Maine Innovation Economy Action Plan

How Science and Technology Can Drive Economic Growth and Benefit All Maine People

2023–2027

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EXECUTIVE SUMMARY

Every day, thousands of Maine people go to work at businesses that compete in the global economy by leveraging innovations developed by Maine researchers. From farmers and food processors to lab technicians and those transforming Maine's forests into a nanocellulose powerhouse, businesses are turning the work of our public, private, and nonprofit research institutions into tangible economic opportunities. They employ the full spectrum of workers, from cleaners and delivery drivers, to salespeople, project managers, and executives, and their payrolls indirectly support even more businesses and workers. They are innovating, growing, and successfully competing in today's global economy.

As Maine seeks to build a resilient 21st century economy, these businesses are pointing the way. And yet, the potential of research and development (R&D) to build prosperity has not been fully realized. Historically, Maine's R&D investments have been low — just 1% of GDP compared to the national average of almost 3%. In 2021, Maine ranked 44th of the 50 states by this measure. Maine voters and businesses have continually supported meaningful contributions of both public and private dollars, but not enough to create transformative, statewide growth.

In this 2023-2027 plan, the Maine Innovation Economy Advisory Board (MIEAB) presents a vision for science and technology as drivers of economic opportunity across the state. It acknowledges the significant investments made to date and affirms the potential to realize even greater gains by replicating the proven success of partnerships between Maine researchers and innovators.

Vision: A resilient, innovation-driven economy that creates opportunities for all Maine people

Realizing this vision will require the commitment and coordination of researchers, educators, policymakers, and business leaders; a rigorous focus on R&D that yields tangible opportunities for Maine businesses; attention to workforce development; and a transformative funding increase. This is possible through the pursuit of five complementary goals:

Goal 1: Increase R&D to 3% of GDP while focusing on activities that directly support Maine industries

This long-term goal calls for a transformational increase in the amount of R&D occurring at Maine's public, private, and nonprofit institutions. Priority should be placed on work that yields direct economic opportunities for businesses and communities across Maine.

Goal 2: Strengthen pathways to successful commercialization

Turning the research accomplishments of Goal 1 into commercial success requires cultivating entrepreneurship and innovation within enterprises.

Goal 3: Prepare an innovation workforce

Maine residents must have the skills to innovate across a broad range of industries, within companies large and small, and to access high-quality employment opportunities. And Maine businesses need talent to innovate and grow.

Goal 4: Help businesses & communities thrive in the face of climate change

In the coming years, Maine industries and communities will face critical, even existential, challenges due to climate change. And Maine's R&D community must be a ready source of knowledge and innovation to help them adapt and thrive.

Goal 5: Strengthen Maine's R&D ecosystem

Lastly, Maine must continue improving its framework for R&D investments and activities, ensuring coordination, collaboration, efficiency, and maximum benefits for all involved. It also must raise public awareness of R&D's role in economic development.

BACKGROUND

About MIEAB

In 2007, the state of Maine established the Maine Innovation Economy Advisory Board (MIEAB) to coordinate R&D activities and foster collaboration among public, private, and nonprofit research institutions and the business community. The board includes thirty representatives of these groups, all appointed by the Governor, as well as the president of the Maine Technology Institute and the director of the Governor's Office of Policy Innovation and the Future (see Appendix I for a list of current members). MIEAB also serves as Maine's steering committee for the federal Established Program to Stimulate Competitive Research (EPSCoR). This program helps strengthen the innovation infrastructure of regions with historically low levels of R&D activity.

About This Plan

This plan has two roles. First, it is the Science and Technology Plan required to receive EPSCoR funds. The program requires jurisdictions to identify their research priorities and a framework for allocating R&D resources. This document outlines Maine's priorities at the time of publication. Given the pace of scientific advances and economic change, MIEAB recognizes that additional opportunities may arise within the next five years. A sector's omission from this report should not be interpreted as a lack of support or barrier to resources.

Second, this plan helps MIEAB coordinate the R&D activities of Maine's public and private research institutions, and guide public investments. It fulfills MIEAB's statutory duty to create a plan every five years to improve Maine's standing in the global economy. MIEAB created this plan with support from the University of Maine's EPSCoR office. Over the course of almost 18 months, the office conferred with a broad range of stakeholders representing public, private, and nonprofit institutions across Maine (see Appendix II). The board guided the synthesis of their recommendations into this vision and plan.

Since 2017...

MIEAB released its last action plan in 2017. It focused on R&D, human capital, and entrepreneurship, and, for the first time, acknowledged the importance of the non-state networks and organizations driving innovation. Since then, Maine has taken important steps toward strengthening its R&D infrastructure. Later that year, voters passed a $50 million bond to fund the Maine Technology Asset Fund 2.0.

To date, this has created 1,770 direct jobs and been matched by over $224 million in private funds.[1] In 2019, the University of Maine System created its first unified plan for research activities across its seven campuses. Following that, the University of Maine earned the designation of becoming Maine's first top-tier (R1) research university. Meanwhile, the University of New England rose to R2 status. In 2020, Northeastern University launched the Roux Institute in Portland, an ambitious initiative to grow talent in artificial intelligence and other advanced technologies. In 2022, Governor Janet Mills and the state Legislature directed millions in COVID relief funds to research, including $40 million for the Pandemic Recovery for an Innovative Maine Economy (PRIME) initiative. Meanwhile, Maine's congressional delegation has successfully secured tens of millions annually for R&D investments across the state. This plan recognizes Maine's changing circumstances, opportunities, and ambitions, while building on the findings and recommendations of the 2017 plan.

Alignment with Other Plans

As MIEAB created this plan, it reflected on decades of work by Maine research institutions, businesses, educators, and policymakers. It leveraged their expertise, experience, and recommendations to create a coordinated, complementary plan to help Maine advance in the global economy. This plan aligns with, and builds on, the following initiatives and reports.

