason Quinn, PhD. Professor, Department of Mechanical Engineering, Walter Scott, Jr. College of Engineering, Colorado State University

- Universities involved: **Colorado State University, University of Colorado- Boulder, University of Colorado- Colorado Springs**, Utah State University, Purdue University, University of Texas- El Paso, University of Auckland New Zealand, Virginia Tech University, University of Utah, Cornell University
- CHECRA funding to CSU: $75,000 per year
- Sponsor (NSF through Utah State University) funding to CSU: $80,000 per year

Project Description
ASPIRE is an NSF Engineering Research Center that pursues innovative infrastructure and systems solutions to guide society on the best path forward to **electrifying the transportation sector**. ASPIRE's fundamental research and workforce development efforts are catalyzing practical transitions to widespread electrification in transportation with seamless integration of interconnected intelligent systems infrastructure. With the ultimate goal of enhancing the quality of life for all, ASPIRE's goals include improving air quality, as well as increasing economic opportunity and access to clean, affordable transportation. ASPIRE is the first center of its kind to take a holistic approach to addressing these challenges by creating a seamless, ubiquitous charging experience for all users and vehicle classes.

To date, **ASPIRE has secured over $134 million** in committed funding, with $29.9 million in Year 4 alone, to support the Center's ongoing efforts in fundamental research, commercialization, and societal impact. ASPIRE's research progresses rapidly, swiftly moving from initial exploration to the application of fundamental discoveries. Initial explorations were conducted in the first three years and have now advanced to pilot demonstrations in 2024. The ASPIRE center is on the **cusp of achieving many firsts in the world** including the **deployment of a 1-megawatt wireless charger** for local and regional operation of heavy-duty trucks and a **high power in-road wireless charging** system on a state highway for heavy-duty trucks. As society adopts these technologies, we continue conducting fundamental research to better understand and enhance their performance in real-world scenarios through testing, simulations, and modeling.

Use of Funding

The research project at CSU is led by Jason Quinn, with **funding support allocated to Noah Horesh and David Trinko, who serve as the project's technical leads**. CSU's efforts have focused on **optimizing transportation electrification** through an integrated techno-economic analysis and life cycle assessment across various vehicle classes and charging systems.

In Year 4, the research focused on sustainability outcomes to support the evaluation of nationwide deployment strategies for dynamic wireless power transfer, direct current fast charging, and battery swapping systems. These findings directly contribute to the project's integrated evaluation model, serving as key input data and evaluation criteria.

Collaboration with the CU Boulder team has strengthened the integrated evaluation model by incorporating CU Boulder's power grid systems and air quality modeling with CSU's cost and greenhouse gas emissions analyses. **This combined approach between CU Boulder and CSU enables a comprehensive assessment of technologies across multiple performance metrics.**

Additionally, CSU partnered with hardware researchers and industry members to develop an open-source costing and emissions evaluation tool for dynamic wireless power transfer. Industry stakeholders, including **Cummins, AECOM, Electreon, ENRX, and InductEV**, have utilized the tool for their analyses.

Results Achieved

Funding from CHECRA has been instrumental in expanding the Colorado teams' research capabilities, enhancing grant proposal development, and fostering industry collaborations and support. **<u>CHECRA funding has been critical in sustaining CSU's involvement in ASPIRE, directly leading to several major accomplishments in the state of Colorado</u>**, including:

1. The publication **of two research articles in Nature Portfolio** journals, showcasing the prestige and impact of our research.
2. The **launch of our Colorado-based startup company** funded by the U.S. Department of Energy, translating our research innovations into commercial applications.
3. The award of a **U.S. Department of Energy grant in collaboration with Smartville Inc.**, further advancing our research to support the commercialization of Smartville's battery repurposing products for energy storage system integration.

Two Nature Portfolio Publications
Published in *Nature Communications*, "Comparing costs and climate impacts of various electric vehicle charging systems across the United States" analyzed the **deployment implications of direct current fast charging, battery swapping, and dynamic wireless power transfer**. This study compares the total cost of ownership and greenhouse gas intensity of electric vehicles using these charging systems. Based on nationwide infrastructure deployment simulations, the change to total cost of ownership from adopting electric vehicles varies by scenario, vehicle category, and location, with local fuel prices, electricity prices, and traffic volumes dramatically impacting results. Further, electric vehicle greenhouse gas intensity depends on local electricity mixes and

infrastructure utilization. This research highlights the responsiveness of electric vehicle benefits resulting from technology advancements, deployment decisions, and policymaking.

The second publication, featured in *Communications Earth & Environment*, “Fuel shifts reduce most of the greenhouse gas emissions from transportation in the United States”, assessed the **effectiveness of different strategies to decarbonize passenger transportation**. This study evaluates the life cycle emissions of various transportation options under average and maximum ridership scenarios, quantifying emissions reductions through mode shifts and technology advancements. The findings show that electrified transportation achieves half the greenhouse gas emissions of petroleum-fueled options in 2023, with projections indicating a reduction to one-fifth by 2050. Battery systems currently contribute up to one-fifth of lifetime emissions of electric vehicles and buses, with this share expected to increase to half by 2050 as electricity emissions decrease with grid decarbonization. The study concludes that shifting away from light-duty vehicles can achieve near-term greenhouse gas reductions, though long-term reductions are primarily driven by transportation electrification powered by decarbonized electricity.

Launch of Start-Up Company Specializing in Electric Transit Buses

CHECRA funding directly contributed to securing a $200,000 Phase I grant in non-dilutive funding to launch our team’s Colorado-based startup, Optimized Kinetics LLC. Optimized Kinetics is partnered with CSU ($60,000) on the Small Business Technology Transfer grant through the U.S. Department of Energy’s Vehicle Technologies Office. The company specializes in developing innovative electrified fleet transition plans for government bodies, public fleets, and private entities, focusing on cost, reliability, and emissions implications.

The Small Business Technology Transfer grant has enabled Optimized Kinetics to develop tools that support cost-effective electrification decisions across all transportation modes, initially applying them to transit agencies. These tools serve two primary purposes:

- Reducing the planning costs of electrification by eliminating the need for individual entities to develop bespoke planning tools.
- Identifying optimized strategies to consolidate electrification infrastructure deployment and minimize operational costs.

By efficiently deploying infrastructure, these tools enhance the benefits of public and private investments in electrification, reducing costs, alleviating air pollution, and lowering greenhouse gas emissions. Preliminary results indicate a **73 percent reduction in capital costs** for transit charging infrastructure deployment compared to existing transit agency plans.

