



**Colorado Energy Research Collaboratory**  
*Partners for Clean Energy*

## **ECONOMIC IMPACT REPORT**

**2008-2015**

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

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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.

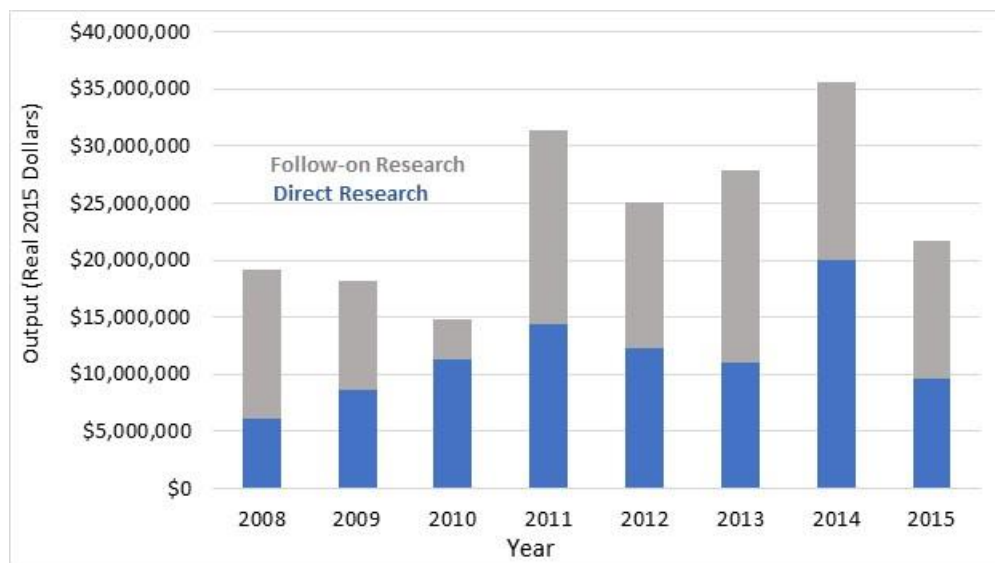
### **Methodology: IMPLAN Model**

The economic impact of the \$96.6 million of Collaboratory leveraged research spending was analyzed using the IMPLAN model. IMPLAN ([implan.com](http://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
<b>Total Effect</b>	<b>133</b>	<b>\$71.3</b>	<b>\$106.4</b>	<b>\$193.9</b>

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. For more information go to [www.regionalsummit.org](http://www.regionalsummit.org)

Collaboratory website: [www.coloradocollaboratory.org](http://www.coloradocollaboratory.org)

## **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](http://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*

<b>Year</b>	<b>Next-Generation Funding by Year of Initial Collaboratory Investment</b>	<b>Next-Generation Funding by Approximate Year of Expenditure</b>
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
<b>Total</b>	<b>\$52,891,778</b>	<b>\$52,891,778</b>