- "30 and 1000" (2001) popularized research by the former state Planning Office estimating that increasing Maine's R&D funding to $1,000 per worker and raising the percentage of adults with a four-year degree to 30% would boost incomes to the national average. At the time, R&D funding was about $255 per worker (44th in the nation).[2] This report illustrates both Maine's long-standing knowledge of R&D's unique power and chronically low funding levels.
- Maine's Ocean Energy Act of 2009 laid out a vision for a robust renewable energy industry, encompassing both offshore wind and tidal power. The bill received unanimous bipartisan support in the Legislature.
- In 2016, 100 of Maine's leading businesses, educational institutions, and nonprofits formed the MaineSpark Coalition, endorsing the goal of 60% of Maine residents holding a postsecondary credential of value by 2025.

1 Brian Whitney, "Yes, MTI's MTAF Program was Worth the Investment!" Maine Technology Institute blog, August 31, 2022.
2 Maine state Planning Office, "30 & 1000: A Progress Report: Our Knowledge-based Economy Development Strategy," March 2003.

- In 2016, the Maine Algal Cluster Advisory Group released the Maine Algal Cluster Initiative report, highlighting key challenges and opportunities for advancement of a micro- and macro-algae industry in Maine.
- In 2018, a unique collaboration among industry, academia, and government launched the Forest Opportunity Roadmap/Maine (FOR Maine), outlining a new vision for Maine's forest products sector based on innovation and diversification.
- The University of Maine System (UMS) Research and Development Plan (2019) marked a new, coordinated approach to R&D across the System's seven campuses. With historic clarity and ambition, it set a course toward increased investment and impact across Maine.
- In 2019, the state of Maine released its ten-year Economic Development Strategy: A Focus of Talent and Innovation. Like the UMS plan, this report called for increased coordination and alignment of effort across public, private, nonprofit, and education sectors.
- In 2020, the Harold Alfond Foundation announced $500 million in new grants to Maine institutions innovating in education, workforce development, research, and job creation.
- As Maine recovered from the initial impact of COVID-19, the Governor's Economic Recovery Committee issued Recommendations to Grow and Sustain Maine's Economy (2020). This plan calls for investment in innovation, entrepreneurship, and talent to drive economic prosperity.
- Maine Won't Wait (2020) is the state's four-year climate action plan. It calls for increased investments in R&D activities that advance climate solutions. As background to the plan, the Maine Climate Council's Scientific and Technical Subcommittee published Scientific Assessment of Climate Change and Its Effects in Maine, a detailed report on the predicted impacts of climate change on Maine's residents, businesses, and communities.
- In 2021, Governor Mills and the Legislature passed the Maine Jobs & Recovery Plan, directing nearly $1 billion in federal funds toward the initiatives prioritized in the 2019 ten-year strategy and the 2020 economic recovery recommendations.
- Since 2009, the Maine state Chamber of Commerce, Educate Maine, and the Maine Development Foundation have promoted workforce and R&D investments in their Making Maine Work reports. The 2022 edition calls for expanding the size and capabilities of Maine's workforce, increasing R&D, and targeting high value-added industries. It notes, "state government can double its investment in R&D annually without running out of viable projects."[3]
- The Maine Economic Growth Council emphasizes the importance of R&D in its annual report, Measures of Growth (2022). It recommends R&D spending as a percentage of Maine's economy increase from its current level of about 1% to the national average of 3% by 2030.
- The Bioscience Association of Maine's Life Sciences in Maine report (2022) shows the industry's recent job growth in Maine has outpaced all other New England states.
- In 2022, Governor Mills and the Legislature established the Maine Space Corporation to better coordinate and support the state's research, higher education, and manufacturing capabilities in this emerging industry cluster, and to better leverage its unique geographic assets.

3 Maine state Chamber of Commerce, Maine Development Foundation, Educate Maine, 2022, *Making Maine Work*, pp. 17.

Global and National Context

As Maine strives for innovation and resiliency, shifting national and international conditions create both challenges and opportunities. In any given year, demand for Maine goods and services is heavily determined by the overall health of the U.S. economy. At the same time, Maine can leverage its unique assets to find outsized opportunities beyond its borders. The world is clamoring for solutions related to clean energy, sustainable food networks, healthcare, aging populations, and natural resource management. Maine is uniquely positioned to provide these solutions and turn them into business opportunities *if* it makes strategic R&D investments.

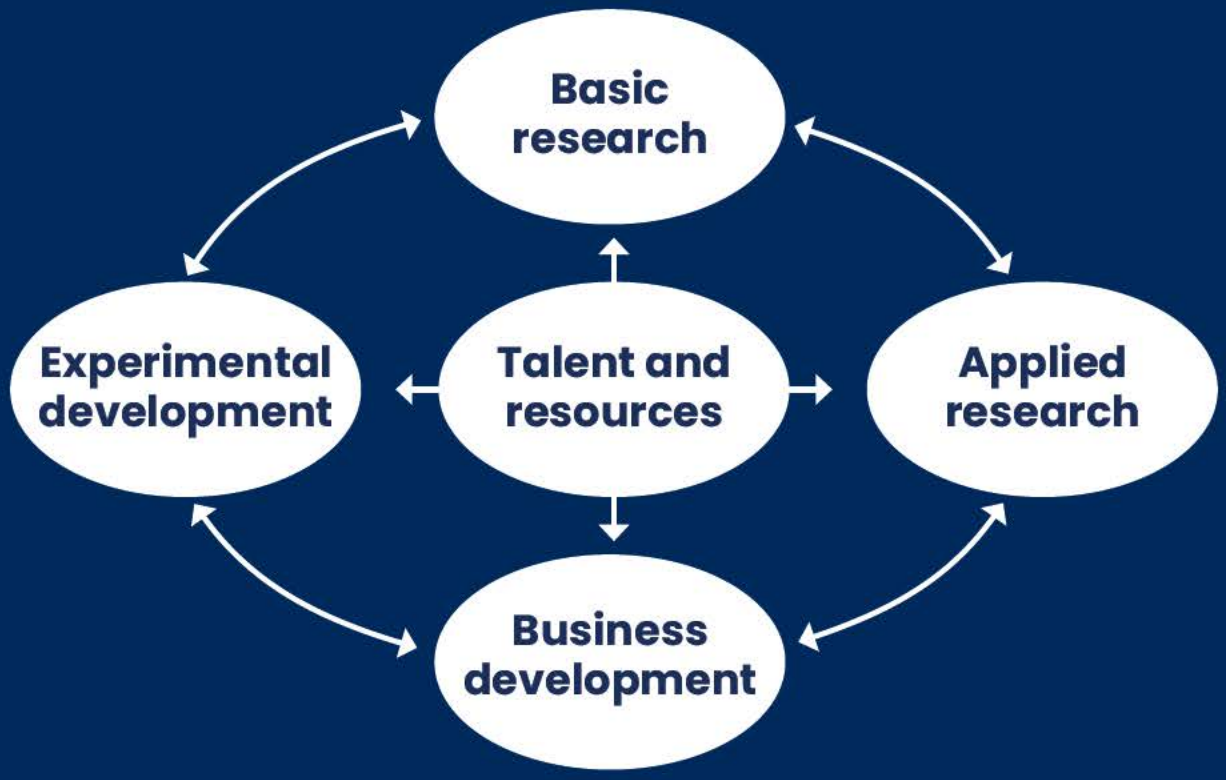
The coming decade promises to yield specific opportunities related to new sources of federal funding. The Infrastructure Investment and Jobs Act of 2021 and the Inflation Reduction Act of 2022 allocated billions for public infrastructure, climate resilience, clean energy, and related initiatives. The CHIPS and Science Act of 2022 and a recent Executive Order supporting innovation in biotechnology and biomanufacturing present additional opportunities. In all, federal funds could create unprecedented openings for Maine communities, businesses, and research institutions. Through this plan, MIEAB urges enhanced collaboration to help them successfully attract and leverage these funds.