Ongoing efforts by Optimized Kinetics, in partnership with CSU, include the development of additional Small Business Technology Transfer proposals to secure further funding, specifically:

- **$1.1 million Phase II proposal** to enhance transit electrification models developed during the Phase I award.
- **$200,000 Phase I proposal** aimed at developing corridor refueling solutions for vehicles using energy-efficient fuels such as electricity, hydrogen, and compressed natural gas.

Optimized Kinetics plans to enter the market upon securing a Phase II grant, offering consulting services to the Colorado transit market, which has set a goal of deploying 1,000 zero-emissions buses by 2030. The team believes their solutions can **provide substantial long-term savings for Colorado transit agencies**, facilitating a cost-effective shift toward transportation electrification.

New CSU Project with Smartville Inc., Including Early-Career Faculty

CSU's involvement in ASPIRE has also led to a collaboration with Smartville Inc. on a **$5.9M** U.S. Department of Energy project focused on **grid energy storage using repurposed electric vehicle batteries**. Our team is conducting a techno-economic analysis to evaluate total system costs, improve system competitiveness, and identify optimal target market sectors. Additionally, our team is assessing the total sustainability benefits of repurposed batteries compared to new lithium-ion battery energy storage systems and end-of-life electric vehicle battery recycling. The goal is to identify strategies to reduce the life cycle greenhouse gas emissions of repurposed batteries.

This project has also facilitated the inclusion of a **new assistant professor**, **Vincent Paglioni**, from CSU's Systems Engineering Department. Vincent Paglioni is performing a failure modes, effects, and criticality analysis on Smartville's products for both utility and commercial sector deployment. His work will enable Smartville to assess failure rates across their full systems, helping to:

- Diagnose observed performance issues.
- Predict system reliability under varying environmental and operational conditions.
- Improve Smartville's ability to enhance the long-term resilience of its energy storage solutions.

By integrating techno-economic analysis, sustainability assessment, and reliability modeling, this collaboration is positioning Smartville's repurposed battery systems as a competitive, sustainable solution for grid energy storage applications.

Appendix F: CSU ROOTS

Project Title: Root genetics in the field to understand drought adaptation and carbon sequestration

PI: John McKay, PhD. Professor, Department of Agricultural Biology, College of Agricultural Sciences, Colorado State University

- CHECRA funding to CSU: $134,000 per year
- Sponsor (DOE) funding to CSU: $10,741,602 total

Project Description
We have successfully developed a high-throughput phenotyping platform to measure root system traits at scale in agricultural field experiments. This was done with ARPA-E funding and included a collaboration with **Czero Inc., a design and engineering firm based in Fort Collins, Colorado**. This platform is now being used to identify genetic variation in root traits, and the effect of this variation on drought adaptation, Nitrogen use efficiency and soil carbon sequestration. We are applying this technology to answer basic research questions regarding the **genetic basis of how crop roots sense and respond to soil moisture and Nitrogen**. In addition, we have funded collaborations to evaluate the root traits in the private sector breeding programs of **Corteva, Syngenta as well as public sector breeding programs of the International Maize and Wheat Research Center and national breeding programs across Africa**. This project ended on 2 January 2025.

In this project, we moved forward on two technology areas, first, a field-based study in maize on the genetics of root system architecture and its relation to nitrogen-use efficiency (NUE) using our high-throughput phenotyping (HTP) platform for root pulling, and secondly the development of the MEMS 2.0 ecosystem biogeochemical model to improve quantification of farm-scale soil carbon and greenhouse gas emissions.

Optimizing a proprietary root and soil sampling technology HTP vehicle to understand genetics of root traits in the field.
John McKay at CSU and Chris Topp at Danforth. We used time series sampling of roots and soils to quantify Nitrogen Use Efficiency and soil carbon inputs of maize genotypes across soil moisture gradients for lines relevant to the Corteva breeding program. We conducted large scale split plot field trials with varying levels of the factors irrigation and Nitrogen to evaluate germplasm and identify loci controlling variation using the HTP system. Varieties were also evaluated at Corteva sites in the cornbelt and Danforth farm in Missouri, to establish responses across sites. We identified genetic loci associated with root traits and correlations of root traits with NUE.

Incorporating root and soil characteristics into the MEMS 2.0 soil and ecosystem biogeochemical model.
Keith Paustian Lab –We have extended MEMS model implementation, including data assimilation capabilities using remote sensing observations, into the 'unsupervised' functionality of the COMET-Farm platform. Tests will involve performance of the model for 30 crop species/ varieties and multiple combinations of management practices (tillage, fertilization, irrigation, etc.), across the full range of soil and climate types within agricultural production regions within the US. The new parameters for root and soil characteristics allows better modeling of genetic variation in crops.

Francesca Cotrufo Lab – A major innovation will be to use the empirical data from the field studies (in *1*, above) to model genetic variation in nitrogen use efficiencies and soil C input. We have analyzed soils derived from the CSU field trials for C and N stocks, in the different soil physical fractions represented by the MEMS model, using both physical fractionation with elemental analyses, and Fourier transformed infrared spectroscopy. Data will be used to link crop nitrogen use efficiencies with soil C sequestration and provide data to bridge the field trials with the model development, for verification of model predictions.

Use of Funding

CHECRA funds have been used to support salary for the **project manager, PhD student assistantships and tuition, and hiring of undergraduate students from Colorado** to participate in supervised research projects. Five undergraduates from across four colleges at CSU were able to participate in research because of CHECRA funds.

Results Achieved

Task 9: Genes controlling root traits
This field season we successfully planted field experiments for the mutant lines *slah2/3*, *rtl1*, and *dro1*, along with their respective wild types under two levels of N. We also planted a field experiment for our DH lines with two replicate blocks of each of two levels of irrigation treatment. In total, our field experiments encompass more than 1900 2-row, 20-foot plots, with some additional 4-row plots for obtaining better estimates of yield effects. **These field experiments will allow us to validate and better characterize the root system and yield effects of our candidate genes, including quantification of root biomass differences at depth and responses to nitrogen and water levels.** We pulled a similar number of root systems as last year, an amount that we have found high enough for genetic analyses.

Overall, as part of Task 9, we have measured RPF and root system architecture on a range of diversity and mapping populations in maize. These results reveal a large range of diversity in root traits and their plasticity to the environment. We then used genome-wide data to use linkage and linkage disequilibrium approaches to map causal polymorphisms underlying this variation in root traits. The genetic basis of the root traits is highly polygenic, and we are able to map about 100 QTL of moderate effect size.