## Results

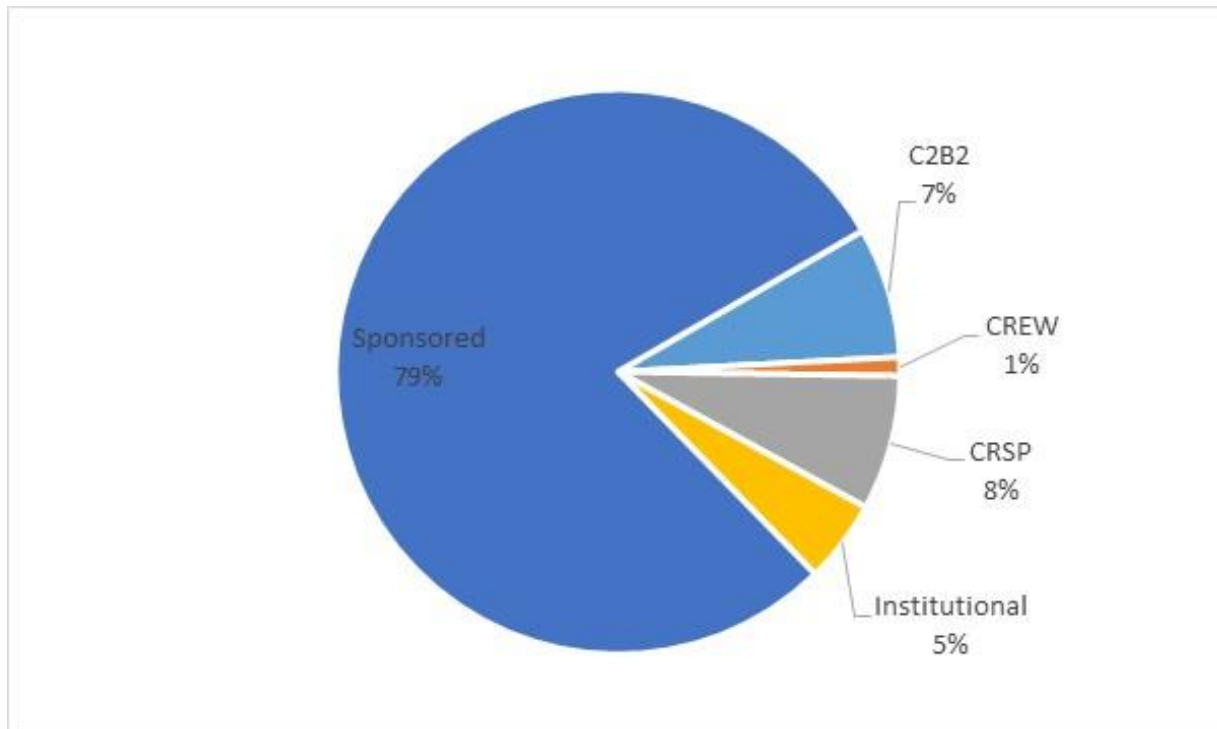
The \$7.96 million of state research funding was leveraged into \$53.5 million in first-generation research projects co-funded by the Collaboratory with industry, DOE, NSF, and other sponsors for an economic impact of \$93.3 million from 2008-2015. The impact on value added (GDP) was approximately \$51.2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

<b>Impact Type</b>	<b>Average Employment</b>	<b>Labor Income (\$ Millions)</b>	<b>Value Added (\$ Millions)</b>	<b>Output (\$ Millions)</b>
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
<b>Total Effect</b>	<b>64</b>	<b>\$34.3</b>	<b>\$51.2</b>	<b>\$93.3</b>

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
<b>Total Effect</b>	<b>69</b>	<b>\$37.0</b>	<b>\$55.2</b>	<b>\$100.6</b>

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.