The R&D–Business Development System

Research, product development, and business growth are mutually informing processes that yield the best results when knowledge and questions flow readily among all involved, and when all parties can access the talent and resources needed for their work.

Basic research helps scientists understand the underlying causes of observed phenomena. Applied research leverages that knowledge to achieve a specific, practical purpose. Experimental development turns that work into new products or processes (or improves existing ones). Business development turns these ideas into tangible economic opportunities, ultimately generating wealth and resources to reinvest in the system.

The flow of knowledge and ideas within this system is multidirectional. The market demands observed by businesses drive the work of experimental developers. In turn, the hurdles they encounter spark questions of basic and applied researchers. Each activity plays a critical role in economic development, and each requires sustained investment to create an engine of long-term economic growth.



INTRODUCTION

This plan presents a vision of science and technology as transformative forces creating opportunity throughout Maine. It highlights five goals necessary to achieve this vision. The full potential of R&D to bring transformative growth to Maine cannot be fully realized unless all five advance simultaneously. They are interconnected and interdependent. For example, funding for research initiatives creates opportunities to train Maine's future workforce and generates new processes and technologies that drive business activity. In turn, this activity creates opportunities for more workers and catalyzes more investments. A well-functioning framework for R&D coordination galvanizes the entire process and ensures that every investment yields its maximum return.

This document begins by presenting the vision and the five goals. Next, it shows how these goals will be achieved through specific activities in thirteen priority areas. Appendix IV shows how these priority areas support and build on the seven technology sectors that have guided Maine's R&D investments since 1999. Many of the priority areas combine elements of multiple sectors in new and creative ways. In doing so, they are building on Maine's historical comparative advantages to create new opportunities across many industries.

R&D's Role in Sustainable Development

Lasting, equitable growth requires progress across many dimensions of a state's economy, society, and environment.

Maine businesses, researchers, and educators operate within the broader context of the state's economic and cultural landscape. Beyond their labs and classrooms, myriad factors influence whether their success translates into tangible benefits for Maine people. Can new hires at growing companies find housing? Can they find daycare for their children? Can products reach customers on time? Is the internet fast enough?

The United Nation's Sustainable Development Goals are a useful framework for understanding the full spectrum of conditions needed to achieve lasting, equitable growth.* Many aspects of this plan directly support one of more of these goals, such as public health, economic growth, climate action, and natural resource stewardship. Still, MIEAB recognizes the need for progress on other critical issues beyond the scope of this plan. These include:

- Affordable, accessible housing
- Quality early childhood care and education
- Strong PreK-12 public schools
- Higher wages for teachers
- Reliable, high-speed internet access
- Racial, ethnic, and gender equity and inclusivity

Progress on these issues and others will be necessary if Maine is to realize the full potential of R&D to generate lasting prosperity that benefits all residents.

*United Nations, "Sustainable Development Goals," accessed December 13, 2022: un.org/sustainabledevelopment.

THE PLAN

Vision

This plan envisions a resilient, innovation-driven economy that creates opportunities for all Maine people. This vision is:

Bold

It envisions a transformative increase in R&D to push Maine onto a higher growth path and yield benefits for generations.

Built on Success

Maine's proven R&D successes are the cornerstone of this evidence-based vision. It prioritizes the sectors and programs that have generated the most opportunities for Maine businesses and workers.

Socially Inclusive

It recognizes the need for R&D investments, especially those supported by taxpayers, to improve the lives of all Maine people. It emphasizes the importance of workforce development to ensure that all interested workers can acquire the skills to thrive in technology-intensive careers. It also supports commercialization, which extends the opportunities created by R&D to people with a broader range of skills, interests, and levels of education.

Geographically Inclusive

It envisions R&D investments across a range of sectors that collectively benefit the entire state, growing opportunities across Maine's rural forests, farmlands, coastline, and urban centers.

Aligned

It is informed by a comprehensive review of plans guiding the current work of Maine leaders in public policy, research, education, workforce development, and the environment. It builds on, and aligns with, these plans to leverage the best thinking of Maine leaders and ensure the efficient use of valuable resources.

Comprehensive

It recognizes the contributions of a broad range of stakeholders — including businesses, investors, educators, workers, taxpayers, and public, private, and nonprofit research institutions — and calls for aligning them for maximum mutual benefit.