We have since “cloned” the genes for several of the larger effect QTL. After identifying the causal gene models, we have now moved to trying to better understand the molecular biology and physiology of seven genes that control variation in the regulation of root system size and function.

Task 10: Nitrogen Use Efficiency (NUE) in Elite Germplasm

We have successfully planted field experiments with a set of 20-25 ERA hybrid lines under different levels of N in Fort Collins, as well as Corteva sites in Illinois and Indiana to improve our rankings of NUE and its correlation with root system traits. We do see variation in performance responses to applied N in these lines. Averaged over the two years, one hybrid, PH19, exceeded 65 lbs grain per lb N. We found an additional 4 lines that exceeded 65 lbs grain per lb N in one year and averaged at least 63 across the two years. We have also found a positive correlation between RPF and yield in low-N conditions, suggesting that the larger roots improve NUE under limited N.

Task 11: Soil carbon and nitrogen modeling

In April 2024 we completed the year 3 soil sampling on 97 plots for the main experiment using the same sampling design as the previous three years and the year two sampling for 26 plots in the extended field where we took two cores per plot and spit them into the same 5 depths and consolidated the two cores. We quantified the coarse and fine roots in these soils and for year one and two sampling and we find a significant difference ($p<0.001$) in coarse roots by depth and by genotype ($p=0.008$). Similar for both years, we see much greater amounts of coarse roots in the surface depth and we see greater amounts of coarse roots in the PH7 genotype, which also has high root pulling force. For the fine roots we see a significant depth effect ($p<0.001$) with surface soils having a much greater root biomass than deeper soils, but not a significant genotype effect on the fine root biomass.

We created and submitted the MEMS V1 documentation to the ecosystem modeling consortium of the Soil Carbon Solutions Center to facilitate usage of the model.

Model simulation scenarios for the effects of increase in root biomass below 20 cm on soil C and soil N dynamics, and verification against measured data was met by simulations of various scenarios, for example those we are publishing in Cotrufo et al (2024, Deepening root inputs: potential soil carbon accrual from breeding for deeper rooted maize. Global Change Biology, in press).

Task 12: Technology to Market

We created and submitted the MEMS V1 documentation to the ecosystem modeling consortium of the Soil Carbon Solutions Center to facilitate usage of the model. The consortium provides access and non-exclusive license to models and data to enable rigorous soil carbon and greenhouse gas quantification via a shared access platform. The MEMS V1 model is now available through this site and is being used by Academia and Industry, with major engagement from investigators at Michigan State University and Shell Oil.

McKay has met with a T2M consultant regularly and they are working on drafting a pitch and setting up meetings with the relevant business and science leaders at Corteva regarding our discovery and **provisional patent** on the gene and trait for deeper roots for maize. We are in the process of finalizing and analyzing the 2024 field data on the mutants and wildtypes of this gene, including the degree to which this mutation affects growth and yield under reduced Nitrogen levels. We have also examined the membrane physiology of alleles at this gene using heterologous expression. These data will be used to update the patent application as well as for the T2M discussions with Corteva.

Broader Impacts and Benefits to the Institution and the State of Colorado

PI McKay is a Professor in the Department of Soil and Crop Sciences at Colorado State University and an Adjunct Professor in the Department of Ecology and Evolutionary Biology at University of Colorado Boulder. McKay serves on PhD committees at both Universities and organizes and participates in meetings to organize research coordination among faculty at both Universities. McKay collaborates with and publishes papers with faculty, postdocs and graduate students at both Universities. McKay has led successful grant proposals that funded research at both CSU and CU. **McKay is currently PI or co-PI on grant projects totaling $22M in funding from NSF, DOE and the Gates Foundation** that is supporting undergraduates, PhD students, technicians, research scientists and supporting staff across the University.

Corteva and Syngenta have seed sales, research and employees in Colorado including PhD scientists trained at CSU. In addition, **Corteva Agrisciences is a large, public US breeding company with employees, operations and thousands of customers in Colorado**. **Czero is a private company based in Colorado and employs mostly graduates of CSU and CU.**

Corn is the annual crop that produces the largest value in Colorado. In terms of acres Colorado farmers produce an average of 1,250,000 acres of corn annually which is second in acres only to wheat (2,000,000 acres of wheat). These two crops accounted for over 87% of the total acres in Colorado in 2023 (USDA 2023). **Our research is working to identify genetic solutions to reduce Nitrogen fertilizer input in annual cropping systems. If successful, this research will reduce the rise in concentration of greenhouse gases** that are causing global warming and climate change. Collaborators include faculty, senior scientists, postdocs and graduate students across three departments and two colleges at CSU.

Appendix G: CSU Engines

Project Title: NSF Engines: Colorado - Wyoming Climate Resilience Engine (CO-WY Engine)

PI: Cassandra Moseley, PhD. Vice President for Research; Professor, Department of Forest and Rangeland Stewardship

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Project Description

- Universities involved**: Colorado State University**, **Colorado School of Mines**, **University of Colorado Boulder**, **University of Denver**, **University of Northern Colorado, Metropolitan State University of Denver**, **Colorado Community College System**, University of Wyoming.
- Project Lead: Innosphere Ventures
- CHECRA funding to CSU: $500,000 per year
- Sponsor (NSF via Innosphere Ventures) funding to CSU: $300,000 per year
- Sponsor (NSF) funding to the CO-WY Engine lead: $7,500,000 per year; $15,000,000 total

The Colorado-Wyoming Climate Resilience Engine (CO-WY Engine) is a collaborative initiative focused on driving innovation in **climate resiliency across the Colorado-Wyoming region**. The CO-WY Engine 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. The Engine is building resilience by **harnessing the advanced sensing and computational assets of our region for the development of decision support capabilities** to address pressing challenges such as wildfire and drought. The Engine will align 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 CO-WY Engine is funded by the U.S. National Science Foundation (NSF), with the Colorado-based non-profit Innosphere Ventures, as the lead recipient.

The NSF announced that the CO-WY Engine was an inaugural NSF Regional Innovation Engine (NSF Engine) on March 1st, 2024. The CO-WY Engine will receive up to $15 million over the course of two years. Engines that demonstrate progress toward well-defined milestones could receive up to $160 million from NSF over 10 years, as we seek to catalyze the NSF funding to draw additional investments into the overall region.

Use of Funding

CHECRA funding unlocks the full potential of the NSF Engine award, enabling the CO-WY Engine to expand the frontiers of technology and innovation, spur economic growth across the state of Colorado, and transform our region into a world-leading hub of innovation.

