Colorado State University

September 1, 2016

Office of the President
102 Administration Building
0100 Campus Delivery
Fort Collins, Colorado 80523-0100
(970) 491-6211
FAX: (970) 491-0501
www.colostate.edu

Fiona Arnold, Executive Director
Michelle Hadwiger, Deputy Director & Director of Global Business Development
Colorado Office of Economic Development and International Trade
1625 Broadway, Suite 2700
Denver, CO 80202

Re: Annual Report from the Colorado Energy Research Authority

On behalf of the Board of Directors of the Colorado Energy Research Authority ("the Authority"), in accordance with Section 24-47.5-102(3), Colorado Revised Statutes, I respectfully submit this report regarding the activities of the Authority during calendar year 2015.

The principal statutory purpose of the Authority is to direct the allocation of State matching funds to support research proposals of the Colorado Energy Research Collaboratory, a research consortium consisting of the Colorado School of Mines, Colorado State University, the University of Colorado Boulder, and the National Renewable Energy Laboratory ("the Collaboratory").

An Impressive Record of Successful Investment of State Funding

In 2006, the General Assembly appropriated $2 Million per year for three fiscal years, ending in June, 2009. H.B. 06-1322. These State matching funds were appropriated to the Authority for allocation to the Collaboratory. The Collaboratory has since then used these matching funds to attract and supplement funding from federal and private sources.

Under Section 24-47.5-103, as originally enacted in 2006, the Authority was required to demonstrate by June, 2012 that at least $6 Million in federal grants or contracts for renewable energy research in Colorado had been secured through the Collaboratory programs. In 2012, we reported that the General Assembly's 2006 commitment of $6 Million had attracted federal and industry funding in excess of $37 Million, far beyond the $6 Million baseline requirement.

Today, I am proud to report that the economic impact of Collaboratory operations and research funding in the state of Colorado has, over the years, resulted in an impressive return on the state's investment. Simply put, **between 2008 and 2015, the Collaboratory investment of almost $8 million was leveraged to attract more than $96 million in externally sponsored research, with an associated impact on the local economy of almost $194 million.** In more specific detail, the total economic impact of $193.9 million on Colorado constitutes a return of 24:1 on the state's original $7.96 million investment.

The state's investment in the Collaboratory has been extraordinarily productive economically, scientifically and technologically. A more detailed breakdown of the first-generation and next-generation

leveraged research for the past eight years is revealed in our recent Collaboratory economic impact report to be published in September 2016. **See Appendix D**.

The measurement of the Collaboratory's effective leveraging of State matching funds is a dynamic process. Many research projects that received State funds through the Collaboratory have spawned second, third, and now fourth generations of research, funded by federal, industry, and foundation sources. However, these subsequent generations of research generally receive no additional matching funds. As mentioned previously, between 2008 and 2015, the $7.96 million of state funding was leveraged into $96.6 million from industry, DOE, NSF, and other sources to support Collaboratory research projects. This total includes $53.5 million of first-generation sponsored research projects co-funded by the Collaboratory, and $43.1 million of sponsored research funding expended from 2008-2015 for next-generation research. Another $9.7 million committed by sponsors for next-generation research from 2016-2019 is not included in the total leveraged research because expenditure of these funds falls outside the 2008-2015 state funding period.

Subsequent to the General Assembly's 2006 appropriation of $6 Million, former Governor Ritter directed $2 Million to the Authority in 2010 (earned by and distributed to the Authority in 2011). Governor Ritter required that these funds be used for the same purposes and be accounted for in the same manner as defined by the General Assembly in 2006. Consistent with Governor Ritter's direction, the use of these funds has been and will continue to be reported in accordance with the General Assembly's requirements in Section 24-47.5-103.

The initial award of funds by the General Assembly and Governor Owens in 2006, Governor Ritter's 2010 commitment and the General Assembly's 2014 appropriation, with Governor Hickenlopper's support, have been essential to the shared goal of establishing Colorado as a clean energy research leader. The commitment of state funds allows the Collaboratory to successfully attract private support for the Collaboratory's centers and to successfully compete for federal research funding.

In **Appendix B** to this report, I summarize the two new grants awarded by the Authority and the Collaboratory in support of groundbreaking research in 2015. In most of the past eight annual reports from the Authority, the activities of the Collaboratory centers have dominated the discussion, because the centers received most of the state funds and conducted most of the Collaboratory-supported research activities. Each of these centers has been managed by a leadership team that includes representatives from all four of the Collaboratory institutions, with one institution serving as the lead. In short, these centers – and their great success to date – exemplify true collaboration.

The Collaboratory leadership, the Collaboratory center's management teams, the world class researchers, and the many administrative personnel who support research at the four Collaboratory institutions are responsible for the success of the Collaboratory. They are responsible for the scientific, technological, and economic benefits flowing to the State of Colorado. On behalf of all seven of the Directors of the Colorado Energy Research Collaboratory, I offer our thanks and admiration to these many outstanding individuals.

The Authority Board has authorized the Executive Committee to develop a forward-looking plan. Please see **Appendix C** to read the full Collaboratory 2.0 report for broadening the reach and impact of the Colorado Energy Research Collaboratory. This new model is a consequence of the cessation of state funding for the Collaboratory.

With full recognition that the State's funding has been critical to the Authority's and the Collaboratory's success, we are grateful for the past commitment of Colorado's elected leaders to the missions of the Authority and the Collaboratory.

Looking Towards the Near Future: Regional Clean Energy Innovation Multi-state Partnership

The Collaboratory is a uniquely successful model of true collaboration. We hope to use lessons learned as we host a regional clean energy innovation summit on the University of Colorado's Boulder campus on September 19, 2016. Our goal is to explore regional clean energy innovation opportunities through public-private partnerships, building on the recommendations as described in the National Research Council's 2012 Report, Rising to the Challenge, as:

- Linking local energy needs and regional industrial development to convert government R&D investment into domestic companies, industries, and jobs
- Utilizing private businesses, research universities, and economic development agencies to mobilize support for regional energy cluster initiatives
- Building on existing knowledge clusters and comparative strengths of a geographic region to address regional energy needs

We will use breakout sessions to explore regional strengths, needs and opportunities in grid/storage, food/energy/water, energy/climate and renewable sources that serve the North-Central / Inter-mountain West region of the United States. We are inviting nine states to join Colorado (ND, SD, NE, KS, MT, WY, UT, ID and NM). The upcoming regional summit will include representatives from industry, academia, national labs, NGO's, state economic develop agencies, state energy offices and government.

The Directors of the Colorado Energy Research Authority are grateful for the past support of Colorado's Governors and the Colorado General Assembly, and we are proud that we have exceeded your and our expectations in the effective investment of these State funds. We will be pleased to respond to any questions you may have at this time or in the future.

Sincerely,

Anthony Frank, Ph.D.
President and Chancellor, Colorado State University
Chair, Colorado Energy Research Authority

Copies:

Governor Hickenlooper
Directors of the Colorado Energy Research Authority

Appendix A

2015 Colorado Energy Research Authority

Board of Directors

Anthony Frank, Ph.D., President, Colorado State University
Chancellor, Colorado State University System
(Chair)

Paul Johnson, Ph.D., President
Colorado School of Mines

Martin Keller, Ph.D., Director
National Renewable Energy Laboratory
(Vice-Chair)

Philip DiStefano, Ph.D., Chancellor
University of Colorado Boulder

Jeffrey Ackermann, M.N.M., Director
Colorado Energy Office

Michelle Hadwiger, Deputy Director
Colorado Office of Economic Development & International Trade

Mark Sirangelo, CEO
Sierra Nevada Space Systems

Appendix B

2015 Collaboratory Activity

The total disbursements of Authority funding for 2015 were $666,667.

Renewable Carbon Fibers FOA 996

1. DOE awarded $3.5 Million to the NREL/CSM/CU team
2. Matching fund cost share commitment from Collaboratory was $500,000
    - $300,000 distributed to Colorado School of Mines
    - $200,000 distributed to CU Boulder
3. The principal researchers: Adam Bratis (NREL), John Dorgan (Mines) and Ryan Gill (CU Boulder).
4. The original proposal leverages expertise in biomass deconstruction at NREL and carbon fiber production/testing at Oak Ridge National Lab (ORNL) and DowAksa. The strategy is to convert biomass-based intermediates into carbon fiber-suitable acrylonitrile (ACN) that involves integrating catalytic and biocatalytic steps that have already been demonstrated in isolation. CU Boulder and Colorado School of Mines offer significant separation and purification technologies, in addition to the capabilities of NREL and ORNL, that can be employed at different stages of carbon fiber production. The NREL-led team's selected proposal offers a strategy to convert biomass-based intermediates into carbon fiber-suitable ACN. Besides Oak Ridge National Lab, NREL, CU Boulder, Colorado School of Mines and Dow Aksa, other partners include Idaho National Lab, Biochemtex, Johnson Matthey and Ford.

Next Gen PV III FOA 990

1. DOE awarded $1,335,226 to the NREL/CSM team
2. Matching fund cost share commitment from Collaboratory was $166,667
3. The principal researchers: Aaron Ptak (NREL) and Corinne Packard (Mines)
4. This project entitled "Optimized, low-cost, >30% efficient InGaAsP/Si tandem solar cells" includes researchers from NREL and Colorado School of Mines. The project will leverage the basic science and high-quality of quaternary InGaAsP III-V alloy systems recently demonstrated innovations in wafer reuse and best-in-class Si technology to create a mechanically stacked two-junction tandem cell architecture promising to surpass state-of-the-art efficiencies in a process that is economical and compatible with standard PV fabrication lines.

IP filings, Licenses, spinouts or jobs occurring in the calendar year 2015 that resulted from research that received Collaboratory matching funds. The following are aggregated from all four institutions. No data is available on spinouts or jobs created:

- Patent filings – 6
- Provisional patent status – 2
- Patent granted -- 1

Appendix C

Collaboratory 2.0

Broadening the Reach & Impact of the Colorado Energy Research Collaboratory

Executive Summary

The Colorado Energy Research Collaboratory is at an exciting crossroads. We have demonstrated the success of the program to enhance the collaboration among NREL, CSU, CSM, and CU for greater impact. As we explore the possibilities for the next decade, we envision greater collaboration with industry, state and federal partners to enhance the reputation of the Front Range as an energy leader and in the process grow our economic impact for Colorado and the nation. The report that follows outlines the actions to be taken to achieve our ambitious goals with key actions summarized as:

- **Regional Innovation Workshop**: The Collaboratory will lead a Regional Energy Innovation Workshop in September drawing on the expertise of the three Colorado Universities, the strengths of the Colorado industry, the capabilities of NREL and regional national labs and the partnerships with state and federal entities. The goal is to work together to define a regional energy strategy that we can collectively execute and that positions Colorado as an energy leader internationally.
- **Collaboratory Research Focus**: The Collaboratory has identified four focus areas where national needs and our institutional capabilities overlap: *Food-energy-water nexus, Biomass conversion to fuel and value-added products, Energy and climate, and Grid resiliency.*
- **Industry Action Board**: Leverage the Collaboratory member's industry partnerships by establishing an expanded industry board that will advise and advocate for the Collaboratory's strategic initiatives with State and National officials.
- ***Operational Principles:*** Moving forward, University VPR's/VCR's will rotate on an annual basis leading the CERC Board while maintaining an administrative assistant. In the short term, we will continue matching collaborative grants that line up with identified focus areas using up to 20% of remaining funds. We will re-evaluate hiring an executive director after the Collaboratory plans are solidified.

Expanding Collaboratory Economic Footprint

The research and development pursued by the Collaboratory historically has focused on the energy sector and related needs supported through solicitations by USG sponsors, principally DOE. The evolution of the sector has seen greater breadth and emergence of potential impact that could be made by the Collaboratory. For example, the biomass conversion into non-fuel high value materials such as long chain polymers or structural materials conducted by Collaboratory members presents new opportunities to expand areas of investment and to include new sectors for resource partnerships and economic development. In this example, new biomass conversion into high value would include opportunities in aerospace and textile industries and could be an opportunity to explore new strategic partnerships in those sectors.

Broadening from the foundations laid by the Collaboratory in the energy sector could also include better integration with utility infrastructures desiring new energy sustainable practices. Other opportunities for Collaboratory expansion include managing energy assets in agriculture operations, aerospace, water utilities and in urban planning activities. Collaboratory members are all active in these areas of emergence that also provide considerable job and economic growth opportunities in the Front Range. Interactions with agencies such as the Colorado Department of Agriculture, Denver Water and specific multinational companies in this space such as JBS, Ardent Mills, Leprino, Ball Aerospace, Sierra Nevada, Lockheed Martin, Google and Panasonic are examples of industries that have unmet needs in creating net zero enterprises and maximizing profits.

Growing Industry Engagement - It is clear from the state budget projections that the coming years are likely to be highly competitive for securing state support for the Collaboratory. Therefore, a specific strategy to solicit industry partnerships will be pursued. It will start with soliciting industry input on the best way to engage industry representatives in an advisory action board. Drawing from the industry partnerships held by each of the Collaboratory members, the industry representatives and sectors that would fit best with the expanded vision for the Collaboratory will be explored. We will also explore the value of the Collaboratory in other aspects of technology transfer and innovation that would be of interest to the industry. One goal of our long term resource planning should be to establish a much stronger relationship with industrial partners both regionally and nationally. This will diversify our funding base and could add significant leverage to our state aspirations for support.