Implementation

MIEAB is the principal entity responsible for implementing this plan. Its work will include:

Awareness & Coalition Building

MIEAB's membership will promote this vision within their organizations and across their established networks. Given Maine's size, MIEAB's thirty well-connected members can effectively share the plan's vision and recommendations with partners across Maine's research, education, and business communities. Members will strive to align messaging and policies, coordinate resource allocation, and avoid duplication by working with allies in state government, PreK-12 schools and higher education (public and private), healthcare, and groups such as the Bioscience Association of Maine, Educate Maine, Environmental and Energy Technology Council of Maine (E2Tech), Focus Maine, FOR/Maine, Maine & Company, Maine Center for Entrepreneurship, Maine Climate Council, Maine Technology Institute, Maine Venture Fund, MaineSpark, and organizations involved in geospatial mapping.

Progress Reviews

MIEAB will review progress on this plan and its goals as part of its ongoing work. Building on existing systems, it will monitor changes in R&D expenditures, and postsecondary training and education reported annually by the Maine Economic Growth Council and Educate Maine.

Updates

During its reviews, MIEAB will assess the need to modify this plan in response to changing external conditions. Maine's EPSCoR office will record these modifications for inclusion in future updates.

Economic Impact

Technological innovation and workforce development are proven ingredients for economic growth that creates lasting, well-paid jobs.[4] According to the Maine Department of Labor, occupations in science, technology, engineering, and mathematics pay 93% more on average than those in other sectors.[5] Moreover, they are growing faster. From 2012 to 2022, Maine science and technology jobs grew 21%, compared to just 3% growth for jobs in other sectors.[6] Through 2028, these sectors are expected to grow another 6% while the rest of Maine's job market remains relatively flat, growing just 0.3%.[7]

Within this very broad sector, some fields are expanding even faster. For example, jobs in life sciences have grown 48% from 6,456 in 2011 to 9,540 in 2021 — the fastest pace of any New England state.[8] The average annual pay for these positions is $108,000.[9] Information technology jobs are also growing quickly. They are expected to nearly double from 10,600 in 2012 to 20,200 in 2028.[10]

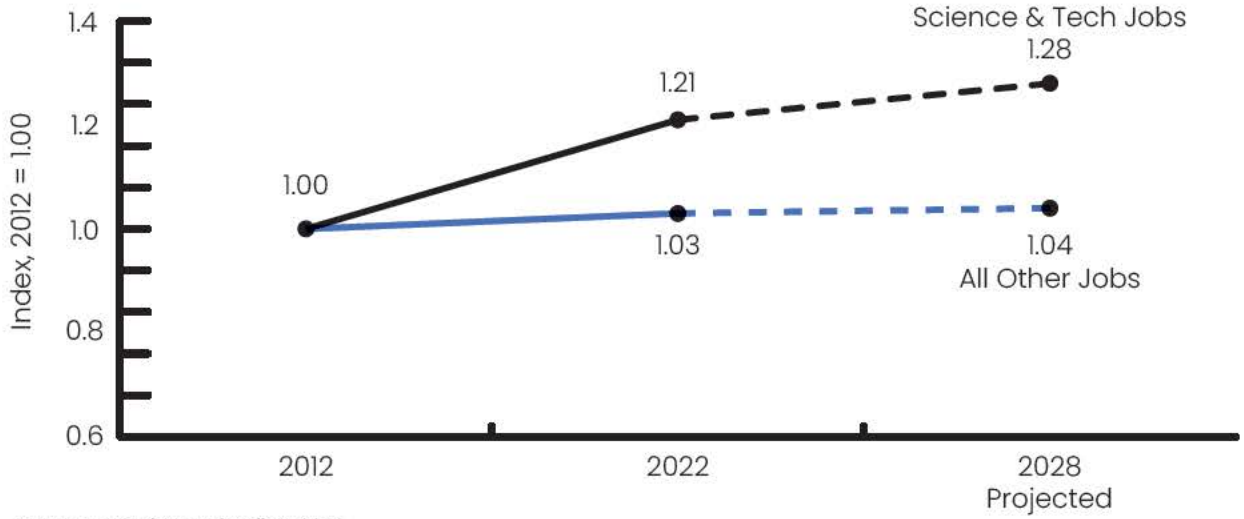
Science and technology jobs directly benefit those who hold them, and indirectly benefit the communities in which they and their families live, and the businesses they frequent. Moreover, the sales, investments, and grants they generate and attract support other Maine businesses in industries as diverse as construction, accounting, and transportation.

Job Growth in Maine's Science and Technology Sectors

	2012	2022	2028 Projected	2022-2028 Change	
				Number*	Percentage
Science and Technology Sectors	52,388	63,130	67,093	3,963	6%
All Other Sectors	634,866	656,963	658,747	1,785	0.3%

Source: Crawley and Bailey, 2022
**Numbers may not add due to rounding*

Science and technology sector jobs are expected to grow faster than jobs in other sectors.



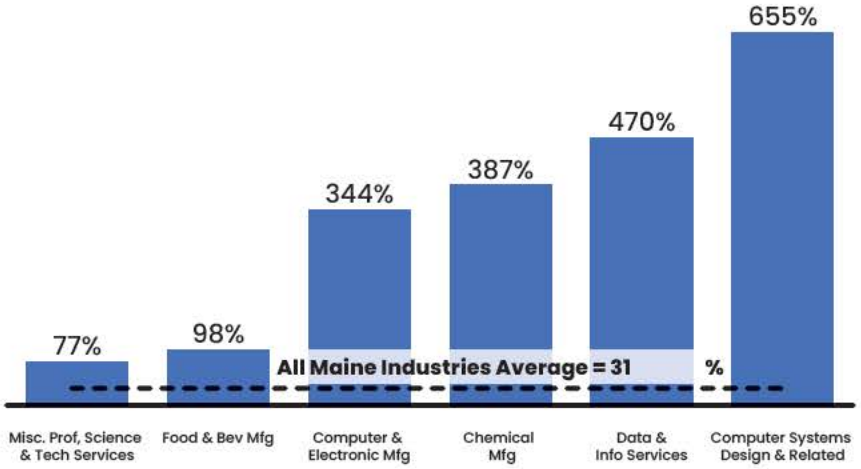
Source: Crawley and Bailey, 2022

4 Todd Gabe, *The Pursuit of Economic Development: Growing Good Jobs in U.S. Cities and States*, Palgrave Macmillan, 2017.
5 Maine Department of Labor, Center for Workforce Research and Information, "Maine Workforce Outlook: 2018 to 2028."
6 Andrew Crawley and Megan Bailey, "An Economic Overview of the Science and Technology Sectors of Maine's Economy," June 2022, EDA University of Maine Staff Paper 2022-108: Technical Report.
7 Ibid.
8 Bioscience Association of Maine, "Life Sciences in Maine: state of the Industry," 2022.
9 Ibid.
10 Crawly and Bailey, 2022.