CHECRA funding was allocated to strategic areas of the CO-WY Engines activities:

1. **Convening state officials** to identify synergies and develop a five-year strategic plan to ensure the Engine's success (work accomplished through CSU's Center for the New Energy Economy)
2. Supporting the **success of the companies and researchers who received either R&D grants or Translational grants** through the CO-WY Engine's newly launched grant making process (work accomplished through CSU's Institute for Research in the Social Sciences)
3. Supporting the **commercialization/startup program** (work accomplished through Innosphere Ventures)
4. Supporting **new project development** and establishing Colorado as a national leader in reliable climate technologies and advanced sensing and computation for environmental decision-making (work accomplished through Innosphere Ventures).

Results Achieved

Convening State Officials
The Center for the New Energy Economy (CNEE) at Colorado State University (CSU) facilitated **engagement with state officials to explore how the Engine's actionable strategic plan can and should align with the State's economic and environmental priorities**. With the support of both the Colorado and Wyoming governors and their senior staff, CNEE planned and convened a joint meeting with participants from both states, held at CO-WY Engine headquarters in Fort Collins. The meetings with governors focused on the challenges to developing a regional science and technology ecosystem, and also on how state cooperation could lead to significant economic growth in the region.

CNEE achieved results that benefited the state of Colorado by delivering on three tasks:

- Strategic discussions with political leaders from Colorado and Wyoming defined the role of both states in supporting the CO-WY Climate Resilience Engine, identified synergies, and developed recommendations for a five-year strategic plan to ensure the Engine's success.

- Meetings with state officials in Colorado, Wyoming allowed each state to identify their unique concerns and priorities, while the joint meeting brought those priorities together to shape strategic priorities for the CO-WY Engine.

- CNEE compiled input from meetings with state participants that help define the states' roles in the CO-WY Climate Resilience Engine and summarized findings, recommendations, and next steps for CO-WY leadership team. Complementing the summary report, CNEE shared additional material related to contact and grant management through a dedicated Google Drive folder, which is maintained by the CO-WY Engine.

State engagement meetings facilitated by CNEE were an excellent opportunity to establish relationships between the CO-WY Engine team and state officials from Colorado and Wyoming. The joint meeting helped break down barriers between the states by providing ample time to formally discuss commonalities and differences as well as time to meet direct counterparts for informal discussion. Participants were pleased with the presentations and discussions and appreciated the time to get to know their counterparts from the other state.

There was discussion on how the CO-WY Engine can be present and impactful in both Wyoming and Colorado - states that often approach issues in different ways but also have a long history of partnership on a wide range of issues. Feedback from these convenings is being utilized by the Engine to **develop its five-year strategic plan, ensuring that it is well aligned with the current challenges and priorities of Colorado**. Additionally, the grants administered by the Engine will unlock additional opportunities for researchers, innovators, and state efforts to **expand innovation ecosystems in Colorado**.

Supporting Success of Researchers and Companies Receiving Grants from the Engine

The Institute for Research in the Social Sciences (IRISS) at CSU worked with the CO-WY Engine leadership team to develop engagement activities for partners and provide technical assistance for Use-Inspired R&D and Translation grantees, including: 1) **designing engagement meetings** with various engine partners, 2) **informing the grant process** for Use-Inspired Research and Development (R&D Grants) and Translation Grants, 3) **identifying and supporting the needs of teams funded** by the R&D and Translation grants.

During the nascent phase of building this economic ecosystem, the Engine hosted a variety of meetings and workshops to understand the users of new technologies, sensing, and computation. The **<u>needs and priorities expressed by Colorado participants have been used to shape the Engine strategic priorities and to shape the Requests for Proposals for the Engine administered R&D and Translation grants</u>**. For example, local water utilities and wildfire managers expressed the need for more detailed climate models in order to engage in more effective management.

The Round 1 and Round 2 RFPs have each been shaped and refined by these community conversations across the state so that the RFPs are relevant to the specific challenges and desires of Colorado resource managers and local government priorities. In these workshops, we consistently heard about specific challenges that local government, utility providers, and resource managers are facing related to achieving their own climate action goals, and these were translated into the language for the RFP to encourage applications that address these identified challenges. Additionally, the grantees are being provided with targeted coaching and facilitation to assist them in achieving their goals during the short (1 year) performance period.

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

1. **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.*
   Lead institution: Colorado State University
   Lab Partner: National Ecological Observatory Network (NEON)

2. **Methane Emissions Analysis:** *Evaluation of monitoring, reporting, and verification (MRV) technology for cattle feedlots.*
   Lead institution: Colorado State University
   Lab Partner: National Institute of Standards and Technology (NIST)

3. **Wildfire Risk and Prediction:** *Mapping Vulnerability: Assessing the Built Environment's Susceptibility to Wildfires through AI and Big Data.*
   L**ead institution:** University of Colorado Boulder
   Key partners: CoreLogic, CyVerse

4. **Wildfire Risk and Prediction:** *Predicting Regional Wildfire Risk through Climate-Wildfire-Power-System Interactions.*
   Lead institution: Colorado School of Mines
   Key partners: Xcel Energy, Tri-State Generation and Transmission, Fire Adapted Colorado

Colorado-based winners of the Translation grant RFP included:

1. **Complex Earth Sensing/Soil Carbon Capture Data & Analytics:** Next-Gen Soil Monitoring: Wireless Printed Sensors for Agriculture
   Company name: Page Technologies
   Key partners: Syngenta Group, University of Wyoming, 3 Rocks Ranch, Colorado State University, Growing Gardens, Meshcomm Engineering

2. **Methane Emissions Analysis**: Commercialization of an enhanced methane leak detection platform
   Company name: Aquanta Vision Technologies Inc
   Key partners: CSU METEC, SeekOps, CSU Strata, Chevron Studio, Rose Rock Bridge

Supporting the Commercialization/Startup Program

The CO-WY Engine **startup program offers a suite of customized services and resources to empower climate resilience startups – advancing the startup ecosystem in Colorado.** The startup program provides the opportunity for climate-focused entrepreneurs to join a startup community dedicated to pioneering solutions for water quality and availability, soil health, air quality, wildfire preparedness & response, and more. This program aligns with the Engine's goal to support startups that in part build a nationally recognized ecosystem for climate resiliency, fueling commercial growth and creating a diverse, innovation-driven economy across Colorado.

Translating new technologies from the lab to the market is an essential role of an NSF Engine. The Startup Program is now a foundational program that will support well over one hundred startups from the region over the coming decade.