The long term resourcing of the Collaboratory will require additional discussion and planning over the coming year. The pursuit of state support should actively continue and the Collaboratory should dedicate efforts to bring awareness of the Collaboratory's impact at the Capital. Specific resources should be identified to advocate for the Collaboratory in the legislature and opportunities to introduce specific legislation in support of the Collaboratory should be pursued. These include using existing Legislative Affairs assets in the Collaboratory and might be included in the rotation of administrative functions. Specific opportunities to align the Collaboratory with the Governor's priority budget requests should be sought especially if there is opportunity to leverage significant federal government or industry support match (e.g. National Manufacturing Initiatives). Participation by Authority Board members in these efforts could add significant impact to potential outcomes.

Current Focus

The next year will be critical to establish the working structure of the Collaboratory 2.0 going forward. The fall term will be used to host a regional meeting to refine the areas of research focus - four of which are articulated in the Appendix. This will provide inputs for the long term strategic planning focus and include regional and multinational industry and government leadership represented by the multiple federal agencies in the region.

Regional Innovation Workshop - Innovation is recognized as a key contributor to economic growth. The American Energy Innovation Council (AEIC) noted that, "Public investment is critical to generating the discoveries and inventions that form the basis of disruptive energy

technologies"; however, they systemically underinvest in research and development since they cannot capture the full economy-wide value of new knowledge that is generated. AEIC recommended a tripling of government investment in energy R&D which the President's Council of Advisors on Science and Technology (PCAST) fully endorsed. As a result, the FY17 Department of Energy (DOE) has requested a 10% increase in budget over FY16; a $5.8 billion dollar agency-wide proposal for mission innovation.

There are several elements to this proposal, but the establishment of regionally-based clean energy innovation centers focused on regional innovation capabilities, needs and opportunities is an important opportunity for the Collaboratory. Historically, federally funded R&D has not been connected to state and regional industrial development and bridging that gap can create the local talent and technology base to help convert these investments into domestic companies and jobs for the future. Bringing together educational institutions, private industry, economic development agencies, State and Federal leaders, and National Laboratories will help identify competitive strengths for regional cluster initiatives within a specific area. The Collaboratory universities and NREL are situated in the North Central Clean Energy Partnership Region and are working collectively to host a workshop in September. The Workshop is planned for September 19, 2016 and initial discussions suggest focusing on the topics identified within the Collaboratory. Additionally, the Front Range offers a unique intellectual capacity that can address climate change and other energy-related challenges that are essential for meeting COP21 goals for our nation.

While we recognize a focus on the Front Range may be too myopic, we have also reached out to support the University of New Mexico's Regional Innovation Workshop on July 5th to support and identify potential intersections of interest with the Southwest/Central region. We are also teaming with the Northwest region to support the University of Washington's meeting. There is also a possibility of identifying a specific workshop between the Northwest and the North Central regions to evaluate the potential of unique resources such as nuclear/renewable energy synergies.

Short Term Operational Plan - The Collaboratory continues to provide a unique source of collaborative funds amongst the university. In the next year we will use limited Collaboratory funds to continue to incentivize collaborations and cost share against national solicitations for energy research funding. This has been a highly successful model for Collaboratory operations as reflected by the significant economic gains and impact made using this investment model, the subject of a recent economic impact report. We propose to continue cost sharing for a very limited number of proposals and allocate 20% of the existing account (estimated total is $1.8M) over the next 18 months. Proposals funded in this period (approximately $360K) would be carefully scrutinized by the Collaboratory executive leadership to seek alignment with the 4 areas of focus identified and for which opportunities are presented in the appendix. Efforts would be made to leverage collaborations within the Collaboratory and internal seed investments being made in the Collaboratory institutions. These funds could also be used to attract regional industry partnerships.

In the short term, until more long term planning and resources are identified, the operations of the Collaboratory overseen previously by the Executive Director will be inherited by the

participating institutions in an annual rotation model. It is anticipated in the next year this will be include administrative support for meeting and event planning and proposal reviews. We will retain a .5 FTE assistant who will provide these services in the coming year. Each institution will take prime responsibility for overseeing these functions on an annual rotating basis. CSU will be responsible for the first year of administration of Collaboratory functions.

Short Term Leadership Structure **-** The leadership structure for operating the Collaboratory in its past mode of operations were effective as evidenced by the historic impact of investments made. For example, the selection of collaborative proposals to cost share has been made expeditiously and provided key support to great new ideas and researchers. Going forward, the leadership required could change and may need additional strategic leadership inputs to set direction and investments. In the next year we will explore new leadership structures that may be required as the long term planning proceeds. One example could be the creation of an industry advisory board to the Collaboratory as a way to gain valuable inputs on unmet needs in industries of import and build relationships of support. The Authority Board roles should also be examined to seek optimal use of leadership in identified focus areas. This could include more active roles in fundraising and advocacy for the Collaboratory at the state legislature. We will evaluate the need for replacing the Executive Director in the next year as we identify more clearly the operating model for the Collaboratory.

Next Steps

Organize and Convene regional workshop	Q4 2016
Develop long term plan for Collaboratory 2.0	Q1 2017
Define governance structure	Q1 2017
Define role of Industry board and identify key leaders for participation	Q4 2016

Collaboratory 2.0 -- Proposed Research Focus Areas

The Collaboratory has identified four focus areas where national needs and our institutional capabilities overlap. These include:

- **Food-energy-water nexus** (alternative water resources, reducing the dependency of the energy systems on freshwater, co-management of energy and water resources, reducing the dependency of the energy systems on freshwater)
- **Biomass conversion to fuel and value-added products** (biobased process development pipeline, algae and cyanobacteria, renewable advanced materials, heterotrophic organism engineering)
- **Energy and climate** (GHG emission reporting and abatement, other imaging and sensor technologies and applications)
- **Grid resiliency** (microgrid power systems, cyber security, grid management systems, energy storage)

The Collaboratory researchers are actively involved in all these areas at present, and the latter three categories have benefitted substantially from Collaboratory funding. Efforts to connect researchers in the food-energy-water areas are underway. Recently the Collaboratory has

generally been reactive in the sense that requests for funding have been driven by individuals at several institutions collaborating in response to a federal FOA. Looking ahead, we anticipate these focus areas will naturally evolve as new research needs become apparent and new capabilities emerge to address these issues. For example, we anticipate closer connections with local and national industries through such projects as the NNMI initiatives (National Network for Manufacturing Innovation).

Food/Energy/Water Nexus

Reagan Waskom, CSU; Karl Linden, CU; Jordan Macknick, NREL; John McCray, CSM

KEY RESEARCH TOPICS

1. Use of alternative water resources, including brackish groundwater and O&G produced water, to meet shortfalls in freshwater supplies, including water to grow food.
    a. Interested companies could include: Noble, Haliburton, Schlumberger, MWH, Encana and GE
2. Climate change impacts and decision support for energy development planning under changing water supply conditions.
    a. Interested companies could include: Xcel, PG&E, Duke and other large utilities
3. Co-management of energy and water resources through a combination of distributed and centralized infrastructure and operational decision-making frameworks.
4. Reducing the dependency and vulnerability of the energy system on freshwater resources, as it relates to the transportation sector, thermoelectric generation, and hydropower.
5. Determining the risk and mitigating potential environmental impacts of energy production, generation and consumption on freshwater sources.
6. Understanding the dynamics between societal expectations, policy, and technical issues.
7. Resource recovery, nutrient management, and carbon sequestration in low-energy or energy positive wastewater treatment solutions
    a. Interested companies could include: Bioelectric, LLC; Hysummit, LLC; Denver Metro wastewater treatment plant, Denver Water, Xcel (Cherokee plant), Suncor

Biomass conversion to fuel and value-added products

Adam Bratis, NREL; Ken Reardon, CSU; Matt Posewitz, CSM;
Ryan Gill, CUB; Jeffrey Cameron, CUB

KEY RESEARCH TOPICS

Biomass and Biotech:

1. Biobased process development pipeline from feedstock improvement to refining of the final product.
2. Improve and deploy algae and cyanobacteria in the production of renewable biofuels and other sustainable bioproducts.
3. Develop new biopolymers to produce renewable biomaterials that are cost effective relative to petrochemical routes.

4. Use our heterotrophic organism engineering and process engineering capabilities to advance strain selection, organism improvements and process engineering for the bioenergy, brewing and food industries.
5. Focus on hemp and cannibas to identify and extract high-value products, improve bioprocessing procedures for nutraceuticals, improve feedstock strains, and process residual biomass.
6. Biological capture and/or conversion of stranded methane and CO2 to biofuels and biopolymers.

Companies which may be interested in this research:

1. National/International
    a. ExxonMobil
    b. Phillips 66
    c. Dow
    d. DuPont
    e. Cargill etc.
2. Larger Colorado Companies:
    a. Whitewave Foods
    b. Chipotle
    c. Leprino
    d. Gates
    e. Coors
3. Smaller Colorado Companies:
    a. Ardent Mills
    b. Longmont Dairy
    c. JBS Five Rivers
4. Colorado Polymer Companies:
    a. Gates
    b. Reynolds Polymer Tech
5. Hemp/Marijuana:
    a. Growers: Livwell, Maggies Farm, DBDRx farm
    b. Oil extractions: Bluebird Botanicals, Nuleaf Naturals
    c. Biofuels: PureVision Technology, PureHemp Technology
    d. Note: National (Rocky Mountain) Hemp Association is based in CO.

Energy & Climate

Bob McGrath, CU; Dag Nummedal, CSM; Garvin Heath, NREL; Bryan Wilson, CSU

KEY RESEARCH TOPICS

1. Methane Measurement & Mitigation:

- Colorado has established a reputation as the national leader in measurement & mitigation of methane emissions from oil & gas production methane:
    - Major industry / EDF (Environmental Defense Fund) studies by CSU & CU/NOAA
    - Industry / RPSEA / Collaboratory study with CSM, CSU, and CU/NOAA

    - ARPA-E MONITOR project at CU, NOAA, NIST
    - ARPA-E MONITOR field test site contract to CSU / CSM
  - Identified as a national priority by interagency task force led by the White House/OSTP
  - State of Colorado passed first methane measurement law and is co-leading national task force
  - Strong engagement by Colorado oil & gas companies (Noble, Anadarko); opportunities for Colorado aerospace industry for remote monitoring, 5 tech startups identified
  - Strong future funding potential by government (DOE/Fossil, EPA, DOT/PHSMA, USDA, NSF), industry (oil & gas, cleantech investment), and environmental community (Environmental Defense Fund and others)
  - Potential future, high impact research topics
    - Source attribution to enable discernment amongst the multiple sources of methane
    - Cost effective strategies for identification and quantification of super-emitters
    - Better understanding of the root causes of failures that lead to emissions and the persistence (temporal variability) of episodic emission sources
    - Quantification of emissions from abandoned O&G infrastructure
2. **Greenhouse Gas Emissions Reductions Research in Colorado**
  - Carbon Capture Utilization and Storage - Team: Braun, Tilton, Way, Gutierrez, Sitchler (CSM)
  - Carbon Negative Oil - Team: E. Dean, H. Kazemi (CSM)
  - Coal Gasification - Team: Porter (CSM)
  - Safety and efficiency of subsurface CO_2 Storage–Team: Gutierrez, Sitchler, Illangasekare (CSM)
  - Methane Emissions Quantification/Reconciliation – Team: Zimmerle (CSU), Petron (NOAA), Heath (NREL), Smits (CSM)
  - Methane emissions sensing technologies - Team: Tilton, Zhang, Smits (CSM), Zimmerle (CSU), Petron (NOAA)
  - Safety of subsurface methane storage and transportation – Team: Mooney, Fleckenstein (CSM)
3. **Global Green House Gas (GHG) Emission Reporting & Analysis System (GHG-ERAS)**
  - GHG-ERAS has emerged from the Annual DOE "Big Ideas" Summit with potential for Seed Funding in FY17. If appropriated funds by Congress, ERAS could potentially receive $70M/yr for the next 5-10 years
  - The goals are GHG-ERAS are to
    - To provide science-based data to measure progress and ensure the success of DOE's clean energy innovation programs to reduce energy-related GHG emissions
    - To support International partners towards global success of limiting global temperature rise to below 2˚C (Paris Accord Target)
  - NREL is one of 11 DOE National Laboratories supporting GHG-ERAS
  - Our Front Range regional team is exceptionally well positioned to contribute to this initiative should it be funded by leveraging across ongoing Front Range initiatives such as:
    - New methane sensor development under ARPA-E funding – George (CU),

- Well-head methane leakage detection funded by EERE – Smits et al. (CSM)
- Airborne monitoring of CO_2 and other GHG emissions by NOAA, NCAR, CU's Institute for Alpine & Artic Research Center (INSTAAR), and CU's Collaborative Institute for Research on Environmental Sciences (CIRES)
- Orbital satellite based GHG emissions regularly conducted by NCAR and by CU's NASA sponsored Laboratory for Space & Atmospheric Physics (LASP)
- Extensive NCAR HPC modeling of atmospheric chemistries and GHG emission effects on global and regional climate and weather patterns

• Potential Industry partners include: Chevron, Southwestern Energy, ExxonMobil (XTO), Norway's StatOil, the American Gas Association and US-China Clean Energy Research Center.