Another way to measure science and technology's economic contribution is through Gross Domestic Product (GDP), the sum of all goods and services produced in a year. From 2000 to 2021, the combined GDP of all Maine industries rose 31%, adjusting for inflation. The chart below shows how certain sectors that rely on science and technology grew even more. "Miscellaneous professional, science, and technology services," the category that includes much of Maine's life science research industry, engineering firms, and technical consulting services, grew 77%. Food and beverage manufacturing grew 98%.

This sector includes businesses that turn raw foods, often harvested from Maine's farms and waters, into products for consumption. Output grew even more — over 300% — among Maine computer and electronic manufacturers, chemical manufacturers, data and information service providers, and computer systems developers. These trends highlight why investments in science and technology are essential for economic development.[11]

Growth of Select Science & Technology Sectors (2000-2021, Real GDP)



Source: U.S. Bureau of Economic Analysis

GDP Growth of Select Science and Technology Sectors

	GDP ($ millions, inflation-adjusted)		
	2000	**2021**	**Change**
All Maine Industries	48,490	63,595	31%
Select Science and Technology Sectors			
Miscellaneous professional, scientific, and technical services	1,442	2,553	77%
Food and beverage and tobacco product manufacturing	549	1,087	98%
Computer and electronic product manufacturing	140	623	344%
Chemical manufacturing	186	908	387%
Data processing, hosting, and other information services	47	267	470%
Computer systems design and related services	142	1,073	655%

Source: U.S. Bureau of Economic Analysis

11 Darrell M. West, "R&D for the Public Good: Ways to Strengthen Societal Innovation in the United states," October 10, 2022.

GOALS

This plan is organized around five goals, each of which is integral to achieving the vision. Goal 1 addresses funding and the prioritization of R&D that directly supports Maine industries. Goal 2 focuses on commercialization. Goal 3 tackles workforce development. Goal 4 outlines R&D's role in addressing climate change. Goal 5 calls for improvements to Maine's R&D ecosystem.

These reflect a return to the style of goals used in Maine's 2010 plan, rather than the state-rank goals proposed in 2017. The latter sought to improve Maine's rank within the Milken Institute's Science and Technology Index. Understanding Maine's position relative to other states is essential, but changes to it are due as much to decisions made outside Maine as within it. The goals and metrics in this report offer more clarity and accountability to Maine leaders.

This section explains the five goals, highlights some of the activities and institutions that are moving Maine toward them, and explains the resources or actions needed to accelerate this movement.

Goal 1: Increase R&D to 3% of GDP while focusing on activities that directly support Maine industries

Summary: This long-term goal calls for a transformational increase in R&D — large enough to push Maine onto a permanently higher growth path. This is not simply a request of state government. Rather, it is a challenge to all Maine institutions, businesses, and organizations involved in R&D. It embraces the contributions of researchers across the public, private, and nonprofit sectors, and prioritizes activities that result in tangible opportunities for Maine businesses.

Background: R&D activity in Maine totaled about $685 million in 2019, the most recent year available.[12] This equaled 1% of the state's gross domestic product (GDP), compared to the national average of about 3%. By this measure, Maine ranked 44th of the 50 states. It lagged other states in private sector and university R&D investments relative to GDP, while the nonprofit sector contributed a relatively high proportion of spending. Things have likely changed since then, but this ranking suggests the need for heightened emphasis in all areas if Maine is to be a competitive state in attracting new R&D-intensive businesses.

Although Maine's R&D spending is modest by national standards, it supports critical pockets of employment, innovation, and growth. Traditional industries such as agriculture, fishing, and forestry have benefited from long-standing partnerships with Maine's public universities. Newer industries like bioscience have grown through sustained investments by private and nonprofit organizations, supported by federal and state public funds.

The Maine Economic Improvement Fund (MEIF) has supported many of these partnerships. The Legislature created MEIF in the 1990s to support commercially promising R&D within the University of Maine System. Three-quarters of MEIF dollars go to the flagship University of Maine, where annual R&D funding has increased from $25 million when MEIF started to over $150 million today. This work has helped UMS develop the strategic capacity to support hundreds of small businesses and thousands of jobs by developing new products and processes.[13] For every $1 in MEIF funding, UMS leverages $6 in co-investment.

Maine has made additional valuable R&D investments since MIEAB created its last plan in 2017. Shortly thereafter, voters passed a $50 million bond to fund the Maine Technology Asset Fund 2.0. To date, this has created 1,770 jobs and been matched by over $224 million in private funds.[14]

In 2018, the UMS Board of Trustees identified research and economic development as its top strategic priority.[15] The following year, it embraced a new, coordinated approach to R&D across its seven campuses. It focused squarely on research and economic development that supports Maine industries, and emphasized the System's "ample capacity to grow research partnerships with the private sector, as well as commercialization outputs of university research."[16] These efforts are beginning to yield fruit. In 2021, the University of Maine's R&D expenditures reached nearly $150 million, a record high, and in 2022 it became the first Maine institution to earn an R1 Carnegie Classification for very high research activity.

In 2020, Northeastern University launched the Roux Institute in Portland, an ambitious initiative to grow talent in artificial intelligence (AI) and other advanced technologies. The institute, made possible by the vision and philanthropy of David and Barbara Roux, is partnering with Maine companies to advance workforce skills through graduate education and research opportunities. It seeks to transform Portland into a hub for innovation.