8 companies have received specific startup services since February 2024 that include:

- Training Programs: Specialized training focused on challenges unique to climate resilience.
- Connections with Partners: Opportunities to collaborate with corporate, university, and national lab partners.
- Internships and Pilot Programs: Access to partially sponsored internships and pilot testing.
- Expert Mentorship: Support from experienced advisors across a range of sectors.
- Investor and PR Support: Guidance on capital access, including private and non-dilutive funding opportunities, and assistance with public relations and communications.

New Project Development – Establishing Colorado as a Leader in Reliable Climate Technologies, Advanced Sensing, and Computation

As a part of project development, the Engine is committed to fostering an interconnected network of cross-sector partnerships, advancing regional engagement, and applying for other funding opportunities that leverage this federal funding.

The Engine conducted numerous ongoing **co-creation and co-production meetings** on thematic areas of the engine with corporates, national labs, startups, and university partners around varying themes in climate innovation, including wildfire, water availability, and soil health. These meetings **will result in proposals for the next round of our grant RFPs** and other opportunities to enhance Engine translation and workforce development.

The Engine also completed and published a **Workforce Needs and Gaps Assessment**, as well as a **5-year Workforce Strategic Plan**.

Appendix H: Mines Flexible Hybrid SOFC CHP System

Mines PI: Robert Braun
Period of Performance: 01/24-12/24
Mines Funding from Sponsor: $4.5M over three years.
Total CHECRA Funding: $400,000 ($133,000 first installment paid in January 2025)

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 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. Industrial partner will cross-train unionized manufacturing associates to facilitate domestic supply chains. *This component has been 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 (≤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

Technical Progress. The project began in October of 2024. Progress has been made on a variety of fronts, including new design modifications for the 30-kW test module to be characterized at Mines, Mines pressurized stack test facility modifications to accommodate a new 5-kW stack test module, new CSU facility hardware procurement actions and demonstration test facility design modifications are now underway at the CSU Powerhouse. Advanced IC engine design and full system controls development have also been initiated, along with supporting numerical model development activities on a number of fronts.

Community Benefits: Plan activities made significant progress in the 1st four months of the project, prior to being terminated after January 25, 2025. The following summarizes those initial accomplishments. The Mines DEIA Lead provided two separate informational seminars six months prior to contract execution. The SWE Luncheon attracted ~ 100 students to hear a brief seminar on Mines research in green hydrogen production and electrochemical energy storage. The talk featured the contributions of undergraduate students towards the research objectives, and opportunities for student engagement. Prof. Braun hired M.S. Thesis student Katie Lake (her) as a fully supported graduate student to investigate Energy Equity task efforts.

A second seminar was provided to ~ 60 students attending a joint luncheon of the SHPE and the National Society of Black Engineers (NSBE). The joint luncheon and speaking engagements were arranged by Mines Teaching Professor Dr. Andrew Guerra. Dr. Guerra serves as SHPE Faculty Advisor, and is directly supported by this DOE program. The seminar was followed by a panel of SHPE / NSBE graduate students who spoke to undergraduates on their motivations to attend graduate school and become engaged in research.

These efforts have generated interest among SWE, SHPE, and NSBE student chapters for positions in this CHP program. One fully supported female graduate student has already been appointed at Mines, and a second female graduate student was appointed at Colorado State University. One additional underrepresented student is expected to be hired in Q2.

The 2024 SHPE National Convention begins on October 30; our low-carbon CHP program is providing full support for eight Mines SHPE students to attend the five-day conference. One Mines student will provide a technical presentation at the conference, providing an opportunity to acknowledge DOE support for his participation.

One Mirror Mentoring Student Ambassador was appointed during Q01. This student has been taking weekly visits to Alameda Junior / Senior High School, encouraging high-school students to pursue STEM college degrees, and informing them of strategies for success. These regular visits are growing report between the Student Ambassador and the high schoolers, potentially serving to increase applications and enrollment from the underrepresented at Mines. We note that this Student Ambassador will one of the eight Mines students to attend the SHPE National Convention as part of this DOE program, and will provide a technical presentation. This presentation will include visible acknowledgement of DOE support for his conference participation.

Examples of benefits to Colorado:
In addition to the work accomplished in the Community Benefits tasking, our proposed energy equity and Justice40 research can play a crucial role in ensuring equitable access to clean and affordable energy solutions for all communities. While the CBP has been officially terminated, we believe there are elements of it that are relevant to Colorado. 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 aim 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 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.
- Product supply chain and environmental life cycle assessment

Two of the three awardees are Colorado institutions (Mines, CSU) with support provided for seven faculty, three FTE researchers, and 15 students – seven graduates and eight undergraduates. The project is tasked to leverage and solicit area organizations as stakeholders for feedback and Q&A from Coors Brewery, Colorado Energy Office, EVRAZ Steel, Suncor, Bureau of Indian Affairs, Xcel Energy, the Payne Institute, Mines Rocky Mountain Industrial Assessment Center (RMIAC), GreenLatinos and Colorado Department of Public Health & Environment. RMIAC is tasked with provide energy assessments to low-income communities and informing local communities about equitable decision making and options to implement more efficient processes. Furthermore, the project benefits from direct industrial collaboration (and letters of support) from the Ft. Collins-based Woodward, Inc. and Denver-offices of Xcel Energy.

Appendix I: NAWI Project 3.20: Mobile Demonstration DPR: Comparison of RO and non-RO DPR for aerobic and anaerobic effluents
Professor Karl Linden

Project Description

This project investigates the use of ultraviolet advanced oxidation processes (UV/AOP) to destroy trace organic contaminants in recycled purified water applications to protect human health and the environment. These results will inform direct and indirect potable reuse treatment train configurations by identifying more electrically efficient and cost-effective UV/AOP treatment schemes. This research is conducted both at CU Boulder and at the Colorado Potable Reuse Demonstration Trailer, operated by the School of Mines. This pilot study has been in collaboration with Denver Metro Water Recovery and South Platte Renew's pilot and research center (PARC).

The principal persons involved in the project are graduate student Ryan McKeown and Professor Karl Linden. The CHECRA funds are specifically to support the graduate student assistantship. The total Federal Funding is $150,000. This funding has also leveraged other funds from the California Department of Water Resources.

Funding from CHECRA is specifically to support the graduate student assistantship for Mr. Ryn McKeown

Results achieved

In the water reuse demonstration trailer, the UV pilot systems were characterized for hydraulics using tracer studies on both the UV254 and the UVLED reactors to understand their respective hydraulic residence times. The residence times will inform the calculations required to compare reactor performance across different flow rates.