4. Oxy-Combustion: Motivated by greenhouse reduction goals

• Burning fuels in gas turbines & engines using oxygen rather than air produces an exhaust stream of only CO_2 and water, simplifying the task of isolating CO_2 for sequestration

• High temperature operation is a challenge, but can be managed through advanced combustion, better high temperature materials, and new designs of turbine blades & combustion components

• Identified as an emerging priority by DOE/Fossil Energy and utilizes expertise in Collaboratory institutions (Combustion: CSM, CU, CSU; Materials: CSM, CSU, NREL; thermal design: NREL, CU, CSU, CSM) and Colorado industry (Woodward, Barber-Nichols, Lockheed-Martin, Sierra Nevada, others)

• Not an area of current excellence, but Collaboratory institutions have the technical capabilities to respond to this emerging opportunity area.

5. **Energy storage**

a. Seen as a critical element of managing an electric grid with greater levels of variable renewable energy production.

b. Technical aspects of deployment, management and system effects are proposed within the Grid Resiliency topic area.

c. Additionally, gaps exist to understand the economic and climate *impacts* of the increased utilization of energy storage, for instance that can enable increased penetration of variable renewables:

i. Scenarios of increased penetration considering other changes to the grid through economic and operational optimization

ii. Paired techno-economic and environmental analyses are needed to estimate: materials requirements, capital costs, resulting electricity price, and achievable GHG reductions levels.

Grid Resiliency

Jim Cale, NREL; Dan Zimmerle, CSU; Salman Mohaghegi, CSM; Tyrone Vincent, CSM; Bob Erickson, CU; Mari Shirazi, NREL

KEY RESEARCH TOPICS

Resilience of the energy system:

1) Energy Security: Rapid detection and isolation of critical electrical loads, to be supplied through an islanded microgrid, with particular focus on industrial plants and manufacturing systems.
   a) Subtopics include: ability to continue to service critical electrical loads when grid is weak or blacked-out; ability to identify imminent failure of the grid and respond; ability to "clean up" faulty power when connected to a weak grid, and focus on *critical infrastructure:* industry, medical, first responder, military, etc.
2) Cyber Security: Ensuring confidentiality, integrity and availability of systems and components against potential cyber intrusions.
3) Systems Integration: The integration of key supporting technologies such as energy storage, controls, demand response and distributed energy generation.

Companies which may be interested in resilience research:

i. Local utilities
ii. Major equipment manufacturers: Schneider, Eaton, Caterpillar, Woodward, etc.
iii. IT companies that want to move into the energy space: Google, Intel
iv. Startups in microgrid space: Spirae
v. International players trying to enter U.S. equipment space: LG, Toshiba
vi. Grid-connected battery manufacturers: Tesla/Matsushita, A123, LG Chem, Toshiba

Advanced Manufacturing:

4) High-speed magnetic and acoustic sensing for non-destructive evaluation and process control, including embedded data acquisition and fast computational processing
   Data analysis, pattern recognition and machine learning for quality control and situational awareness across the plant
5) Advanced sensing and control for oil and gas well exploration and gathering systems
6) Energy security and management for manufacturing plants, such as microgrid capability and demand response for normal and contingency circumstances, resulting in higher energy efficiency.
7) Wide bandgap power electronics for MVDC microgrids

Companies which may be interested in advanced manufacturing research:

i. Defense and aerospace companies: Lockheed Martin, Raytheon, and Ball Aerospace
ii. Companies supporting the oil and gas industry: Hydro Technologies
iii. Wide bandgap semiconductor companies: GE and Cree

Appendix D

Colorado Energy Research Collaboratory

Partners for Clean Energy

FINAL REPORT ON ACTIVITIES AND IMPACTS

2008-2015

Colorado School of Mines
Colorado State University
National Renewable Energy Laboratory
University of Colorado Boulder

September 1, 2016

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INTRODUCTION TO THE COLLABORATORY

The Colorado Energy Research Collaboratory ("The Collaboratory") is a clean energy research consortium, focused on renewable energy, energy efficiency, and the reduction of adverse impacts from fossil fuels. It is a uniquely Colorado partnership. The Collaboratory unites the science and engineering research capabilities of four outstanding institutions: Colorado School of Mines, Colorado State University, the National Renewable Energy Laboratory, and the University of Colorado Boulder.

Together, these four institutions offer a breadth and depth of clean energy and energy efficiency research capabilities – and a spirit of cooperation – unmatched by any American clean energy research community. The Collaboratory works closely with public agencies, industry partners, and universities and colleges to:

1. Develop renewable energy products and technologies for rapid transfer to the marketplace
2. Support economic growth with renewable energy industries
3. Educate the finest energy researchers, technicians, and workforce

Proud of its service as an economic driver for Colorado, the Collaboratory works with many Colorado, United States, and multinational renewable energy companies and with many of the world's leading oil and gas companies.

MANAGEMENT OF STATE FUNDS

Between 2006 and 2014, by legislative action of the Colorado General Assembly and administrative action by Governor Bill Ritter, the State of Colorado allocated a total of $10 million to the Colorado Energy Research Authority, for use by the Collaboratory. The state funds made available to the Collaboratory have been used with great success to attract private and federal funding through three different activities:

1. Industry-University Research Centers

Four industry-university research centers were established to coordinate Collaboratory investments in strategic areas. Industry partners paid annual membership fees, generally matched with state funds on a 1:1 basis. Industry representatives and Collaboratory center leaders identified research categories, invited proposals from researcher teams, jointly reviewed proposals and selected the best proposals for funding. Projects were selected based on merit and were not limited to the technical thrusts of the centers. Project funding amounts typically ranged between $50,000 and $100,000 for six to twelve months of research. The four centers are:

- Colorado Center for Biorefining and Bioproducts
- Center for Research and Education in Wind
- Center for Revolutionary Solar Photoconversion
- Carbon Management Center

2. First-Generation Leveraged Research

Collaboratory funds have been strategically invested to leverage additional funding for research priorities. Sources particularly include the U.S. Department of Energy (DOE), the National Science Foundation (NSF), other federal agencies, and private industry. Most DOE funding opportunities require the applicants to provide "cost share," ranging from 5 percent to 50 percent of the total project budget. The Collaboratory leaders consider requests to use Collaboratory funding for cost share on proposals only if two or more of the four Collaboratory institutions are participating in the proposal. This practice has proven to be extremely successful, both by bringing high-quality, high-profile research to Colorado, and by increasing communication and collaboration among researchers at the four institutions.

3. Next-Generation Leveraged Research

State funds allocated to the Collaboratory have been used to support the four designated industry-university centers and to co-fund sponsored research in partnership with industry, DOE, NSF, and other sources. Those research activities represent first-generation research. But later generations of research have frequently grown out of the first generation, building upon key scientific findings and critical relationships established with sponsoring agencies or companies. Collaboratory funds have been strategically invested in research activities deemed to have significant potential for leveraging next-generation sponsored research that is enabled by the initial Collaboratory co-funded work and is supported with new external funding. Collaboratory investments have already generated second, third and even fourth generations of research.

FUNDING AND IMPACTS

The state of Colorado invested $7.96 million in the Collaboratory from 2008-2015. The $7.96 million of state funding was leveraged into $96.6 million from industry, DOE, NSF, and other sources to support Collaboratory research projects from 2008 to 2015. This total includes $53.5 million of first-generation sponsored research projects co-funded by the Collaboratory, and $43.1 million of sponsored research funding expended from 2008-2015 for next-generation research. Another $9.7 million committed by sponsors for next-generation research from 2016-2019 is not included in the total leveraged research because expenditure of these funds falls outside the 2008-2015 state funding period.

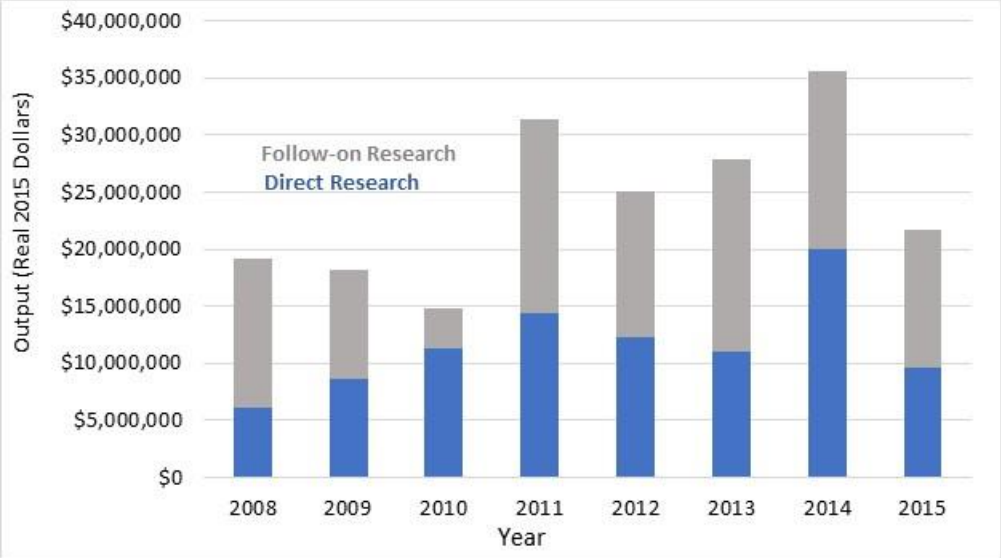
Methodology: IMPLAN Model

The economic impact of the $96.6 million of Collaboratory leveraged research spending was analyzed using the IMPLAN model. IMPLAN (implan.com) is an input-output model designed to support state and regional economic analysis, creating industry multipliers based on underlying economic data specific to the region of study. A multiplier is a numeric way of describing the full effects of money changing hands within an economy. The IMPLAN v.3 model was developed specifically for the state of Colorado using national and Colorado economic and demographic data. All Collaboratory leveraged research funding was assigned to scientific research and development services (sector 456) in the IMPLAN model. The impacts are presented in fixed, 2015 dollars, and discounted using model price deflators.

The IMPLAN model shows that the direct spending of $96.6 million in Collaboratory leveraged research funding had a total economic impact of $193.9 million on Colorado. This total is shown by

year on Figure 1. Of this total impact, $103.6 million constitutes the net value added to the gross domestic product (GDP) of Colorado from 2008-2015. The total economic impact of $193.9 million on Colorado constitutes a return of 24:1 on the state's original $7.96 million investment. The state's investment in the Collaboratory has been extraordinarily productive: economically, scientifically and technologically.

Figure 1: Economic Impact of Collaboratory Total Leveraged Research, By Year



Employment and labor impacts of Collaboratory operations and research were also estimated by the IMPLAN model and are shown on Table 1. The model projects an average direct employment (headcount) impact of 43 workers per year with an average annual wage of $72,700. The wages for these high-quality direct jobs are 34 percent higher than the 2015 state average wage of $54,179. The total employment impact is 133 workers per year, averaging $48,700 per worker.

Table 1: Economic Contribution of Collaboratory Total Leveraged Research on The Colorado Economy, 2008–2015 (Real 2015 Dollars)

Impact Type	Average Employment	Labor Income ($ Millions)	Value Added ($ Millions)	Output ($ Millions)
Direct Effect	43	$34.1	$44.9	$89.5
Indirect Effect	47	$21.2	$33.3	$55.1
Induced Effect	43	$16.0	$28.3	$49.3
Total Effect	**133**	**$71.3**	**$106.4**	**$193.9**

This analysis does not include societal benefits stemming from the energy research performed and the economic impact from licensed technology and spinoff companies. The following pages highlight some of the major Collaboratory research activities and their potential for transformative solutions to the nation's energy challenges. These activities position Colorado as a national and international headquarters for clean energy research and technology commercialization.

RESEARCH HIGHLIGHTS

The Collaboratory is first and foremost a research organization. The primary goal is to create and commercialize technologies for clean energy technologies or improvement of energy efficiency. The Collaboratory also supports regional economic development by advancing Colorado as a national and international headquarters for renewable and sustainable energy technologies.

The Collaboratory has received recognition within Colorado and nationally for its coordinated approach to energy research and regional economic development. In 2008, the Metro Denver Economic Development Council awarded the Chair's Award for Outstanding Efforts in Economic Development to the Collaboratory. In 2014, the Collaboratory was recommended as a model for technology transfer efforts by DOE laboratories in other regions of the country. (*Going Local: Connecting the National Labs to their Regions for Innovation and Growth*, Brookings/ITIF/CCEI, 2014).

The Collaboratory supports world-class research at the four participating institutions to address our national need for clean energy and energy efficiency, and connects this research to commercial markets through partnerships with industry. The effectiveness of these efforts is illustrated through brief descriptions of five major research activities:

1. Fuel from Cellulosic Biomass

Production of gasoline- and diesel-fuel molecules from biomass is a Collaboratory research priority linking unique regional strengths and national needs. Collaboratory institutions have world-class expertise spanning the biofuels process, including crop selection and engineering, product isolation, biologic and abiotic catalytic processing, product refining, and economic and market development. Sustainable feedstock development and more effective processing of biofuels are cornerstones that can be used by large and small businesses in Colorado and elsewhere, from farms to factories, to create products of value.

One of the major successes in this area was the National Advanced Biofuels Consortium. With $1 million of Collaboratory funding to help meet cost-sharing requirements, a national team led by Collaboratory institutions leveraged $35 million of federal DOE funding and $15 million of private industry funding to investigate three topics: high-temperature conversion of cellulose; high-temperature depolymerization of lignin; and low-temperature depolymerization of lignin. The objectives of these efforts were to increase knowledge of underlying biofuels-related chemistry, and to move the technologies toward improved process performance and hydrocarbon yields.

The research team successfully advanced four technologies that can produce high-quality fuel from biomass, utilizing existing fuel production and distribution infrastructure. They successfully tested more than 10 liters of fuel produced from biomass, and established requirements for construction materials in biorefineries. The research also reduced the modeled cost of fuels from cellulose by up to 50 percent, and showed these fuels to have greater than 60 percent reduction of greenhouse gas emissions versus petroleum-derived gasoline and diesel fuel.