In 2022, Maine Governor Janet Mills and the state Legislature directed millions in COVID relief funds to research, including $40 million for the Pandemic Recovery for an Innovative Maine Economy (PRIME) initiative. These funds are supporting innovation

12 Camoin Associates.
13 University of Maine System, "Maine Economic Improvement Fund Report 2022," 2022.
14 Brian Whitney, "Yes, MTI's MTAF Program was Worth the Investment!" Maine Technology Institute blog, August 31, 2022.
15 University of Maine System, "Research and Development Plan FY20–FY24," 2019.
16 Ibid, pp. 8.

within the seven targeted technology sectors listed in Appendix IV.

Public funds have supported significant investments of private dollars, such as the Jackson Laboratory's $160 million Charles E. Hewitt Center (including $1.7 million from the Maine Technology Asset Fund (MTAF)), C&L Aerospace's facility expansion in Bangor ($2.6 million from MTAF), and Bristol Seafood's $5 million investment in its processing facility ($740,000 from MTAF).

Maine's congressional delegation has been an important ally to its research institutions, successfully securing tens of millions annually to bolster R&D activities across industry and academia. In the FY23 federal budget alone, Maine Senators Susan Collins and Angus King, and Representatives Chellie Pingree and Jared Golden collectively secured more than $50 million in direct appropriations for R&D activities and related infrastructure at the University of Maine, Bigelow Laboratory of Ocean Sciences, the Jackson Laboratory, Mount Desert Island Biological Laboratory, and the Downeast Institute for Marine Research.

This goal calls for building on these successes to significantly increase the overall level of R&D occurring at Maine's public, private, and nonprofit institutions; prioritizing sectors that build on Maine's historical comparative advantages; and jumpstarting economic activity across the state. Increasing R&D spending from 1% to 3% of GDP would mean going from $500 million–$600 million annually (the current level) to about $2 billion per year.

Actions: To reach this goal, MIEAB recommends that Maine:

Build on Existing Strengths and Assets: Leverage investments in activities that help Maine develop the critical mass of talent and commerce needed for transformational growth.

Postsecondary Institutions: Further expand the R&D and commercialization capacity of Maine's public, private, and nonprofit research institutions, and incentivize collaboration among them. Increase funding for the critical Maine Economic Improvement Fund, while documenting return on investment and prioritizing partnerships with private entities, local communities, and other institutions.

Tax Credits: Review, improve, reinstate, and expand state R&D tax credits to be more broadly applicable (including commercialization activities in partnership with Maine research institutions) and less difficult to document.

Public Funding: Create a dependable source of state dollars for R&D investments and expand the Maine Technology Institute's budget to reflect the full potential for innovation within companies at all stages of development, including early-stage R&D activities.

Federal Grants: Increase matching grants and technical assistance for Maine companies and research institutions applying for federal R&D grants and contracts, Small Business Innovation Research, and Small Business Technology Transfer opportunities.

JAX

Cancer is the leading cause of death in Maine, attributable to over 3,400 deaths in the state in 2020. Cancer incidence is also a chronic problem, with rates in Piscataquis, Penobscot and Hancock counties exceeding the rest of the state. Over the long term, cancer mortality is steadily decreasing, due in part to declines in smoking, enhanced early detection, and more effective treatments designed and tested using mouse models.

The Jackson Laboratory, a nonprofit research institution based in Bar Harbor, is the leading distributor of mouse models in the U.S., including strains specifically designed for immuno-oncology — a therapeutic strategy that uses the immune system to recognize and destroy cancer cells. The JAX Charles E. Hewett Center in Ellsworth is home to several strains of this highly important research mouse, including the NSG™ mouse used in precision immuno-oncology research.

The Hewett Center is the product of JAX innovation and investments by the state of Maine through the Maine Technology Institute. A $1.7 million grant (matched dollar-for-dollar by JAX), helped the laboratory design and pilot systems for its "next-generation vivarium." A subsequent award of $12.5 million from the Maine Technology Asset Fund 2.0, matched by a JAX investment of over $67 million, saw the Ellsworth project through its second phase of construction.

Now in its fourth and final phase of construction, the Ellsworth campus will be fully built-out by January 2024, bringing a total of 370 R&D jobs to Hancock County, made possible by a total JAX investment of over $250 million. The laboratory mice raised at the Hewett Center will continue to deliver a strong return on state investment by sustaining jobs, generating regional economic growth, and helping to develop cancer therapies.

MaineHealth Innovation

Formed in 2020, MaineHealth Innovation leverages the ideas, insights, and expertise of care team members throughout the MaineHealth system to develop novel solutions to unmet care needs. Through programs such as the Innovation Cohort and the Innovation Fund, MaineHealth Innovation builds connections to drive diversity of thought, educates to produce creative problem-solvers, and funds to accelerate ideas. The work has resulted in real improvements in care and service available to the system's over one million patients.

Like many rural places, Norway, Maine, has a shortage of eyecare specialists and 40% of the area's' approximately 13,000 patients with diabetes were not receiving recommended retinopathy screenings. Dr. Brain Nolan saw an opportunity to incorporate these screenings into patients' routine primary care appointments via AI screening tools. Nolan formed a team, including medical assistants Billijoe Prech-Child, Brianna Walker, and Sadie Kenney, to advance this opportunity, and applied for funding through the MaineHealth Innovation Fund.

MaineHealth awarded the team $20,000 to purchase an EyeArt AI Screening System and cover initial screenings. This funding has led to an increase in diabetic retinopathy screenings, and patients can receive results at the end of their normal primary care appointments.

MaineHealth Innovation helps make projects like this a reality and continues to expand its programs, infrastructure and partnerships. Most importantly, MaineHealth Innovation is fostering a culture of innovation to support MaineHealth's vision of working together so its communities are the healthiest in America.

National Labs: Provide direct support to strengthen partnerships between Maine research institutions and national research institutions, including national laboratories.

Measurement: Building on existing systems, MIEAB will monitor the state's R&D spending as reported by the Maine Economic Growth Council in its annual Measures of Growth report.