Experiments were performed using the GAC-effluent water at the bench scale using combinations of UV254, UVLED, H2O2, and chlorine. The steady-state hydroxyl radical concentrations were determined experimentally at the bench scale for conditions across the UV technologies and added oxidants. At the pilot-scale, experiments were performed to determine the steady-state hydroxyl radical concentration for UV254/H2O2 at various flow rates. Hydroxyl radical pilot-scale UV254 and UVLED experiments are ongoing.

We are working on experiments to determine the fluence delivered by each reactor using an approach called chemical actinometry. Experiments to determine the inactivation of viruses through the UV systems under the different operating conditions will occur during the next period.

This research has direct benefits to the State of Colorado in management of water resources. Colorado is a leader in the regulation of reusing wastewater resources and we are working on developing technologies that will create purified water to meet the objectives of water sustainability in Colorado. The produced water will be of quality to be potable or be of sufficient quality to meet various beneficial uses such as in energy development, agriculture, and irrigation. The project is aiming to meet the goals outlined by the Colorado Department of Public Health and Environment (CDPHE).

NAWI – CSU Optimizing Electric and Water Grid Coordination

Project Title: Optimizing Electric and Water Grid Coordination under Technical, Operational, and Environmental Considerations

PI: Steven Conrad, PhD. Associate Professor, Systems Engineering, Walter Scott College of Engineering, Colorado State University

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Project Description

- Universities involved: **Colorado State University, National Renewable Energy Lab**, and Electric Power Research Institute (Nalini Rao, PI)
- CHECRA funding to CSU: $30,611 per year
- Sponsor (DOE) funding to CSU: $265,661; Total Federal Funding Leveraged: $800,998

Enabling, renewable energy compatible, alternative water treatment will **provide Colorado and the globe capacity to address scarce water resources**. Energy compatible water treatment processes provide a significant opportunity to ease the strain on the renewable energy grid and realize cooptimization potential. **This project is examining strategies to manage and coordinate water system operations and the electric grid such that desalination treatment processes can be compatible with electrification efforts**.

The project examines strategies for coordinated operation of desalination and water treatment facilities through:

1. Load shifting – Adjusting water treatment schedules to align with renewable energy availability.
2. Load shedding – Reducing or pausing treatment processes when electric grid demand is high.
3. Ramping – Adjusting treatment intensity based on fluctuating energy supply.
4. Energy storage – Integrating water treatment with battery or thermal storage systems.
5. Renewable energy generation scheduling – Aligning treatment operations with peak solar and wind energy production.
6. General demand response – Engaging in grid stabilization programs.

This research is directly relevant to supporting Colorado's water and energy goals. By understanding how water utilities operate and treat water, Colorado water utilities can reduce operational costs, improve energy efficiency, and contribute to grid reliability. This project is aiding with resilient solutions for the state.

Use of Funding

CHECRA funds were utilized to support faculty salary and one graduate research assistant appointment, working toward the research aims described below.

Results Achieved

CSU, the National Renewable Energy Lab and the Electric Power Research Institute, are working to achieve the following objectives and **create toolset to help assist water utilities balance their energy and treatment needs against the demands of the renewable energy grid**.

CSU has continued work on developing a digital twin model to simulate operations of an advanced water treatment facility and report water quality and energy performance metrics impacted by the studied energy grid scenarios. **After this project, *Colorado Utilities will be able to utilize the digital twin platform as a tool to realize their site-specific analysis, control, and optimization assessments. This research is additionally valuable to the state of Colorado as water treatment and energy demand and utilization become more intertwined as renewable energy systems become a more significant part of the energy makeup*.** To date:

1. This project examined the characteristics and dynamics of digital twins in urban water systems. Using research outcomes from this project, the team at CSU has developed a classification framework for digital twins in urban water systems that will inform the development of the water-energy co-optimization digital twin.
2. This project is currently supporting one graduate student at CSU (Josh Rodriguez) and the
   project is supported by CSU's Scott Undergraduate Research Experience (SURE) program which brings an undergraduate researcher to the research project.
3. Assessment of the dynamic simulation models is underway for predicting the system behaviors of one of the project host sites. The current parameterization activities have shown strong results in the simulation of both single-pass and double-pass reverse osmosis processes, although the model is still being tuned to better handle the minute-to-minute variance that may occur during actual plant operations. Results show that for most scenarios, the current iteration of the reverse osmosis model predicts water production within 10% of the observed value on a minute-to-minute basis, including for periods of significant ramp-up and ramp-down. The water quality prediction is currently being tuned to reduce the error and better capture the minute-to-minute variance.

NAWI – Mines Reciprocating Piston

Title: Reciprocating Piston Batch Reverse Osmosis: Pushing the limits of efficiency and fouling resistance
Project Number: NAWI Task 3.22
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 2024
Mines Funding From NAWI: $306,318
Total CHECRA Funding: $38,520

Summary

While reverse osmosis (RO) desalination is the most competitive and efficient desalination process today for low to moderate salinities in 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 have remaining inefficiencies from brine mixing and high downtime, and large complexities from 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 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 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 will be 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 will treat water at 40 gallons/min.

Outcomes of Project over Past Year:

- 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^{2}ST Water Technology Hub in late August 2024.
- The team was lucky to receive a donation from NGL-EP (midstream oil and gas company) that included a containerized (20' shipping container) RO system that was minimally used in the field. This RO system has been modified to BRO 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.
- We have six students/researchers and a staff member involved in the design and fabrication of the system:
    - Iman Eldib (MS student at Mines, supported by a DOE grant)
    - Sofia Zook (new PhD student at Mines, supported by the Zoma (Walton) Foundation)
    - Adria Lau (PhD candidate at Mines, supported by a DOD grant)
    - Sultan Alnajdi (Purdue University PhD candidate on long-term visiting status in Denver)
    - Sandra Cordoba (Purdue University PhD student on long-term visiting status in Denver)

    - Wayne Loper (technician at Mines, supported by DOE grants)
    - Tani Cath (research associate at Mines, in charge of control systems and supported by DOD)
- Most importantly **(!)** when we started the design, we realized that we can 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 now constructing it with the ability to operate it in:
    - Conventional RO configuration
    - Closed circuit RO configuration (CCRO)
    - Batch RO configuration with bladder pressure exchanger (BRO1)
    - Batch RO configuration with piston pressure exchanger (BRO2)
    - Pulse-flow RO (PFRO)

  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 2025, we are completing the integration of a novel control system into the system and are planning to start shakedown in early March.