2. Fuel from Photoautotrophic Microorganisms

Use of photoautotrophic microorganisms (algae and cyanobacteria) in the production of renewable biofuels is another Collaboratory priority based upon substantial research expertise among Collaboratory institutions at every level of the process chain. With $240,000 of Collaboratory funding provided to help meet cost-share requirements, Collaboratory institutions and other U.S. academic and industry partners successfully leveraged $18.5 million of DOE, industry, and other funding.

Research efforts have been focused on exploration of enzymatic conversion of algal biomass to lipid-based and carbohydrate-based fuels, testing the ability of algal biofuels to function as replacements for petroleum-based fuels, and developing recovery and recycling techniques to minimize use of phosphate, nitrogen, and other nutrients. Accomplishments to date include: the establishment of a biomass processing protocol that maximizes energy return on investment and can be easily adapted to separate and extract valuable chemical streams to improve process economics; verification that fuels derived from algae biomass are suitable petroleum fuel replacements; and establishment of a nutrient recovery protocol that allows the reuse of over 70 percent of the nitrogen required for algal cultivation.

Colorado's research institutions are at the forefront of the algal biofuels field, and this established expertise is successfully attracting federal and private research partners to enable additional advances. DOE-sponsored national and international meetings on research progress were conducted in Colorado, allowing first-hand demonstration of Colorado's world-class research talent and facilities. Collaboratory researchers have produced several high-impact scientific publications that are regarded as seminal within the biofuels research community.

3. Renewable Carbon Fiber Materials

Carbon fiber composites are lightweight, strong, and stiff. These materials are currently used to build lighter, more fuel-efficient, safer motor vehicles and other products including wind turbine blades. In each example, strength and flexibility are essential for the larger systems needed to produce greater amounts of electricity. At present, carbon fibers are made from petroleum and natural gas feedstocks through very energy-intensive processes. The high costs of the raw materials and the energy used in the manufacturing result in a high cost for carbon fibers. The cost constrains use of this product by automotive, aerospace, wind energy, and other sectors.

Collaboratory-supported researchers leveraged $5.3 million in DOE funding to develop and demonstrate a process for creating carbon fibers from renewable biomass feedstocks. This work has been focused on demonstrating the production of carbon fiber-based materials from the chemical compound acrylonitrile (ACN) which is produced from lignocellulosic biomass-derived sugars. The overarching objective is to demonstrate the pathway to a technology that can produce renewable carbon fibers at commercial scale and at a competitive cost.

Currently researchers are deploying a novel synthetic biology platform for the rapid development of microbes that produce carbon fiber precursors. Microbial strains have been successfully modified to economically produce two precursors at laboratory scale, which are then transferred to partners for scale-up and integration with downstream catalytic processing. Efforts are also aimed at developing bioplastics and bioplastic nanocomposites

that address ecological concerns, are biologically derived, and that make use of the unique properties of nanoscale materials.

4. High Efficiency Photovoltaics

Development of more efficient photovoltaic materials and systems is a Collaboratory priority leveraging strengths at all four partner institutions and with major implications for the Colorado economy, the nation, and the world. The Collaboratory invested $1.98 million of state funding to support research projects at the four institutions. These modest research investments attracted an additional $10 million in federal and industry-sponsored solar energy research funding.

Collaboratory researchers are advancing the forefronts of photovoltaic physics, chemistries and opto-electronic materials, as well as development of new laser-based techniques to measure at femtosecond time scales (10^{-15} seconds) the real-time dynamics of electron and positive charge generation, separation, and transport. These processes govern the efficiencies of converting sunlight absorbed by these new materials into solar electricity or solar fuels.

Other research activities are: addressing manufacture of highly efficient silicon solar cells in thin film form (as opposed to standard wafers); development of triple-junction solar cells on patterned silicon templates; low-cost growth of III-V alloys for dual-junction solar cells on silicon; development of very high ionic-conductive proton exchange membranes (PEMs) and solid oxide membranes; and examination of inorganic silicon and germanium clathrates for renewable energy applications.

A fundamental goal of this work is to enable large-scale penetration of photovoltaics into the electricity grid by making them cost-competitive with fossil fuel sources. Colorado is home to a large concentration of scientists with expertise in materials sciences, physics, chemistry, chemical engineering, economics, business and public policy who are working together to advance high- efficiency photovoltaics. These researchers serve as a foundational base of a regional ecosystem of innovation in solar energy.

5. Reducing Methane Emissions

The Collaboratory institutions are leaders in research for detecting and measuring methane lost to the atmosphere while natural gas is gathered and transported from wellheads to local distribution networks. Methane is the primary component of natural gas, a fuel that emits half as much carbon dioxide as coal when burned. But methane is a greenhouse gas many times more potent than carbon dioxide when released into the atmosphere unburned.

With $350,000 of state funds provided by the Collaboratory to help meet cost-share requirements, researchers leveraged $4.9 million from DOE, industry, and other sources to better assess and ultimately reduce methane emissions from natural gas operations worldwide. Research activities include quantification of emissions from natural gas gathering facilities, processing plants, transmission stations and storage facilities; development of more sensitive, accurate, and lower-cost methane detection technologies; and

development of methods for on-site conversion of methane from flare gases emitted at the wellhead to liquid crude oil.

Collaboratory-supported researchers are also deeply involved in long-term efforts by the National Oceanic and Atmospheric Administration (NOAA) to track changing levels of methane, carbon dioxide, and other atmospheric species important in climate change and air quality. Recent findings suggest that methane emissions from oil and gas development vary widely by region. Many regions emit far more of the gas than EPA and international estimates suggest, while other basins emit less. Better understanding of these regional variations are expected to yield keys for reducing methane emissions.

LOOKING FORWARD

The four industry-university research centers supported by the Collaboratory helped to build strong networks of researchers across the four institutions. These networks became the source of numerous teams of Collaboratory researchers who have won competitive research grants from DOE and other federal agencies and other sources. As the level of collaboration among the four institutions has grown stronger, and the close connections to industry partners established through the centers has evolved, future Collaboratory investments will emphasize potential to leverage federal, industry, and other research funds in priority thrust areas.

From 2008-2015, the biofuels, solar, and wind sectors helped to build and broaden Colorado's economy, and these sectors will continue to play a significant role in Colorado's economic growth. Looking forward, Collaboratory leaders have identified four additional areas of energy innovation which will play increasingly large roles in federal funding and in Colorado research and economic growth: the food/energy/water nexus; energy/climate; electric grid and storage; and renewable sources. It is anticipated that these thrust areas will naturally evolve as new needs become apparent and new discoveries and capabilities emerge.

See **Appendix C** for more details as approved by the Collaboratory Authority Board.

Collaboratory Economic Impact Report Appendix A
ECONOMIC IMPACT ANALYSIS

The economic impact of the Colorado Energy Research Collaboratory was analyzed by the Business Research Division of the Leeds School of Business at the University of Colorado Boulder. The Collaboratory works to: 1) develop renewable energy products and technologies for rapid transfer to the marketplace; 2) support economic growth with renewable energy industries; and 3) educate the finest energy researchers, technicians, and workforce.

The Collaboratory has used state funding to support research at the four participating Colorado institutions in partnership with industry and government co-sponsors and to support the following industry-university research centers:

- Colorado Center for Biorefining and Bioproducts (C2B2)
- Center for Research and Education in Wind (CREW)
- Center for Revolutionary Solar Photoconversion (CRSP)
- Carbon Management Center (CMC)

Overview and Methodology

Economic impacts derive from Collaboratory operations, which are funded by the four partner institutions. Additionally, economic impacts derive from research supported and enabled through the Collaboratory. The state of Colorado provided $7.96 million in funding to the Collaboratory from 2008–2015 to support research. The four partner institutions contributed a total of $1.9 million from FY2008 through FY2015 to operate the Collaboratory.

The Collaboratory provided project-level data for the study including Collaboratory funding amounts, total research funding amounts, and budget periods for each project. This included projects supported through the four designated industry-university research centers, as well as for research projects co-funded by the Collaboratory in partnership with other sponsors. Funding for multi-year projects was evenly distributed across the project years.

Economic impact analyses model the direct spending of a company or institution, as well as the indirect spending, which is the ripple effect that direct spending has on other businesses in the community. This term is also referred to as the multiplier effect. A multiplier is a numeric way of describing the full effects of money changing hands within an economy. This includes indirect impacts, which are from spending by the institution or activity within its supply chain, and induced impacts which come from spending by employees in their local communities.

This study uses the IMPLAN model to analyze the economic impact of Collaboratory operations and of research. IMPLAN (implan.com) is an input-output model designed to

support state and regional economic analysis, creating industry multipliers based on underlying economic data specific to the region of study. The IMPLAN v.3 model was created specifically for the state of Colorado using national and Colorado economic and demographic data.

The IMPLAN v.3 model was used to perform the economic impact analysis using 2014 economic data which is the latest available. All research and Collaboratory funding was assigned to scientific research and development services (sector 456) in the IMPLAN model (similar to professional, scientific, and technical services in the NAICS hierarchy). Data were provided in nominal dollars, quantified in the estimated year of expected impact. The impacts are presented in fixed, 2015 dollars, and discounted using model price deflators. For this analysis, all research was assumed to be conducted by institutions within the state.

Scenarios Data and Assumptions

The Collaboratory expended $7.96 million of state funds from 2008-2015 to support the four designated industry-university research centers and research projects co-funded in partnership with other sponsors. In addition, from 2008-2015, the Collaboratory received $1.9 million in institutional support from the four partner research institutions for Collaboratory administrative operations (an average of $59,000 per institution per year). These funds were leveraged to become part of $53.5 million in first-generation Collaboratory research projects. These research projects were co-funded by the Collaboratory along with multiple other sources including industry, DOE, and NSF.

Next-generation or follow-on research builds upon and extends the findings of the first-generation research. Next-generation Collaboratory research is primarily supported by industry, DOE, and other federal sources but with no additional financial support from the Collaboratory. The four research institutions searched research databases and interviewed investigators to identify next-generation research commitments, estimated at $52.9 million. Nearly 60 percent of the next-generation research projects are multi-year, the longest being seven years. Nine projects extend beyond the analysis period in this report (2015). Excluding the committed future funding, next-generation research through 2015 is estimated at $43.1 million.

Table 1: Collaboratory Next-Generation Funding

Year	Next-Generation Funding by Year of Initial Collaboratory Investment	Next-Generation Funding by Approximate Year of Expenditure
2007	$3,028,450	$0
2008	$14,734,999	$5,224,113
2009	$24,007,336	$3,828,614
2010	$489,025	$1,402,344
2011	$1,539,517	$7,176,608
2012	$5,643,628	$5,504,442

2013	$1,426,000	$7,371,186
2014	$2,022,823	$7,030,612
2015	$0	$5,610,578
2016	$0	$3,602,904
2017	$0	$3,204,426
2018	$0	$2,078,810
2019	$0	$857,143
Total	**$52,891,778**	**$52,891,778**

Results

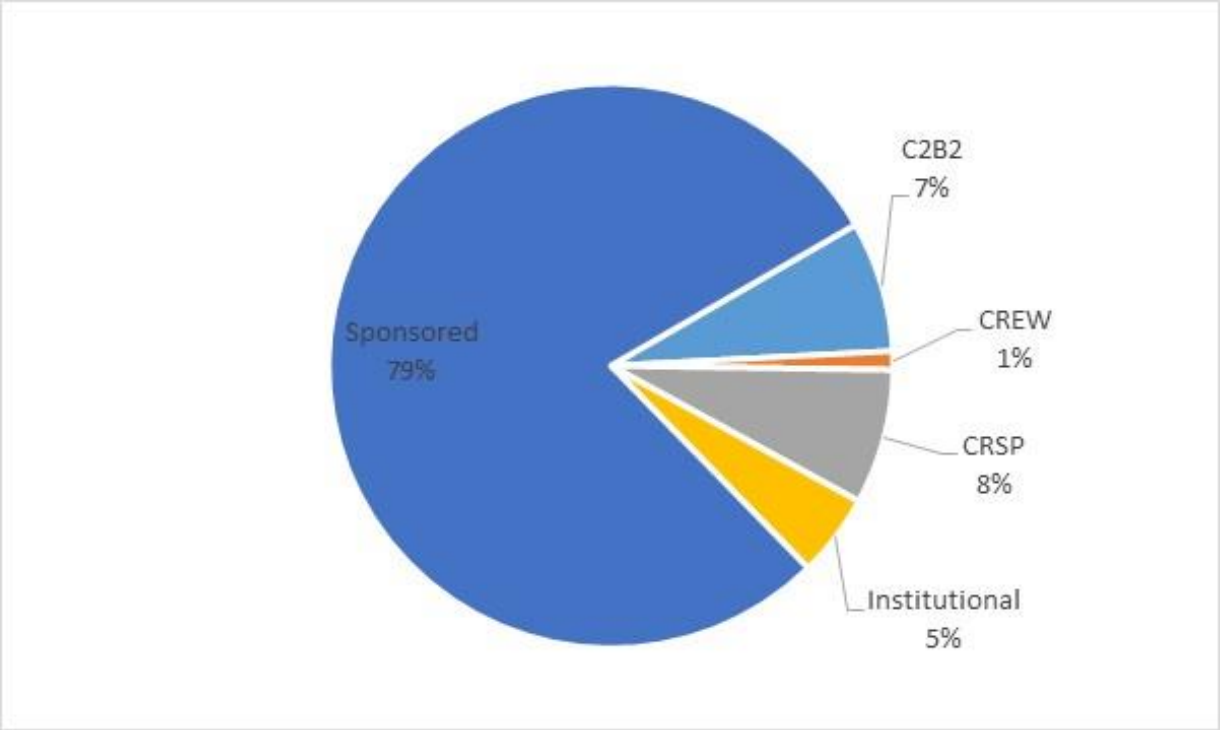
The $7.96 million of state research funding was leveraged into $53.5 million in first-generation research projects co-funded by the Collaboratory with industry, DOE, NSF, and other sponsors for an economic impact of $93.3 million from 2008-2015. The impact on value added (GDP) was approximately $51.2 million. The impacts from co-funded first-generation research are shown in Table 2.

