Colorado Energy Research Collaboratory

Partners for Clean Energy

Economic Impact Report

2008-2015

September 1, 2016

Colorado State University

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NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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

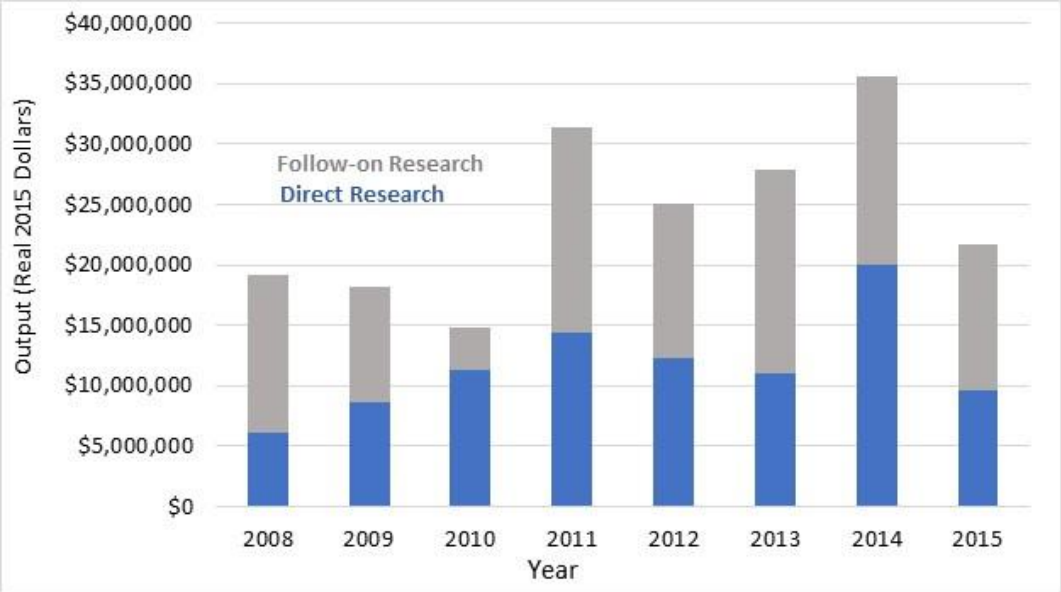
The state of Colorado invested $7.96 million in the Collaboratory from 2008-2015. The $7.96 million of state funding was leveraged into $96.6 million from industry, DOE, NSF, and other sources to support Collaboratory research projects from 2008 to 2015. This total includes $53.5 million of first-generation 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. The Collaboratory explore creating a multi-state collaborative regional clean energy innovation center. Information about summits: www.regionalsummit.org
Collaboratory website: www.coloradocollaboratory.org

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

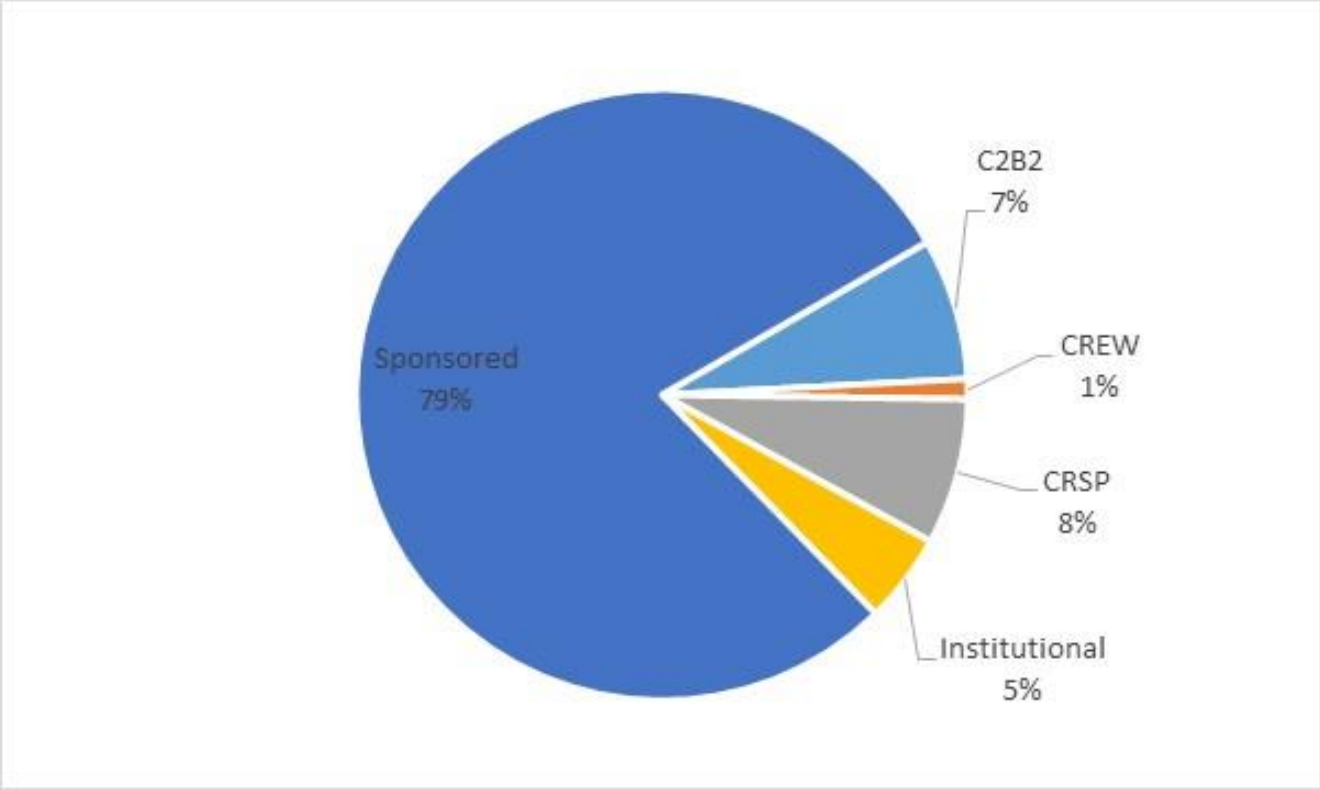
The $7.96 million of state research funding was leveraged into $53.5 million in first-generation research projects co-funded by the Collaboratory with industry, DOE, NSF, and other sponsors for an economic impact of $93.3 million from 2008-2015. The impact on value added (GDP) was approx. $51.2 million.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

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.

Colorado Energy Research Collaboratory

Partners for Clean Energy

www.ColoradoCollaboratory.org