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 life of impacted communities
- Reduce energy consumption and reduce CO_2 emissions associated with desalination of impaired water for advanced reuse applications.

NAWI – Mines Potable Reuse

Department of Energy National Alliance for Water Innovation (DOE-NAWI)
Title: Mobile Demonstration Direct Potable Reuse (DPR) In California: Comparison of RO and non-RO Potable Reuse for Aerobic And Anaerobic Effluents
Project Number: NAWI Task 3.20
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 – 7/2026
Reporting period: CY 2024
Mines Funding From NAWI: $487,928
Total CHECRA Funding: $56,900

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 source water.

In this awarded project we aim to improve the performance and the pipe-parity of DPR through utilization of an existing demonstration-scale, mobile lab owned and operated by the Colorado School of Mines (Mines). We will specifically test the unit in Colorado and California on reclaimed water in areas where water scarcity is significant. And we will use the mobile lab to compare RO-based and non-RO-based DPR in Colorado and California. We will 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 will 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 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 will be 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.

Outcomes of Project over Past Year

- Substantial upgrade of the DPR trailer. Move DPR trailer from the field to the WE^{2}ST Water Technology Hub in Denver for the following upgrades:
   i. Addition of power capacity into the trailer: 240V/100A was added for a total of 240V/200A
   ii. Installation of a new AC unit
   iii. Incorporate an additional treatment train configuration: from existing adsorption→UV-AOP to the ability to operate UV-AOP→adsorption
   iv. Installed a HACH particle counter
   v. Improved plumbing for influent and effluent lines and installation of permanent winterization.
   vi. Continue experiments for parallel project and move the trailer to Metro Water Recovery (secondary wastewater treatment plant/150 MGD)
- Move back to South Platte Renew for operation until the deployment to California. Continue to work with Silicon Valley Clean Water on preparation for deployment

- Established a new pilot pretreatment system to combat very high concentration of ammonia in the influent to the trailer (>50 mg/L). Results so far demonstrate removal to low single digit ammonia concentrations.
- Testing of the new RO system in the trailer demonstrated very low toxicity in the product water (at the level of deionized water…)
- Fabrication of a novel membrane system (based on newly donated membranes) for the separation and removal of dissolved organic matter and PFAS from influent to the trailer.

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.

Media resources

- 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

NAWI – Mines Porous Polymers

Department of Energy National Alliance for Water Innovation (DOE-NAWI)
Title: Porous Polymer Networks and Membranes for PFAS and Selenium Removal from Water
Project Number: NAWI Task 6.10
Mines PI: Christopher Bellona, PhD; Collaboration between Colorado School of Mines, University of California-Berkeley (Jeffrey Long is Project PI) and Electric Power Research Institute (EPRI)
Period of Performance: 2/22 – 12/24
Mines Funding From NAWI: $455,901
Total CHECRA Funding: $90,952

Summary

The presence of emerging contaminants in water resources poses a significant challenge for water and wastewater utilities in the United States. Per- and polyfluorinated alkyl substances (PFASs) has received significant recent press given their recalcitrance, toxicity and ubiquity in environmental matrices and blood. Recently, the USEPA released stringent (less than 10 ng/L) maximum contaminant limits for several PFAS that have far reaching impacts on drinking water utilities in Colorado. Both PFAS and selenium are difficult to remove from water, making treatment costly and labor intensive. This collaborative research project aims to utilize a novel material developed by Berkeley for adsorptive and membrane treatment of PFASs and selenium. In particular, this material has the potential to transform PFAS and selenium treatment as it has very high adsorptive capacity and is relatively cheap to produce (compared to commonly used adsorbents). CHECRA funds are being used in this project to support staffing of this project (e.g., students) related to assessment of this media in real-world treatment applications. The Mines' research group has significant experience in PFAS and selenium removal and is providing treatment expertise to optimize the novel adsorbent material towards real-world application. The ultimate goal is to increase treatment longevity and reduce treatment costs before impending regulations force utilities to treat for these substances.

Project Objectives

We intend to address the following scientific questions as they relate to improving pipe parity metrics:

1. *Water treatment performance*: Can new PFAS and selenium separation approaches with unprecedently high selectivities, uptake kinetic rates, capacities, and regenerabilities be developed using PPNs? Can favorable fluorous-fluorous interactions and anion-exchange be utilized in adsorbents to obtain high PFAS selectivity? Similarly, can appended aminopolyol and aminothiol binding groups enable selective selenium removal?
2. *Cost*: Guided by adsorption and TEA results, can the separation performance improvements offered by PPNs offset their predicted material costs, compared to other

leading technologies? Can the selective capture of PFAS and selenium from wastewater and simultaneous desalination be achieved in one step by PPN-embedded electrodialysis membranes, significantly reducing capital and operational costs?

3. *Sustainability, and human health and environmental externalities*: Can significantly higher PFAS and selenium removal capacities be obtained by PPNs compared to leading technologies, reducing spent waste volumes in single-use applications? What regeneration conditions would allow PPN reuse as well as PFAS and selenium desorption into concentrated, low-volume waste?
4. *Compatibility, and process adaptability*: Can PPN performances be maintained when tested with actual industrial wastewater samples, and when tested in column and electrodialysis prototypes that reflect industrial operations? What factors (e.g., binding group variations) and conditions (e.g., competing ions) affect PPN performance?

Outcomes of Project over Past Year

- NAWI has brought significant opportunities to collaborate with researchers engaged in different types of research (e.g., fundamental versus applied). This is particularly true for this project as it brings together chemists developing new materials (Berkeley) and water treatment engineers developing solutions for PFAS contamination (Mines).
- Mines has completed testing of adsorbent materials (PPNs) developed by Berkely. PFAS uptake by PPNs was shown to be hundreds of times better than commercially available sorbents such as activated carbon and ion-exchange resin. Further testing was conducted to evaluate the effectiveness of developed adsorbents for treating various contaminated water resources.
- The developed adsorbent media has been developed into granules for use in large-scale treatment applications. Testing has begun to quantify performance of this media for full-scale treatment scenarios.
- Mines and Berkeley has finished one manuscript for publication based on this research, are working on an additional manuscript, and recently submitted a patent on the developed technology.
- This project has supported two PhD student at Mines (Bahareh Tajdini; Seyed Khademi), one Post-doctoral research associate at Mines (Bahareh Tajdini), and a research professor (Leslie Miller Robbie).