Goal 2: Strengthen pathways to successful commercialization

Summary: Turning knowledge into commercial success requires entrepreneurship and innovation within enterprises. This goal calls for strengthening the educational, financial, and social supports to help new businesses succeed.

Background: Across Maine, there are thriving businesses whose products and services are rooted in innovations by Maine research institutions. The state's bioscience industry continues a tradition begun more than a century ago by the nonprofit Jackson Laboratory and the Mount Desert Island Biological Laboratory, and expanded in the 1970s by the Bigelow Laboratory for Ocean Sciences, Ventrex Laboratories, and the former Foundation for Blood Research.[17] Now it includes the for-profit companies IDEXX and Covetrus, which employ thousands of Maine workers. Similarly, the wood products industry now encompasses a huge range of biobased materials and products thanks to decades of industry-supported research at the University of Maine. There are innumerable examples of innovation and successful commercialization across sectors as diverse as boat building, software, medical devices, food production, clean energy, and the space industry. Yet the full potential of R&D to generate new businesses has not yet been realized. For example, offshore wind, an industry where Maine's unique potential is only beginning to emerge, is estimated to be a $70 billion revenue opportunity in the next decade[18]

Maine has a vibrant network of organizations that support and connect entrepreneurs, and has established tools for leveraging private and public funds through initiatives such as the Maine Technology Institute (MTI), Maine Venture Fund, Focus Maine, Coastal Enterprises, Inc., and the Finance Authority of Maine. These initiatives support innovation at both new and established companies.

Maine's commercialization investments over the past 25 years have yielded positive results, yet they have not been sufficient to generate transformational gains. In 2020, Maine ranked 33rd of the 50 states in terms of risk capital and entrepreneurial infrastructure, down from 29th in

17 William Hall, "An Industry with a Family Tree: Much of Maine's Biotech Industry Grew Out of Two Firms," Mainebiz, April 29, 2019.
18 Stephanie McClellan, "Supply Chain Contracting Forecast for U.S. Offshore Wind Power," University of Delaware, 2019.

2018.[19] This rank reflects comparatively low levels of venture capital activity; patents; business formation; nanotechnology, clean technology and biotechnology investments; and federal Small Business Investment Company funding.

Actions: In addition to investing in Maine's workforce and raising R&D funding as described in

Goal 1, MIEAB recommends the following actions to strengthen pathways to commercialization:

Start-ups: Increase funding and incentives to support and expand Maine's successful business incubators. Better support innovative new companies that face high up-front costs or long timelines to commercialization.

Existing Companies: Strengthen R&D and commercialization support for existing companies that are ready to grow, including improved access to R&D capabilities at the state's research institutions, and improved "matchmaking."

Incentives: Increase incentives and support structures for the commercialization of licensed intellectual property from Maine research institutions.

Entrepreneurs: Foster the next generation of entrepreneurs and innovators through academic and experiential programming in Maine's elementary, middle, and high schools, Career Technical Education centers, and institutions of higher education.

Regulatory Framework: Facilitate research on permitting, standards, and other regulatory issues that can affect the timely commercialization of R&D-driven discoveries.

Measurement: Building on existing systems, MIEAB will monitor the Maine Economic Growth Council's annual report of Maine's ratio of start-ups to closures in Measures of Growth.

GO Lab

GO Lab, Inc., a privately held building products company, was founded in 2017 with one purpose — to manufacture high-performance wood fiber insulation in North America under the brand name TimberHP.

Led by President Joshua Henry, the company seeks to grow Maine's economy and create new jobs through sustainable and collaborative means. In this effort, GO Lab acquired a mill in Madison that closed in 2016 after decades of operation. The site will produce TimberHP wood fiber insulation, beginning later this year, and is projected to employ about 120 people at full operation.

TimberHP builds on wood fiber's two-decade legacy of proven market success in Europe, offering safe, cost-competitive, sustainable insulation solutions. TimberHP is a value-added, innovative product line for Maine's new forest economy.

In its early stages, GO Lab participated in the UMaine-facilitated Big Gig pitch competition and the Bangor-region Top Gun accelerator program. Early R&D collaborations included work with UMaine's Advanced Structures and Composites Center (ASCC) to test the response of wood fiber insulation boards to a variety of adhesives.

As GO Lab renovates the former mill in Madison and prepares to begin manufacturing TimberHP wood fiber insulation there, the university remains a valued partner for the company. Current collaborations include ongoing work with both ASCC and the School of Forest Resources at UMaine on product testing data monitoring of wood fiber insulated CLT buildings. In addition, discussions are underway exploring next generation technologies to enhance wood fiber board insulation with weather-resistant barriers and biobased adhesives.

19 Kevin Klowden, Aaron Melaas, Charlotte Kesteven, and Sam Hanigan, "state Technology and Science Index: Sustaining America's Innovation Economy," Milken Institute, 2020.

Goal 3: Prepare an innovation workforce

Summary: At the heart of it all, it is about people. This goal seeks to expand the science and technology skills of Maine's workforce, preparing residents of all ages to innovate and find opportunity in today's economy, and providing businesses the workers they need to grow.

Background: Maine is experiencing a very tight labor market. Business leaders recently ranked the availability of entry-level, skilled technical, and professional workers as more concerning than historic issues such as taxes and the cost of doing business.[20] In addition to the housing and recessionary challenges facing many states, Maine's population is among the oldest in the nation, and the number of young people entering the workforce is too small to meet the needs of growing companies.

This challenge is occurring despite the significant progress Maine has made in terms of educational attainment in recent decades. The percentage of adults with a four-year degree or higher has grown from 23% in 2000 to 36% in 2020.[21] The importance of education or training beyond high school both for individuals and the broader Maine economy is now widely accepted.

Maine's progress reflects important investments in workforce development. In 2003, its technical colleges officially transitioned to community colleges in recognition of their expanding role. Since then, enrollment has risen over 50%.[22] In 2015, the community colleges and the University of Maine System signed a comprehensive transfer agreement to reduce both student cost and the time needed to complete a degree. In 2022, Maine's governor and Legislature made community college free for all recent high school graduates.