Table 2: Economic Contribution of First-Generation Research on The Colorado Economy, 2008–2015 (Real 2015 Dollars)

Impact Type	Average Employment	Labor Income ($ Millions)	Value Added ($ Millions)	Output ($ Millions)
Direct Effect	21	$16.4	$21.6	$43.1
Indirect Effect	23	$10.2	$16.0	$26.5
Induced Effect	21	$7.7	$13.6	$23.7
Total Effect	**64**	**$34.3**	**$51.2**	**$93.3**

Overall, the greatest economic impact from co-funded research is derived from co-funding of sponsored research grants from DOE, NSF, and other sources. Co-funded sponsored research accounts for 79 percent of the overall economic impact. Impacts from Collaboratory operations and from support provided to industry-university centers accounts for the remaining 21 percent as shown on Figure 1.

Figure 1: Economic Impact of First-Generation Research by Type



The $43.1 million in next-generation research funding resulted in an economic impact of $100.6 million from 2008-2015 (in fixed, 2015 dollars). The impact on value added or gross domestic product (GDP) was approximately $52.4 million. These impacts are shown in Table 3.

Table 3: Economic Contribution of Next-Generation Research On The Colorado Economy, 2008–2015 (Real 2015 Dollars)

Impact Type	Average Employment	Labor Income ($ Millions)	Value Added ($ Millions)	Output ($ Millions)
Direct Effect	22	$17.7	$23.3	$46.4
Indirect Effect	24	$11.0	$17.3	$28.6
Induced Effect	22	$8.3	$14.7	$25.6
Total Effect	**69**	**$37.0**	**$55.2**	**$100.6**

The $7.96 million of state funding led to $53.5 million in leveraged first-generation research funding and $43.1 million in next generation research from 2008-2015. Economic impacts in Colorado were estimated at $93.3 million for first-generation research, and $100.6 million for next-generation research, for a total impact of $193.9 million from 2008-2015.

The employment and labor impacts were estimated using the economic impact model, which illustrated the employment and wage impact based on industry averages for scientific

research and development services. The four institutions, especially the universities, would likely record a greater employment impact than what is reflected in the model given the utilization of part-time researchers and graduate research assistants. The model projects an average direct employment (headcount) impact of 21 workers per year, averaging $72,700 per worker, and an average total employment impact of 64 workers per year, averaging $48,700 per worker.

SUMMARY AND CONCLUSIONS

This paper provides an analysis of the economic impact of Collaboratory operations and research funding in the state of Colorado. Essentially, between 2008 and 2015, the Collaboratory investment of almost $8 million was leveraged to attract more than $96 million in externally sponsored research, with an associated impact on the local economy of almost $194 million. Specifically, the study found the following:

- The Collaboratory leveraged $7.96 million of state funds into $53.5 million of co-funded first-generation research from 2008-2015.
- Next-generation research expenditures are estimated at $43.1 million from 2008-2015, and $9.7 million from 2016-2019.
- The economic impact of $96.6 million of total Collaboratory-leveraged research from 2008-2015 was $193.9 million.
- Support from the four partner institutions totaled $1.9 million from 2008-2015.

The societal impacts of energy research discoveries, and the economic impacts of licensed research, spinoff companies or technologies, were not included in this analysis.

Collaboratory Economic Impact Report Appendix B
BIOMASS AND BIOTECH RESEARCH

The Collaboratory identifies and enables positive synergies among the state's premier energy research entities. As a result, multi-institutional expertise can be mobilized to identify and capitalize on the most promising biotechnological opportunities and address some of our most pressing societal challenges. The Collaboratory has enabled the formation of several multi-institutional collaborations on bioenergy and biorefining, and these teams have been awarded several highly competitive federal biofuels research grants. The Collaboratory also facilitates the formation of high-quality research teams to provide the private sector with world-class research expertise that is not readily available within most corporations.

BIO-BASED PROCESS DEVELOPMENT PIPELINE

The Collaboratory institutions have world-class expertise in the bio-based process development pipeline, from feedstock improvement to refinement of the final product, including:

- Crop selection and engineering
- Biological and abiotic catalytic processing
- Product isolation
- Economic analysis
- Systems integration
- Feedstock development
- Novel market identification capabilities

These intellectual insights and process development capabilities can be applied to alternative products and sites of deployment. Sustainable feedstock development and more effective processing are cornerstones that can be developed for use by large and small businesses in Colorado and elsewhere, from farms to factories, to create products of value.

PRODUCTS FROM AGRICULTURAL AND WOODY BIOMASS

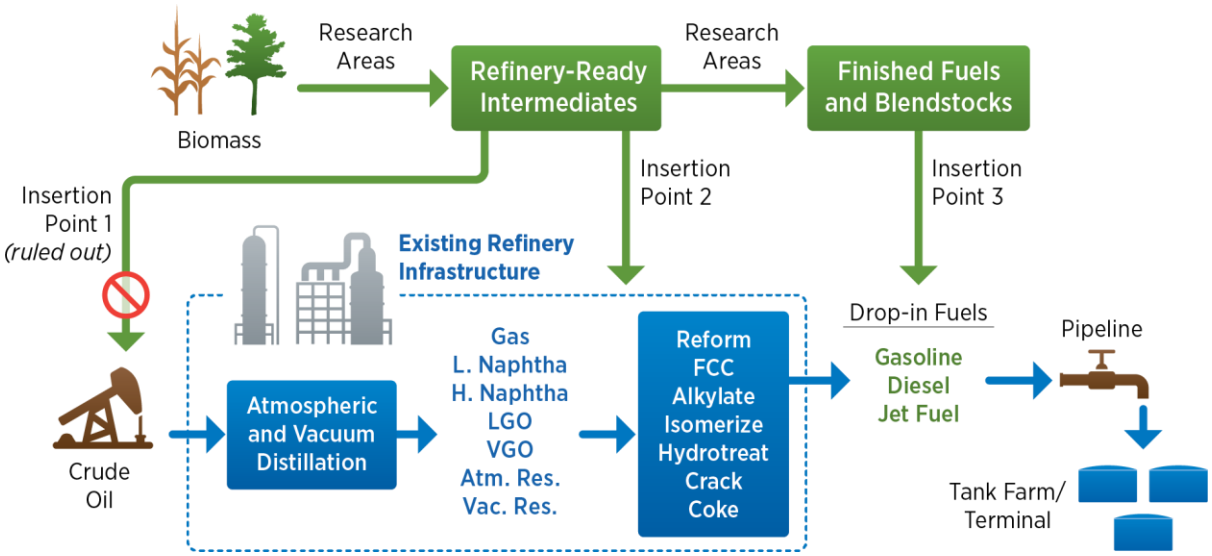
The National Advanced Biofuels Consortium (NABC) was a Colorado-based consortium that won a major DOE competitive research award, and NABC is a prime example of the Collaboratory development pipeline from feedstock to product to market. NABC was established in 2010 to develop biomass-based alternative fuels that can be "drop in" replacements for gasoline and diesel fuel. The funding level was $50 million, with federal funding of $35 million from the American Recovery and Reinvestment Act of 2009 (ARRA), and private funding amounted to an additional $15 million. The Collaboratory contributed $1 million in cost share to support NABC's proposal to the DOE. After NABC was selected by DOE as the primary grantee, the consortium performed research, development, and analysis over a three-year period, ending in December 2013.

NABC brought together 17 partners from academia, national laboratories, and industry. The partners represented the entire fuel production chain, from biomass growers to technology developers and refinery fuel producers. NREL led the consortium and CSM was a member of the fundamentals team, along with NREL, Los Alamos National Laboratory, Iowa State University, and Northwestern University. The NABC team investigated three primary areas:

- High-temperature conversion of cellulose,
- High-temperature depolymerization of lignin
- Low-temperature depolymerization of lignin

The objective of these efforts was to help understand the underlying chemistry and move the technologies toward improved process performance and hydrocarbon yields. The major themes of NABC were to examine technologies that make gasoline and diesel fuel from biomass, and to consider how today's fuel production and distribution infrastructure can be used in the process.

NABC Refinery Integration Strategies



By the end of its three-year run, the NABC:

- Advanced four technologies that make high quality diesel or gasoline from biomass that can fit into today's fuel production and distribution infrastructure.
- Tested more than 10 liters of NABC-produced gasoline and diesel products at the refinery integration partners' facilities for compliance with ASTM International fuel standards.
- Developed a fuels blending model to understand the value of biomass derived materials and the impacts of incorporating the materials into refineries.
- Significantly reduced the modeled cost of fuels production by up to 50 percent by implementing a multitude of technical accomplishments.

- Developed detailed process models for the NABC conversion pathways that were used for directing research, determining economics, and evaluating life-cycle greenhouse gas emissions.
- Established requirements for construction materials required in biorefineries, including information on processes not previously documented in related literature.
- Showed the fuels to have greater than 60 percent reduction of greenhouse gas emissions versus petroleum-derived gasoline and diesel thus meeting the U. S. Environmental Protection Agency Renewable Fuel Standard goals for cellulosic biofuels.
- Established ecological studies on the impacts of dual cropping of switchgrass and loblolly pine. The plots that were established will allow a comprehensive analysis of soil and water quality as well as wildlife impacts. Preliminary results obtained during the duration of the NABC were encouraging.

The Bioenergy Alliance Network of the Rockies (BANR) is a $10 million project funded by the USDA National Institute of Food and Agriculture. The BANR team, led by CSU, consists of five universities, NREL, the US Forest Service, and Cool Planet, a Colorado company. BANR aims to explore the use of beetle-killed and other forest biomass as a bioenergy feedstock, and provide rigorous scientific underpinnings to support a sustainable regional renewable energy industry. There are five project thrusts: feedstock supply; feedstock logistics and processing; system performance and sustainability; education; and outreach.

CSU researchers and their collaborators have been awarded several large DOE and USDA grants to evaluate and improve crops for production of biofuels and other chemicals. These include:

- A $1.5 million 2008 DOE grant to enable exploitation of the genes and pathways relevant to biomass accumulation in grasses. Genes were identified to expedite improvement of productivity in candidate biomass plants (switchgrass, *Miscanthus*).
- A $1.35 million 2011 DOE grant focused on perennial grasses, including switchgrass, for development as new energy biomass crops. The goal of this research was to leverage knowledge from rice to expedite discovery of biomass genes in switchgrass.
- A $1.4 million 2013 DOE grant with the goal of understanding how plants respond and adapt to drought stress at the molecular level as a critical need for developing plants that can grow under water-limiting conditions.
- A $1.5 million 2014 DOE grant which focuses on the oilseed crop *Camelina sativa*. The goal of this project is to improve *Camelina* qualities for an oilseed feedstock in the Great Plains and Western US.

CSU researchers and their collaborators were also active in developing the products of biorefineries. There has been an active collaboration with NREL on biofuel testing, including the evaluation of cellulosic biomass-derived oxygenates as drop-in fuel blend components. Eugene Chen has been funded by the NSF and industry to develop renewable polymers, work that earned him a prestigious Presidential Green Chemistry Challenge Award in 2015.

FUELS FROM ALGAE AND CYANOBACTERIA

Each of the institutions within the Collaboratory has substantial research expertise to improve and ultimately deploy photoautotrophic microorganisms (algae and cyanobacteria) in the production of renewable biofuels and other sustainable bioproducts. Through the activities of the Collaboratory's Colorado Center for Biorefining and Bioproducts, the programs of the four institutions have become highly collaborative.

Colorado's extensive experience in this area is well developed, and member institutions are poised to make additional advances at every level of the process chain: cultivation, strain improvements, product isolation and process development. Phototropic microorganisms are also receiving renewed attention in the area of food security and as animal/fish feed. Collaborations among the Collaboratory institutions can be leveraged for new opportunities in this area.

The Sustainable Algal Biofuels Consortium (SABC) was a collaborative biofuels research effort that involved a highly successful research partnership of Colorado-based and other American research institutions. Selected by DOE for funding, SABC included NREL, CSU, Arizona State University, Sandia National Laboratory, and the Georgia Institute of Technology, as well as industry partners SRS Energy and Novozymes. The overarching objectives of this $7.5 million project ($6 million in DOE funds and $1.5 million in cost share including $240,000 in Collaboratory funds) involved developing strategies to:

- enzymatically convert algal biomass to lipid-based and carbohydrate-based biofuels,
- test the ability of algal biofuels to function as replacements for petroleum-based fuels,
- recover and recycle inorganic growth substrates (e.g., phosphate, nitrogen) to minimize new fertilizer inputs.

Building upon the successful relationships in NABC, the SABC collaboration developed productive synergies between two intrastate research institutions (CSM and NREL), as well as premier research universities outside of Colorado, another DOE national laboratory, and two highly successful industrial partners.