## **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**

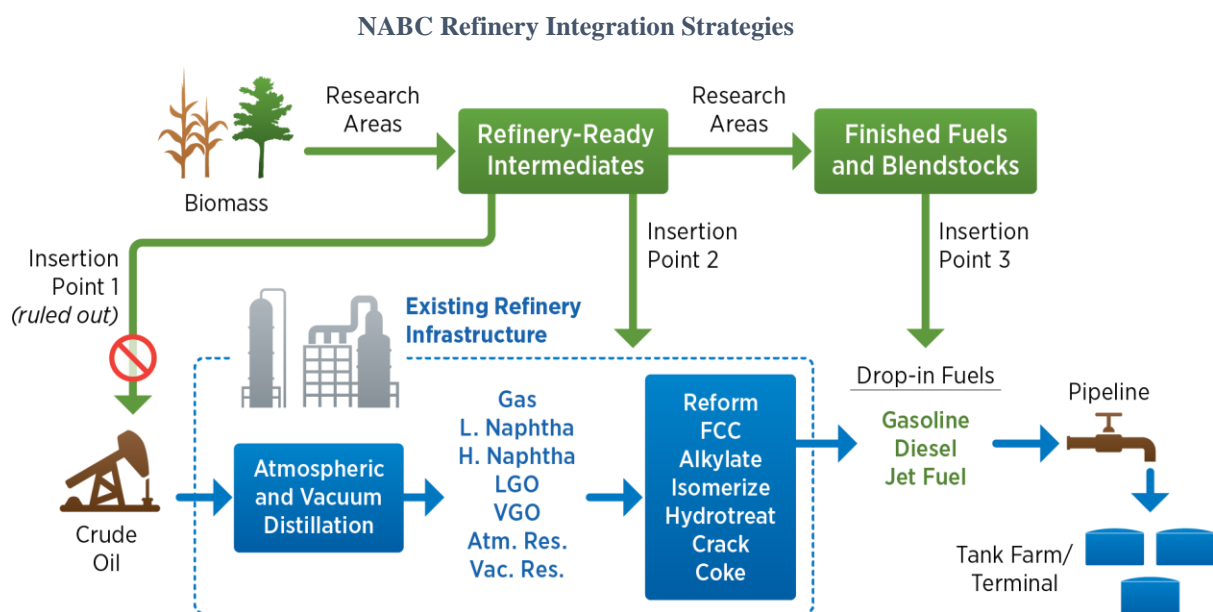
The National Advanced Biofuels Consortium (NABC) was a Colorado-based consortium that won a major DOE competitive research award, and NABC is a prime example of the Collaboratory development pipeline from feedstock to product to market. NABC was established in 2010 to develop biomass-based alternative 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.



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<sub>2</sub> 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.

## **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.

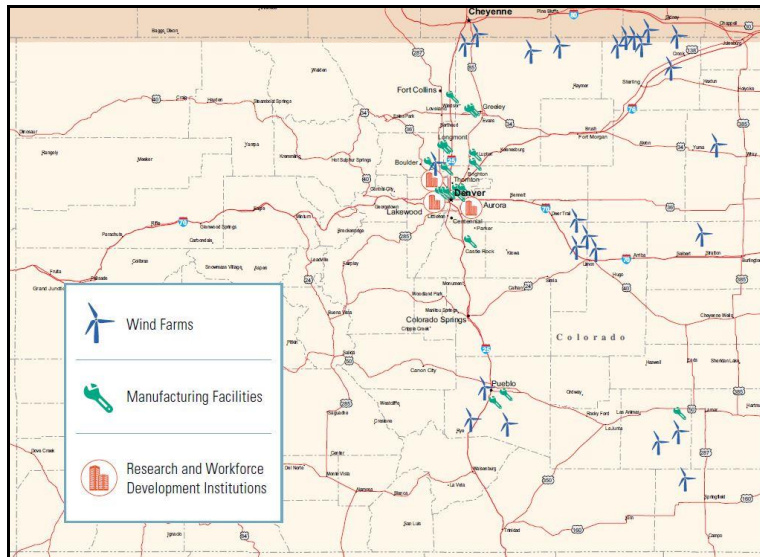
Soon, advanced materials and manufacturing processes will be used to create greater efficiency and reduce the cost of renewable energy from wind turbines. And increasingly, America's factories will produce manufacturing materials from renewable sources that will be lighter, stronger, more sustainable 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.