NAWI – Mines Advanced Process Controls

Department of Energy National Alliance for Water Innovation (DOE-NAWI)
Title: Advanced Process Controls – Autonomous Control and Optimization
Project Number: NAWI Task 5.8
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Period of Performance: 3/2022 – 9/2025 (new cost extension was granted by DOE)
Reporting period: CY 2024
Mines Funding From NAWI: $811,235
Total CHECRA Funding: $162,247

Summary

Operations in water and wastewater treatment facilities are highly focused on continuously meeting the facility's performance standards regardless of disturbances caused by (a) variability in water source, demand, and quality and (b) degradation of critical components, such as process equipment and sensors. So far, the need for reliability has been addressed through redundancy (volumes, equipment); thus, leading to inefficient use of resources. Today, generic models rooted in machine learning, and adaptive control strategies offer a novel promise: the same reliability at unit- and plant-wide scale without redundancy, while spending minimal energy and resources. To evaluate this promise, in this project we develop and test broadly applicable control methods for adaptive optimization. The unique challenge is to design a single control framework that is applicable across a variety of water treatment systems, thus making efficient, low-cost operation available in rural, urban, coastal, and inland settings.

A demonstration-scale system at Mines is the core of the project; we are using a unique mobile lab that demonstrates **direct potable reuse (DPR)** of reclaimed water – a system that was design and constructed in CO with generous funds from the Colorado Water Conservation Board (CWCB), Colorado Springs Utilities, and the National Science Foundation. The core system is comprised of seven processes, including ozonation, biologically active carbon filtration (BAC), coagulation, ultrafiltration (UF), adsorption (GAC, ion exchange (IX), and Fluorosorb® (FS)), ultraviolet irradiation with advanced oxidation (UV-AOP), and chlorination.

Influent into the DPR systems (reclaimed water from municipal wastewater treatment facilities) can have highly variable quality due to daily and seasonal quality changes of the original source water, water use patterns during the day, and plant operating conditions, to list a few. And with the need to continuously produce very high-quality water, a DPR system must adjust rapidly to changing conditions, while individual unit processes in the train have lower rate constants and slow process adaptation.

Project Objectives

Adaptive plant-wide optimal control requires adoption of state-of-the-art methods for statistical process control, modelling, and machine learning. We selected methods based on successes in other industrial sectors and will solve the three most important challenges standing in the way:

Water quality sensors are prone to sensor faults. While short-lived faults, like outliers, can be addressed with state-of-the-art signal extraction tools, incipient and systematic faults, like drift and calibration errors, have resisted a highly automated approach.

While setpoint optimization, setpoint control, and disturbance rejection are feasible for simple process units with commercial hardware and software, there is no generally applicable control framework that allows optimization of complex processes or whole plants, thus preventing adoption in practice.

Treatment plants vary in their design, configuration, and operation. Indeed, a typical plant is customized to account for local and regional context (water demand, water source, legal requirements) and undergoes changes regularly (downtime, equipment degradation). This variety in design, status, and operation leads to customized control solutions for individual plants, which are expensive to maintain and often unaffordable for smaller plants.

We aim to develop and test technology and economic methods to address these challenges in coordination with multiple industrial partners, currently including Colorado Springs Utilities, Aurora Water, South Platte Renew (Englewood/Littleton), Metro Water Recovery, Hach, Carollo Engineers, Toray Membranes, Trojan, Aqua Aerobic Systems, inCtrl Solutions Inc., IntelliFlux Controls Inc., and Rockwell Automation. Most importantly, they provide advice, equipment, and in-kind contributions:

1. Colorado Springs Utilities, Aurora Water, South Platte Renew, Metro Water Recovery: access to data of the upstream plant, maintenance of a **direct potable reuse (DPR)** system, and water, power, and cellular services for the DPR trailer.
2. Hach: donated water quality sensors valued at $160,000 (!)
3. Toray: new ultrafiltration membrane
4. Trojan: new ultraviolet reactors

IntelliFlux Controls Inc.: access to software and industrial insights

Rockwell Automation: provision of control hardware for testing with industrial equipment

Together, these contributions ensure that the developed tools solve meaningful challenges and stand a chance to be broadly adopted in full-scale operations. Furthermore, our methods ar`s being tested on at least three full-scale plants managed by Colorado Springs Utilities (past, 2021-2022), Aurora Water (past, 2022-2023), and Littleton/Englewood South Platte Renew (2003-2024), Metro Water Recovery (2024), and South Platte Renew (again, 2024-2025). The interest in the project is exceeding all expectations, with invitation to test it next in Silicon Valley (CA).

Outcomes of Project over Past Year

So far, the trailer has produced more than 4,000,000 gallons of drinkable water from reclaimed water

The DPR mobile lab was operational at South Platte Renew (from August 2023 to May 2024), Metro Water Recovery / Robert W. Hite Treatment Facility (From May 2024 to September 2024), and back at South Platte Renew (October 2024 to present).

New water treatment processes and water quality sensors were added this year to the trailer, including:

- a high-water-recovery reverse osmosis (RO) system that enable us to compare side by side, simultaneously, and with the same water two direct potable reuse philosophies: carbon-based and RO-based DPR.
- an innovative ultraviolet reactor with LED lights (UV-LED). This new technology will enable disinfection and oxidation of recalcitrant contaminants at lower energy and operating costs compared to the old technology that uses low-pressure mercury lamps.
- New ozone sensors, turbidity sensors, and particle counters were added to the DPR system to enable better monitoring of water quality and investigate better maintenance of sensor for increased reliability.

The work in our mobile demonstration lab attracted attention across the country, and DOE/NAWI awarded us another $1.5M for two years of funding (including $500K cash cost share from the California Department of Water Resources). This funding initiated a unique collaboration between Mines and CU Boulder, and students from CU Boulder are now also conducting research in the trailer.

The national WateReuse Symposium was held in Denver in March 2024. Five full busses and many companies visited the DPR demonstration lab while deployed at South Platte Renew (Englewood).

The demonstration in Englewood brough more companies to invest in our research, including additional recent donations from Hach (water sensors) and membranes from NX Filtration for removal of organic matter and PFAS (>$10,000).

Our 5 months operation at Metro Water Recovery resulted in new internships and projects directed at increasing water quality before discharge of effluent back to the environment in preparation for the implementation of Regulation 31 in Colorado (removal of dissolved organic nitrogen and dissolved organic phosphorous).

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 emerging contaminants. These new technologies will be more energy intensive, require more educated operators and engineers, and will incorporate new concepts in machine learning and artificial intelligence (AI).

- 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.

Media resources:

- 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