The SABC project was funded and managed by DOE's Bioenergy Technologies Office (BETO), which has a significant administrative presence in Golden, CO. As a result, many of the sponsor-mandated research progress meetings were conducted in Colorado, allowing both NREL and CSM to host partnering institutions, as well as DOE representatives, and to demonstrate first-hand the world-class research talent and facilities at both NREL and CSM.

The SABC project helped to lay the research foundation for CSM to successfully compete for several new algal biofuel research grants, which currently include a $10 million collaborative project within the DOE's BETO program (Colorado State University is a partner in this collaboration), $175,000 in a subcontract from NREL to continue the collaboration initiated in the SABC program, and $1 million from ExxonMobil to enable technical advances within their biofuels portfolio.

Significant results from the SABC program included:

- the establishment of a biomass processing protocol that maximizes energy return on investment, and that can be easily adapted to extract targeted chemical streams with greater value than fuels to improve process economics,
- verification that fuels derived from algae biomass are suitable petroleum-fuel replacements, and
- establishment of a nutrient recovery protocol that allows the reuse of over 70 percent of the nitrogen required for algal cultivation.

Colorado's research institutions are widely recognized to be at the forefront of the algal biofuels field, and this established expertise is successfully attracting federal and private research partners to enable additional advances. SABC produced several high-impact scientific publications, including manuscripts co-authored by CSM and NREL that are regarded as seminal studies within the biofuels research community. SABC funding allowed significant expertise to be developed at NREL and CSM, which is being leveraged to secure the funding necessary to address the next series of challenges. SABC funding was also critical for enabling a productive collaboration between NREL and CSM that remains active and allows CSM students access to national laboratory expertise, resources and funding streams. And Colorado State University helped to create algae production technologies to produce feedstock for biofuels, pharmaceuticals and cosmetics.

CSU also participated in the DOE funded National Alliance for Advanced Biofuels and Bioproducts (NAABB) consortium, a three-year, $48.6M project that began in 2010 that was designed to spur the domestic algal biofuels industry and create new jobs. NAABB consisted of 39 institutions and had 2 international partners and $19.1 million in cost-share. The main objective of NAABB was to combine science, technology, and engineering expertise from across the nation to break down critical technical barriers to commercialization of algae-based biofuels. The approach was to address technology development across the entire value chain of algal biofuels production. Sustainable practices and financial feasibility assessments underscored the approach and drove the technology development. CSU researchers developed a process to convert lipid-extracted algal biomass to additional fuels and chemicals, evaluated algal biofuel properties, and investigated the use of algal biomass as a nutritional supplement for livestock.

NEW OPPORTUNITIES IN BIOBASED PROCESSING

- Heterotrophic organism engineering: Heterotrophic organism engineering (and associated process engineering) is a core strength of the Collaboratory. Colorado is home to major bioenergy, brewing and food industries that can benefit from expertise in strain selection, organism improvements and process engineering.
- Hemp and cannabis: The hemp and cannabis industries are recent additions to the Colorado economy. Opportunities likely exist to identify and extract high-value

products, improve bioprocessing procedures for nutraceuticals, improving feedstock strains, and process residual biomass.

- Biological capture and/or conversion of stranded methane and CO_2 to biofuels and biopolymers: Colorado is home to many oil and gas production companies, from small local producers to large multinationals. Many wellheads are not connected to natural gas gathering and transmission pipelines. The capture of this "stranded" methane and conversion of the gas into biofuels and biopolymers will help producers generate income while complying with state and federal emission standards. And Colorado manufacturers will have a local source of biopolymers for new, greener products.

Collaboratory Economic Impact Report Appendix C
RENEWABLE MANUFACTURING

Many of today's products – from cars to construction materials – are produced from metals and plastics that have limited useful lives and are manufactured from raw materials that are not sustainable. All four of the Collaboratory institutions engage in cutting-edge research and commercialization activities focused on the development and demonstration of advanced manufacturing materials that are more durable, more efficient and more sustainable.

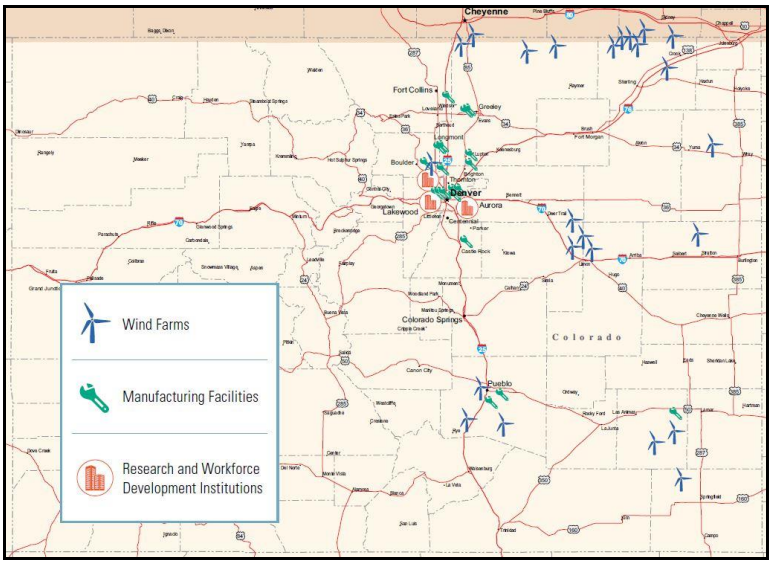
Soon, advanced materials and manufacturing processes will be used to create greater efficiency and reduce the cost of renewable energy from wind turbines. And increasingly, America's factories will produce manufacturing materials from renewable sources that will be lighter, stronger, more sustainable and less expensive than much of the steel used today to manufacture cars and trucks. As a result, tomorrow's vehicles will be lighter and more fuel efficient, with no reduction in safety.

NREL researchers are presently leading collaborative research efforts on two advanced materials and manufacturing projects. The first relates to the use of advanced composite manufacturing to increase the efficiency of wind turbines in generating electricity. The second project focuses on the production of carbon fibers – a key component of many advanced composite materials – from renewable sources.

RENEWABLE COMPOSITES FOR WIND ENERGY

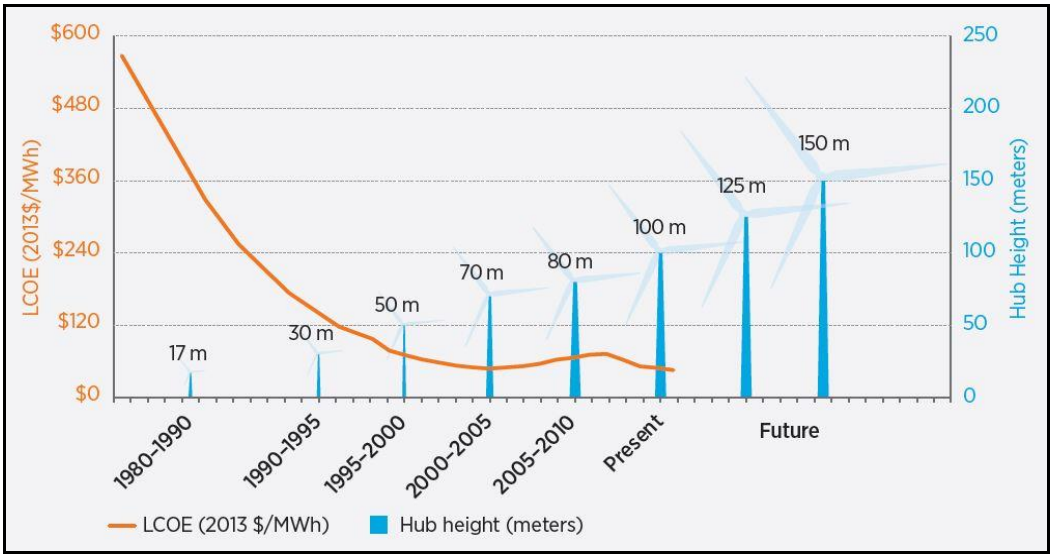
NREL and the three Collaboratory universities are all participating in a DOE-funded program to develop advanced composites manufacturing technology to generate and use energy more efficiently. The DOE-funded Institute for Advanced Composites Manufacturing Innovation (IACMI) is tasked with developing new composite materials and production methods to meet these goals. (http://iacmi.org/) Five research teams are led by senior representatives at the following institutions: NREL is leading the Wind Turbines Technology Area; DOE's Oak Ridge National Laboratory leads the Composite Materials & Processing Technology Area; Michigan State University leads the Vehicles Technology Area; Purdue University leads the Design, Modeling & Simulation Technology Area; and the University of Dayton Research Institute leads the Compressed Gas Storage Technology Area. As the five topical areas of focus suggest, advanced composite materials and fabrication will impact a broad range of manufacturing and commercial activities.

NREL and the Colorado universities are particularly interested in the application of advanced composites to wind power technologies. For NREL, wind power is central to its mission to develop and disseminate renewable energy technologies. In fact, NREL played a key role in bringing wind power technology to commercial scale in the 1980's. Wind power technologies are also a priority for the Colorado universities. Wind power creates Colorado jobs and drives our economy, while bringing clean, affordable power to Colorado residents and industries.



Wind Industry Impact on Colorado
(Source: Winds of Change, E2 Environmental Entrepreneurs)

The blades on wind turbines must be both flexible and strong. As turbine technology grows ever larger, lighter weight and longer blades can capture more energy from the wind, thus producing more electricity. But, in capturing more of the wind, the blades can be subjected to greater loads and stresses, which can damage or even break the blade, taking a wind turbine out of operation. And, even when the longer blades can survive the great stresses, the rotor can transfer these increased loads to the turbine's gear box and generator, potentially causing damage to these key components. Therefore, advanced composite manufacturing technology must be utilized in the areas of blades and other turbine components to allow for greater energy capture without increasing the system loads throughout the wind turbine structure.



Reduced Cost of Wind Energy with Larger Turbine Technology and Longer Blades
(Source: Wind Vision: A New Era for Wind Power in the United States, U.S. Department of Energy, 2015)

NREL is working with the universities and with private industrial wind partners to develop new materials and innovative fabrication techniques that will allow wind turbine blades to meet these challenges. As we build stronger blades, we also build a stronger Colorado and national economy.

RENEWABLE CARBON FIBER MATERIALS

At present, there are no renewable materials that can provide the necessary flex and resistance to meet the challenging performance requirements for wind turbine blades, so most of the wind-related IACMI research is focused on composite materials that are not primarily sustainable and renewable. That next step – the development of high-performing materials from renewable and sustainable sources – is the subject of the second DOE-funded research project led by NREL. NREL, the Colorado School of Mines and the University of Colorado Boulder and working to develop renewable carbon fibers.

Carbon fiber composites are lightweight, but strong and stiff. These materials can help build motor vehicles that greatly improve vehicle fuel efficiency, while providing safety for passengers. The light weight, strength and stiffness of carbon fiber can also be valuable in the manufacture of many other products.

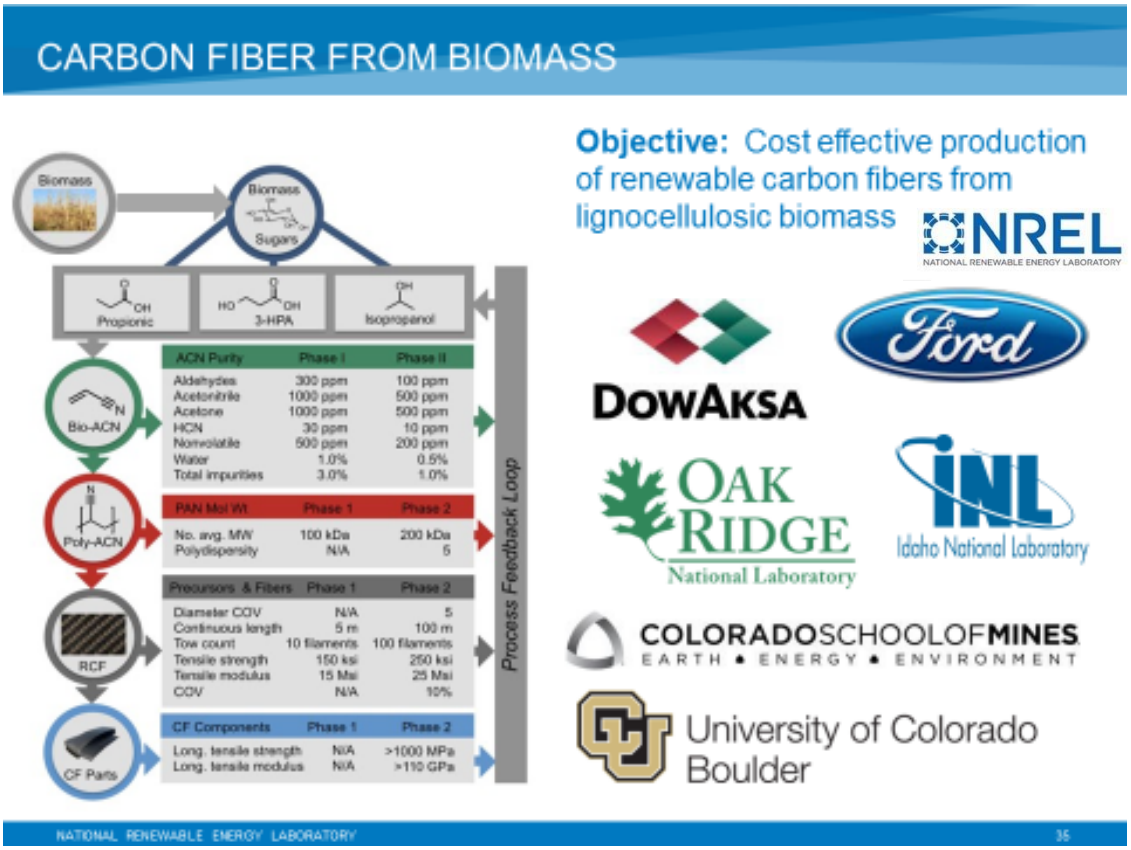
At present, carbon fibers are typically made from petroleum and natural gas feedstocks through processes which are very energy intensive. The variability of the raw material costs and the energy used in the manufacturing result in a high cost for carbon fibers, which constrains use of this product by the automotive, aerospace, wind energy, and other industry sectors.