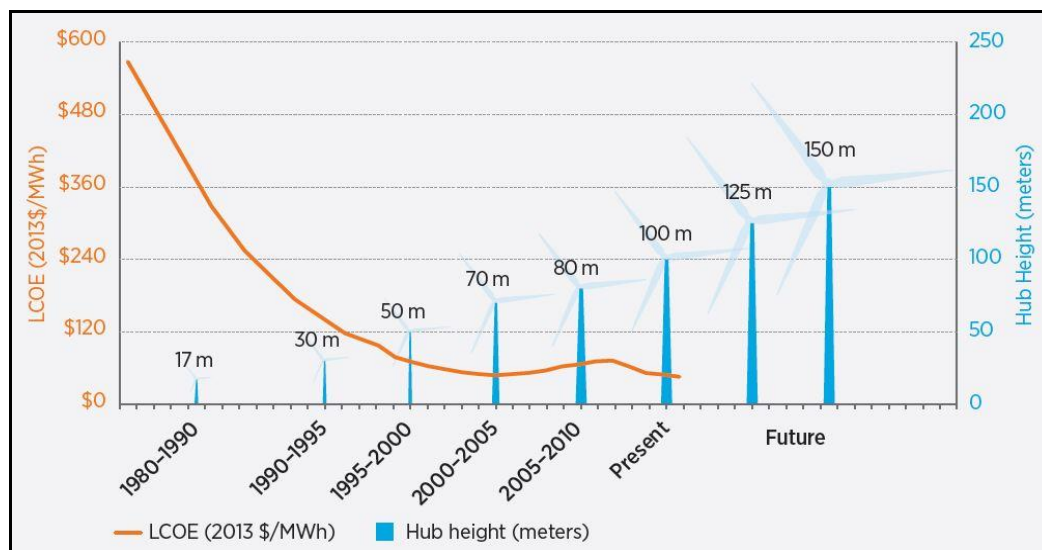
NREL and the Colorado universities are particularly interested in the application of advanced composites to wind power technologies. For NREL, wind power is central to its mission to develop and disseminate renewable energy technologies. In fact, NREL played a key role in bringing wind power technology 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 are 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.

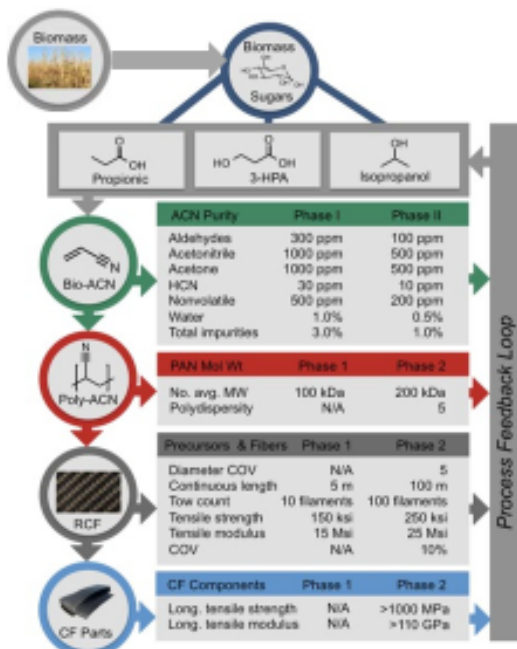
In 2014, the DOE's Bioenergy Technologies Office announced a competition for funding to demonstrate a new technology pathway to produce high-performance/low-cost renewable carbon fibers. NREL, CSM and CU joined with additional research and industry partners to form the Renewable Carbon Fiber Consortium (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.



# CARBON FIBER FROM BIOMASS



**Objective:** Cost effective production of renewable carbon fibers from lignocellulosic biomass



NATIONAL RENEWABLE ENERGY LABORATORY

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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.

## Green Chemistry Pocket Guide

### The 12 Principles of Green Chemistry

Provides a framework for learning about green chemistry and designing or improving materials, products, processes and systems.

1. Prevent waste
2. Atom Economy
3. Less Hazardous Synthesis
4. Design Benign Chemicals
5. Benign Solvents & Auxiliaries
6. Design for Energy Efficiency
7. Use of Renewable Feedstocks
8. Reduce Derivatives
9. Catalysis (vs. Stoichiometric)
10. Design for Degradation
11. Real-Time Analysis for Pollution Prevention
12. Inherently Benign Chemistry for Accident Prevention

[www.acs.org/greenchemistry](http://www.acs.org/greenchemistry)



## 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 optoelectronic 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.

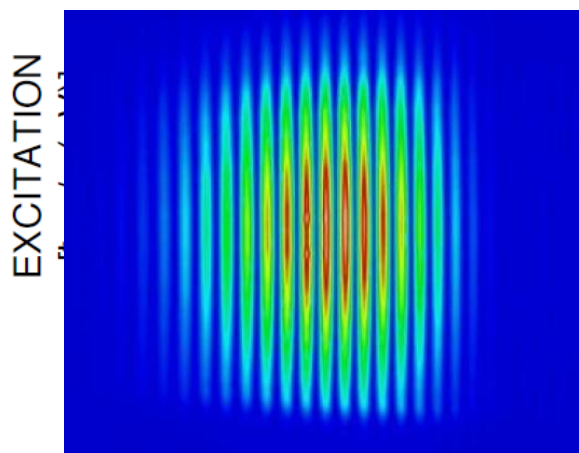


Figure 1: Spectral interferometry (left) measures the oscillations of coherent light waves with sub-femtosecond ( $1 \text{ fs} = 10^{-15} \text{ s}$ ) accuracy, which is *faster than electrons move in semiconductors*.



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.

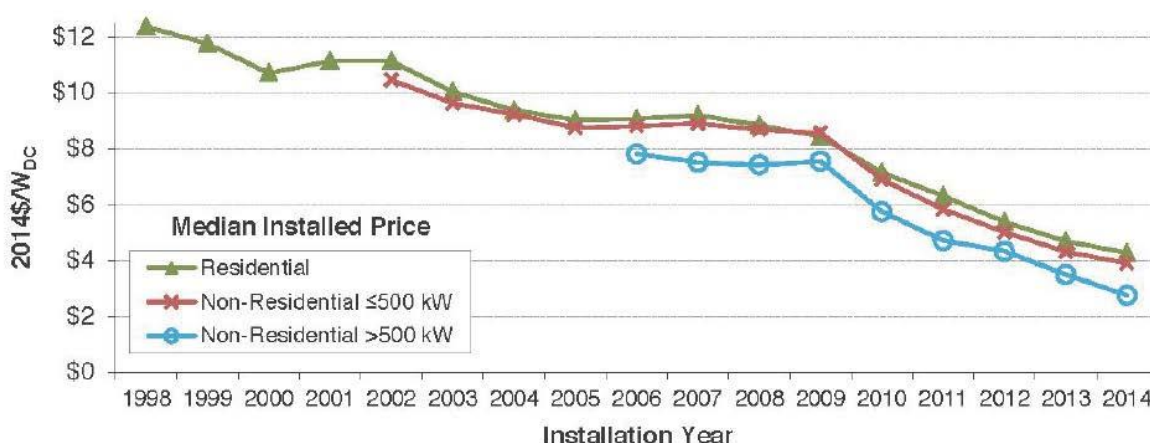
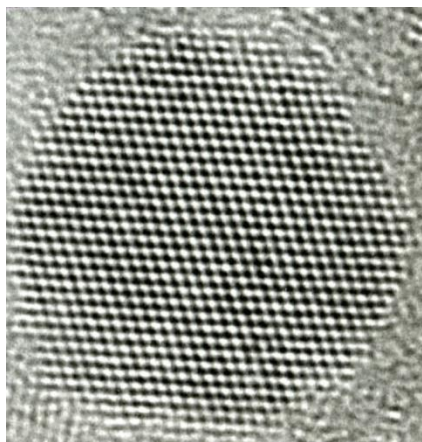


Figure 2: Installed PV Prices Normalized to 2014 Dollars (LBL/NREL *Tracking the Sun* Report Summary, August 2015)

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 \$600,000 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.

## **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.

**For more information:  
Colorado Energy Research Collaboratory  
[www.ColoradoCollaboratory.org](http://www.ColoradoCollaboratory.org)**