In 2014, the DOE's Bioenergy Technologies Office announced a competition for funding to demonstrate a new technology pathway to produce high-performance/low-cost renewable carbon fibers. NREL, CSM and CU joined with additional research and industry partners to form the Renewable Carbon Fiber Consortium (RCFC) and to submit a joint proposal to DOE. In 2015, the RCFC proposal was selected by DOE to receive $5.3 million in funding to develop and demonstrate a process to create carbon fibers from renewable biomass feedstocks.

The overarching objective of the RCFC proposal is to demonstrate the production of carbon fiber-based materials from a chemical (acrylonitrile or "ACN") produced from lignocellulosic biomass-derived sugars. The ultimate deliverable is 50 kilograms of ACN, converted into a carbon fiber (CF) component for performance testing at a modeled commercial production cost of <$1.00/lbs. for ACN. If successful, this project will demonstrate the pathway to a technology that can produce renewable carbon fibers at commercial scale and at a competitive cost.

Under the direction of Professor Ryan Gill, CU Boulder is participating in the Carbon Fiber project by deploying a novel synthetic biology platform for the rapid development of microbes that produce carbon fiber precursors. CU is providing strains modified to

economically produce two precursors at laboratory scale, which are then transferred to partners at NREL for scale-up and integration with downstream catalytic processing.



Professor John Dorgan, Colorado School of Mines, is a co-Principal Investigator on the Renewable Carbon Fiber Consortium and also a member of Colorado's IACMI research team, focused on new materials for wind turbine blades. His work on both of these DOE-funded research projects is guided by his commitment to the twelve principles of green chemistry. In particular, Dorgan studies "ecobionanocomposites," a new class of materials that address ecological concerns, are biologically derived and make use of the unique properties of nanoscale materials. His research focuses on developing new bioplastics and bioplastic nanocomposites which are based on renewable resources as well as on new process technologies for biorefining.

Collaboratory Economic Impact Report Appendix D
ADVANCED SOLAR PHOTOVOLTAICS

Founded in 2008, the Center for Revolutionary Solar Photoconversion (CRSP) brings together the four major Front Range research institutions: the University of Colorado Boulder (CU Boulder), Colorado State University (CSU), the Colorado School of Mines (CSM) and the National Renewable Energy Laboratory (NREL), along with many industry partners, to support revolutionary advances in solar energy conversion and utilization.

CRSP scientists are advancing the forefronts of photovoltaic physics, chemistries and opto-electronic materials, as well as development of new laser-based techniques to measure at the femtosecond time scale (10^{-15} seconds) the real-time dynamics of electron and positive charge generation, separation, and transport. These processes govern the efficiencies of converting sunlight absorbed by these new materials into solar electricity or solar fuels. CRSP seed grant investments have led to numerous federally sponsored research contracts from the Department of Energy's (DOE) Office of Science for advances in new photovoltaic materials, such as quantum dot semiconductors (see sidebar).

CRSP seed grants have also led to R&D contracts from the DOE Office of Science and the National Science Foundation (NSF) for development of new spectroscopic techniques that enable *Multidimensional Femtosecond Studies of Chemical Reaction Dynamics* in these new materials. David Jonas, from the Department of Chemistry at CU Boulder and CRSP CU Site Director, has pioneered these sophisticated, ultrafast, multiple laser beam measurement techniques. Capitalizing on the unique expertise that Jonas and other remarkable scientists from NREL and JILA provide, the Renewable and Sustainable Energy Institute (RASEI) at CU Boulder is co-investing with NREL to establish a Joint Advanced Spectroscopic Facility (JASF) in the new laboratory building within the Sustainable Energy & Environment Complex (SEEC) at CU Boulder.

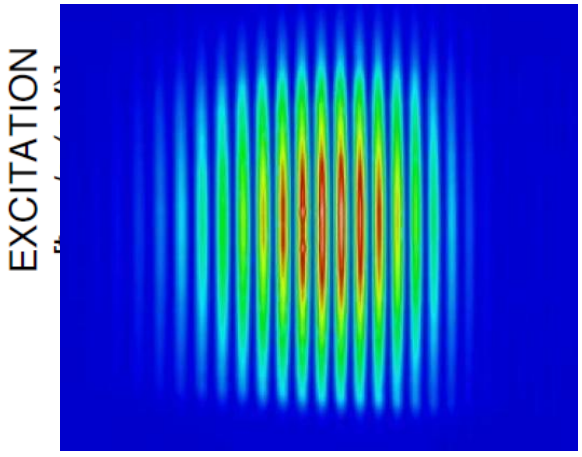


Figure 1: Spectral interferometry (left) measures the oscillations of coherent light waves with sub-femtosecond (1 fs = 10^{-15} s) accuracy, which is *faster than electrons move in semiconductors.*

At the same time that CU researchers are laying the groundwork for highly efficient solar cells of the future, CRSP is also supporting research to bring down the cost per watt of today's solar panels. CRSP investments in the work of Dr. Joseph Beach at the Colorado School of Mines, working with NREL, assisted U.S.-based First Solar, Inc. to reduce the installed price of PV systems from roughly $8 per watt in 2008 to $4 or less per watt in 2014, with the cost of large systems dropping below $3 per watt.

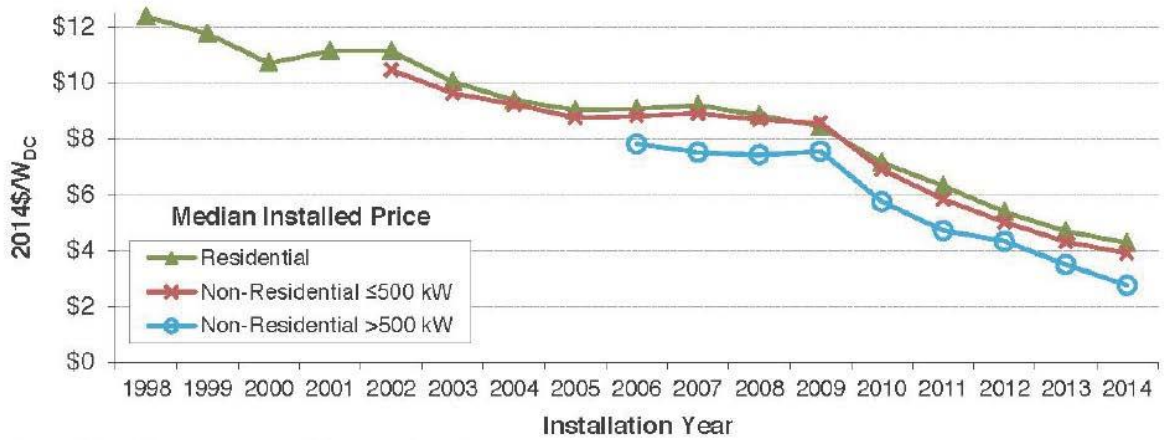
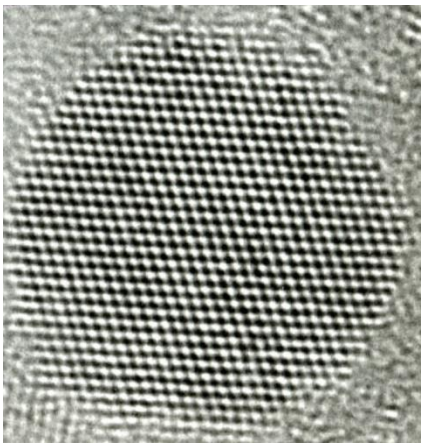


Figure 2: Installed PV Prices Normalized to 2014 Dollars (LBL/NREL *Tracking the Sun* Report Summary, August 2015)

Over the years, CRSP has provided seed funding or matching funding to 40 different research projects to stimulate academic, industry, and government research partnerships in photovoltaic materials and systems, with the amount of seed funding ranging from $25,000 to $100,000. Since CRSP's launch in 2008, CRSP has distributed a total of $1.98 million in state funding to support these research projects. These modest research investments attracted an additional $10 million in federal and industry sponsored solar energy R&D to the Collaboratory institutions.

Importantly too, these research projects served as a foundational base of a Front Range ecosystem of innovation in solar energy that has enabled CU Boulder to attract and retain 40 outstanding faculty members with expertise in materials sciences, physics, chemistry, chemical engineering, economics, business and public policy. These CU Boulder faculty members have successfully competed for currently active solar research grants and contracts totaling over $40 million from federal, industry and foundation sources. Colleagues at CSM and CSU have enjoyed similar successes in attracting additional funding based upon CRSP-supported research.



An electron microscope photo of a spherical quantum dot (QD) of silicon. At this small size, quantum effects become very strong and result in unique photophysical properties. As a result, the photoconversion efficiency of a solar cell is greatly increased when QDs are incorporated.

At the Colorado School of Mines alone, more than 20 seed grants have been funded, in whole or part, through CRSP. These seed grants explored synthesis, modeling, and characterization of isolated silicon nanostructures and nanostructures in novel matrices to create architectures where new physics can be harnessed to optimize energy and charge transport through novel size dependent properties.

Some of this CRSP research resulted in a DOE-funded SunShot project, with funding of $600,000 per year for 5 years. This research led to the exciting and surprising discovery of "hot" electrical carriers, which are excited by light. This paradigm holds the promise of highly efficient silicon solar cells that are manufactured in thin film form (as opposed to thick wafers).

Two other DOE-funded projects, funded through the Next Generation Photovoltaics III program within the SunShot Initiative, were enabled by matching funds provided through CRSP. Both projects are collaborations between Colorado School of Mines and NREL. One project focuses on the development of triple junction solar cells on a patterned silicon template. The second project focuses on low-cost growth of III-V alloys for dual-junction solar cells on silicon. Each project is funded by DOE at $1.5million, plus cost share from CRSP.

Other CRSP research focused on Next-Generation Proton Exchange Membranes (PEMs) and solid oxide membranes, leading to a grant from the Army Research Office (also about $600,00 per year for five years). This research on PEMs has resulted in materials with the highest ionic conductivities (for protons) of any PEM membranes. Similar research on solid oxide membranes also resulted in record ionic conductivities and a collaborative project with a local ceramics company (CoorsTek).

A final CRSP seed project examined inorganic silicon and germanium clathrates for renewable energy applications. This work spawned an international conference, in part based on these materials, which was held at Mines in the summer of 2015. This also contributed to

an Energy Frontier Research Center (EFRC) led by Carnegie Institution of Washington (with Colorado School of Mines as an active participant), which focuses on novel forms of silicon subject to extreme environments.

CSM's Renewable Energy Materials Science and Engineering Center, funded by the National Science Foundation, also funded research on thin films for PV Applications, which was co-funded by NREL's Non-Proprietary Partnering Opportunity program, and related work on high-efficiency silicon-based tandem solar cells (co-funded by NREL's Laboratory-Directed Research and Development program). The principle investigator, Dr. Adele Tamboli, recently received a five-year DOE Young Investigator award to pursue further studies of these materials.

NREL has an extremely strong and comprehensive program in solar energy research, representing roughly half of the DOE's solar funding in the U.S. Solar energy research at NREL spans from basic materials science, including new materials and new fundamental light harvesting mechanisms, all the way to development of reliability standards that PV modules must comply with for the industry as a whole. Within the National Center for Photovoltaics (NCPV) at NREL, the goal is to enable large scale penetration of PV into the electricity grid by reaching the aggressive cost target of 6 cents/kWh (kilowatt hour) by 2020 and 3cents/kWh by 2030 for unsubsidized solar PV installations. At 6 cents/kWh, PV installations are cost-competitive with fossil fuel sources, and the more aggressive 2030 target enables additional funds to be spent on energy storage to address the intermittency of solar and other renewables.

Research in the NCPV includes a variety of leading PV technologies, including crystalline silicon (currently the majority of the PV market), thin-film technologies with CdTe (cadmium telluride) and CIGS (copper indium gallium (di)selenide), high-efficiency III-V materials for concentrated photovoltaics (CPV) applications, and newer technologies such as perovskite materials. NREL's NCPV also includes:

- A Materials by Design program, which integrates theory and experiment to rapidly advance new PV materials
- The world-class Measurements and Characterization Group, which provides certification for PV efficiency measurements, as well as an impressive variety of microscopic measurement techniques to enable understanding the materials science underlying PV materials and devices at multiple scales
- The Reliability Group, which provides standards and testing to the PV industry, and has been measuring in-field performance as well as accelerated testing of commercial modules for decades.

Collaboratory Economic Impact Report Appendix E
REDUCING METHANE EMISSIONS FROM NATURAL GAS

Methane is the primary component of natural gas, a fuel that emits half as much carbon dioxide as coal, when burned. But methane is a greenhouse gas many times more potent than carbon dioxide when released into the atmosphere unburned. The nation's vast natural gas infrastructure – including wells, pipelines, and storage facilities – is one of many sources of methane emissions in the United States. Each of the Collaboratory institutions has been actively engaged in research to define the sources and impact of methane emissions and the mechanisms to reduce or reverse impacts of these emissions.

The Energy Institute at Colorado State University (CSU) has emerged as a leader in research to detect and measure the amount of methane lost to the atmosphere as natural gas is gathered and transported from the wellhead to a local distribution network. Within this vast network, natural gas can travel thousands of miles through pipes, valves, fittings and compressors.

Initially, CSU researchers quantified emissions from gathering facilities, processing plants, transmission stations and storage facilities through research projects sponsored by Environmental Defense Fund and many natural gas companies. This EDF project helped CSU develop critical capabilities in methane research, led by Dr. Anthony Marchese, CSU Department of Mechanical Engineering and the CSU Energy Institute, and Dan Zimmerle, Senior Research Scientist, Energy Institute. In many ways, the most recent Collaboratory-supported methane emissions projects build upon the success of the EDF supported research.

NATURAL GAS GATHERING AND PROCESSING

The EDF Gathering and Processing study began in 2013. The overall goal of the study was to develop a national estimate for methane emissions from all U.S. gathering and processing operations. Few studies had been performed on methane emissions from gathering facilities and, in fact, no reliable inventory existed on the number and size of such facilities in the U.S.

The Gathering and Processing study conducted methane measurements at 114 natural gas gathering facilities and 16 processing plants in 13 states over 20 weeks. The results from the field campaign were published in *Environmental Science and Technology* in February 2015. Further analysis of these results suggest that emissions from gathering facilities are roughly 8 times that currently estimated by the EPA, and the EPA has recently modified its greenhouse gas inventory to include the results predicted by the CSU study.

NATURAL GAS TRANSMISSION AND STORAGE

In a second study, focused on natural gas transmission compressor stations and underground storage stations, CSU and its research partners used multiple and simultaneous measurements at each facility. The field campaign measured emissions at nine storage and 36 transmission facilities operated by industry partners to build a statistical model of national emissions for the Transmission and Storage (T&S) sector. A second paper released by the CSU team for natural gas transmission and storage facilities is part of the largest on-site measurement campaign of the U.S. natural gas infrastructure to date.

METHANE AND CLIMATE SCIENCE

CU Boulder researchers, especially those in the Cooperative Institute for Research in Environmental Sciences (CIRES), a research partnership of CU Boulder and NOAA, have helped to lead a growing national and international effort to better understand the atmospheric implications of oil and gas activities, including those associated with methane. CIRES scientists are deeply involved in the National Oceanic and Atmospheric Administration's (NOAA's) long-term efforts to track changing levels of methane, carbon dioxide, and other atmospheric species important in climate change and air quality. This is a critical part of NOAA's mission, and CIRES researchers embedded in NOAA make the work possible.

Recent findings from CIRES and international partners, suggest that methane emissions from oil and gas development vary widely by region. Many regions emit far more of the gas than EPA and international estimates suggest, but some basins emit less. Intensive regional study is therefore necessary to understand regional and global impacts of oil and gas activity. Chemicals emitted along with methane can damage regional air quality and contribute to health-harming ozone; others chemicals are toxic to people only in very high concentrations. Among the details reported by CIRES and NOAA in recent years:

- North Dakota's Bakken oil and gas field is emitting a lot of methane, but less than some satellites report and less than the latest EPA inventory for petroleum systems indicates.
- Approximately 170,000 pounds (76,000 kg) of methane leak per hour from the Barnett Shale region of Texas, an estimate that agrees with the U.S. EPA's national estimate, but is higher than estimates reported in other commonly used inventories.
- In Colorado's Denver-Julesburg Basin, oil and gas operations produced elevated levels of methane (a greenhouse gas), benzene (an air toxic), and other chemicals that contribute to summertime ozone pollution.
- Methane emissions from fossil fuel extraction and refining activities in the South Central United States are nearly five times higher than previous estimates.
- Quantifying sources of methane using light alkanes in the Los Angeles basin (California), CIRES scientists searching for the source of previously unexplained high levels of methane found that the "extra" methane is likely coming from sources related to fossil fuels, including leaks from natural gas pipelines and other oil/gas activities, and seepage from natural geologic sites such as the La Brea tar pits.
- Global Methane Trend Detection and Analysis

NOAA runs a cooperative air sampling network around the world, to track the changing atmosphere. These samples are translated into "products" like the Annual Greenhouse Gas Index (http://www.esrl.noaa.gov/gmd/aggi/), Trends in Atmospheric Carbon Dioxide graphs (http://www.esrl.noaa.gov/gmd/ccgg/trends/) and similar tools that provide users with relevant atmospheric information. A major role of this NOAA group is to better understand the planet's carbon cycle, including the specific impacts of methane. CIRES science has been critical to NOAA's efforts, and CU/CIRES researchers have been lead or co-authors on papers that evaluate long-term trends in global methane levels.

NEW DIMENSIONS IN METHANE RESEARCH

The Collaboratory-supported proposal to DOE followed closely after CSU's Transmission and Storage study. The two earlier studies provided the best ground-based measurements of methane emissions from natural gas facilities to date, but there are inherent limitations to this measurement regime. For example, reliable data can be obtained only with permission of the landowner or the company operating the facility. Other researchers had experimented with aerial sampling and statistical modeling of methane emissions from aircraft.

In 2014, Collaboratory funds were utilized as matching or "cost share" funds to successfully compete for a grant of more than $3 million from the Research Partnership to Secure Energy for America, a program of the U.S. Department of Energy, for a proposal focused on methane emissions from natural gas infrastructure. DOE/RPSEA selected the proposal of a Collaboratory/CIRES/NOAA team of researchers, organized by Dag Nummedal, of CSM. The project was designed to improve and compare ground-based measurements and aerial estimates of methane emissions from natural gas facilities, and to do so in two different basins: the D-J Basin in Colorado, and a portion of the Fayetteville Shale in Arkansas. The Collaboratory's commitment of $325,000 in support of this proposal was effectively leveraged by the Collaboratory project leaders to attract four large natural gas companies to commit $200,000 each, and 19 other companies to commit $20,000 each.

More specifically, Drs. Garvin Heath (NREL), Dag Nummedal (CSM) and Gabrielle Petron (NOAA) and Dan Zimmerle (CSU) are leading the Collaboratory and NOAA researchers in this project to study two natural gas producing regions, using both ground-based measurements and aerial sampling and statistical modeling to: (a) understand the comparative strengths and weaknesses of each method and (b) to consider how to synthesize or correlate the results from each.

As of June, 2016, all data from the RPSEA study has been collected from both of the producing regions, and the results are being analyzed for reporting to DOE and for publication in scientific and engineering journals. Additional research projects focused on detection and reduction of methane emissions include:

- In June 2016, DOE announced it will provide $3.5 million in funding for CSU and CSM to build and operate the testing facility for ARPA-E's Methane Observation Networks with Innovative Technology to Obtain Reductions (MONITOR) project teams. Led by Dan Zimmerle (CSU) and Dag Nummedal (CSM), these Colorado universities will develop a facility for MONITOR project teams to evaluate their methane sensing technologies in an environment that simulates real-world natural gas well pad conditions. The selection of the CSU/CSM proposal cements Colorado's reputation as the world center for studying and controlling methane emissions from oil and gas operations. The Collaboratory is proud to have committed a portion of the cost share requirement for this proposal.

- In 2015, ARPA-E also announced its selection of a CU Boulder-CIRES-NIST (National Institute of Standards and Technology) team for a $2 million MONITOR award to develop a technology to measure methane and other gases at parts-per-billion concentration levels over kilometer-long path lengths. When employed as part of a complete methane detection system, the team's innovation aims to improve the accuracy of methane detection while decreasing the costs of systems, which could encourage widespread adoption of methane emission mitigation at natural gas sites. Dr. Steve George (CU Boulder) is leading the project team.

- Dr. Al Weimer (CU Boulder), Scientific Director of the Collaboratory's Colorado Center for Biorefining and Bioproducts (C2B2), is being funded by ARPA-E to develop technology to convert flare gases from oil extraction facilities (primarily methane with no route to market) to synthetic crude oil which can be subsequently processed into gasoline, diesel or other fuels compatible with local fuel distribution networks, thereby eliminating a major source of GHG emissions.

Appendix E

The Collaboratory Has Helped Build Colorado's Economy

The following is taken from Metro Denver Economic Development Corporation's Resource Rich website: On Dec. 16, 2015, the Colorado Energy Coalition (CEC), an industry affiliate of the Metro Denver Economic Development Corporation (Metro Denver EDC), released the seventh edition of its Resource Rich Colorado (RRC) report.

The annual study measures and details Colorado's competitive position in the oil, natural gas, coal, renewables, power, alternative fuel vehicle, and environment and sustainability sectors that make up the energy industry.

The analysis also compares Colorado to the 49 other states based on the availability of natural resources for energy generation, energy policies and programs, and the intellectual resources crucial to energy development.

"Colorado is truly 'resource rich' due to its substantial energy resource mix, tremendous intellectual capital with 24 federally-funded scientific research laboratories, and its highly progressive energy policies and programs," said Brian Payer, Consulting Manger with IHS Corporation, and Co-Chair of the CEC's Resource Rich Colorado Committee. "These assets make the state one of the most diverse energy economies in the world."

This year's report highlights a major shift in the affordability of renewable energy, noting that when considering the unsubsidized, levelized costs of new power plant facilities, the cost of wind energy is now at parity with natural gas and the price of solar has shown tremendous price drops.

In fact, since 2009, there has been a 56 percent price drop for the cost of wind generation and a 78 percent cost decrease for solar generation. Further, RRC estimates that more than 400 MW of wind generation and 290 MW of utility-scale solar generation will be installed within Colorado in 2016, boosting the amount of cost-effective renewable energy in the state's power generation portfolio.

Additional key RRC findings:

- Colorado is a clear leader in progressive energy policies and programs. The state is a pioneer in air quality policy, adopting the first state-level regulations on methane emissions from oil and gas operations in 2014.
- The study notes a clear, national trend of retiring coal plants, which Colorado has experienced first-hand as part of the Clean Air-Clean Jobs Act. However, 60 percent of Colorado's net energy generation is derived from coal power.
- When it comes to oil and gas production, the efficiency per rig has increased exponentially, with production increasing in the Niobrara shale formation by a factor of six.

- Following a national trend, the state's per-capita CO2 emissions have dropped steadily from 2005 levels. In August 2015, the Environmental Protection Agency (EPA) finalized the Clean Power Plan, which aims to reduce carbon pollution from power generation by 32 percent by 2030 (from 2005 levels).

The energy industry is vital to Colorado's economy and a key employment cluster in the state. New data show that the energy industry (both fossil fuels and cleantech) directly employs 74,720 energy workers, which support an additional 188,890 indirect employees throughout the state. The industry tallied an overall economic impact in Colorado of $17.2 billion in 2015.

The RRC analysis shows that Colorado's balanced energy economy ranks prominently in several areas:

- Third in total LEED-certified space per capita
- Fourth in Clean Edge, Inc.'s State Clean Energy Index 2015. The state has held a top-five position the past six years in a row.
- Sixth in natural gas production
- Seventh in crude oil production
- Ninth in installed solar capacity at 316 megawatts (MW)
- Tenth in installed wind capacity, with 2,583 MW installed
- Tenth in coal production
- Tenth in alternative fuel vehicle ownership per capita

However, while Colorado's energy industry is experiencing broad success, the state's companies face significant market, regulatory, and political uncertainty, according to Chris Hansen, Principal with Hansen Advisors and Co-Chair of the Colorado Energy Coalition. "While the federal renewable electricity Production Tax Credit received a short-term extension through 2014, currently, an extension for 2015 and beyond remains uncertain, creating an unpredictable environment for Colorado's wind and solar firms," he said.

In addition, Colorado's oil and gas sector is contending with a dramatic decline in commodity prices, which challenges job growth in this key sector of the state's economy, according to Hansen.

"Although the industry does face uncertainty, several factors continue to make Colorado a magnet for energy companies," explained Tom Clark, CEO of the Metro Denver EDC. "The state's low income tax, moderate business costs, skilled energy workers, and diverse resource base continue to attract investment and create jobs in the energy and natural resources sector."

A detailed analysis of Colorado's and the United States' competitive rankings can be found by downloading the full report below.
>> Resource Rich Colorado, Seventh Edition (Executive Summary)
>> Resource Rich Colorado, Seventh Edition (Full Report)

In short, Colorado's cleantech sector is already a significant aspect of Colorado's economy, and its rate of growth is continuing to accelerate.

Among the reasons cited by Metro Denver EDC for Colorado's strong standing as a national energy leader are the quality of and accessibility to our educational and research centers, including the four Collaboratory institutions. The Collaboratory helps to attract employers to Colorado by building an educational and research cluster that serves industry. By educating undergraduate and graduate students in science, engineering, business and other disciplines, the Collaboratory ensures that clean energy businesses and their suppliers can find the talent that will help them succeed.

The nine-county Metro Denver and Northern Colorado region ranked fourth for fossil fuel energy employment and fifth among the nation's 50 largest metros for cleantech employment concentration in 2015, according to Metro Denver EDC. Overall, the energy industry cluster employs 54,720 people in the area. The Collaboratory is playing a key role in creating and supporting homegrown companies and in attracting existing clean energy companies that are looking to relocate. We are grateful that the Collaboratory's role in bringing businesses and jobs to Colorado has been acknowledged by State officials, by the Metro Denver Economic Development Corporation, and by other Colorado economic development agencies.