The Student Loan Repayment Tax Credit (formerly the Educational Opportunity Tax Credit) helps Maine attract and retain residents with college degrees by offering student loan debt relief. In 2016, the state increased benefits for holders of science, technology, engineering, and mathematics (STEM) degrees by making their credits fully refundable. This benefit can help recruit new talent to Maine.[23]

Despite this progress and existing incentives, Maine lacks the critical mass of both entry-level workers and skilled technical workers (including STEM professionals) needed to build and attract large, innovative companies. According to the Milken Institute, Maine ranks 41st of the 50 states in terms of human capital in the STEM fields, down from 37th in 2018.[24] Moreover, student scores in math and reading have fallen over the past decade.[25] Students in rural and low-income communities, where the introduction of engineering concepts in pre-kindergarten through grade 12 is less common, may have further barriers.

Efforts are underway to build resiliency in Maine's workforce. Expanding the talent pool is one of three goals of the state's ten-year economic strategy

bluShift

Sascha Deri founded bluShift Aerospace in 2014 to increase the sustainability of rocketry and provide dedicated launch services for small satellites. In 2021, its Stardust rocket became the world's first commercial rocket launched using nontoxic, carbon-neutral biofuel. Building on this success, the Brunswick-based firm is developing two more rockets: Starless Rogue, designed for suborbital trajectories, and Red Dwarf for low-Earth orbits.

WIth its MAREVL hybrid rocket engine and its nontoxic biofuel, bluShift is creating a sustainable way to serve the growing demand for small-satellite launches. This market is expected to grow to $28 billion within the next decade.

bluShift is funded in part by the Maine Technology Institute, NASA's Small Business Innovation Research grant program, and equity crowdfunding. It plans to launch its suborbital rocket in 2023, with Red Dwarf following two to three years later.

20 Maine state Chamber of Commerce, Maine Development Foundation, and Educate Maine, "Making Maine Work: Critical Investments for the Maine Economy," July 21, 2022.

21 U.S. Census Bureau, 2000 Decennial Census, 2021 American Community Survey, adults age 25 and older with a bachelor's degree or higher

22 Maine Community College System, "MCCS Annual Report 2022", 2022. Fall headcount 2002 (10,127) compared to 2020 (15,948).

23 Penelope Overton, "Maine Considers $42 Million Plan to Lighten College Graduates' Debt Load," Portland Press Herald, February 18, 2022.

24 Kevin Klowden, Aaron Melaas, Charlotte Kesteven, and Sam Hanigan, "state Technology and Science Index: Sustaining America's Innovation Economy," Milken Institute, 2020.

25 National Assessment of Educational Progress, Data Tools: state Profiles, accessed October 31, 2022.

released in 2019 (along with increasing wages and value-added per worker), and the plan recognizes the importance of investing in educator preparation and professional development to improve outcomes in PreK-12 education.

Several structural reforms are improving Maine's workforce development system:

Teacher Preparation and Professional Development: PreK-12 educators and organizations such as the Maine Math and Science Alliance, Educate Maine, the University of Maine's Maine Center for Research in STEM Education, and the Maine Discovery Museum have expanded programs to provide teachers with experiential learning resources to use with students to support their understanding of STEM concepts using evidence-based practices.

Micro-credentials: The University of Maine System, the Maine Community College System, and PreK-12 education partners have worked together to develop a common framework for micro-credentials that are less comprehensive than a full degree program but still provide rigorous training. The University of New England also has a badge/micro-credential program. These short, specialized programs are important for employers seeking specific skill sets and for older students looking to upgrade their credentials while working.

Promotion of Opportunities at Innovative Companies: Many young people are unaware of the world-class innovation happening in Maine, and the career opportunities it affords. New programs such as the Maine Science Festival, launched in 2015, are introducing students and their families to the many ways science and technology are being used in Maine. Long-standing programs such as the Maine State Science Fair are increasing students' capacity to do original research and connecting them to postsecondary education through over $800,000 in scholarship commitments from higher education partners. Innovate for Maine Fellows connect college students with some of the state's most successful companies, showing them opportunities for meaningful careers close to home. Maine Career Catalyst strengthens connections to the state among summer internships at Maine companies.

The state of Maine is piloting a high school internship program through the Maine Jobs and Recovery Plan, and several organizations are developing industry-specific opportunities in growing sectors like aquaculture, clean energy, and sustainable materials. To attract new residents, Live and Work in Maine promotes opportunities at innovation-based employers to people interested in moving to Maine. MaineHealth, the state's largest employer, promotes innovation through its MaineHealth Innovation Center, which provides training and funding to help its 22,000 employees explore creative approaches to providing and improving care.

Statewide Collaborative STEM Partnerships: Maine EPSCoR is strengthening the state's workforce by leveraging federal funding. Their current National Science Foundation EPSCoR Track-1 program (Maine-eDNA) will increase STEM engagement and success among key constituents, and develop innovative educational models and curriculum materials that can be disseminated both statewide and nationally.

Inclusivity: Maine will need the full contributions of every resident if it is to grow its workforce. Programs like Project Login's Girls Who Code encourage BIPOC[26] and female students who have been historically underrepresented in STEM fields. New Mainers Resource Center helps immigrants and refugees translate their prior education and work experiences into U.S. credentials that will allow them to join the workforce at a level appropriate to their training. The Third Space in Portland provides networking and supports to BIPOC entrepreneurs and emerging leaders. Programs like these are important to Maine's economic future.

Actions: These efforts are growing Maine's PreK-12 STEM workforce, but more is needed to realize the full potential of R&D to catalyze economic growth. MIEAB recommends the following actions:

Student Research: Increase recruitment and retention of students by introducing them to research early in their education and providing opportunities for more hands-on research as their knowledge grows.

Career Exploration: Expand students' understanding of different professions and help them see where they might fit into the workforce. Internships in STEM fields introduce students to opportunities within Maine and can be especially impactful for underrepresented minorities, females, rural students, and first-generation college students.

Career Pathways: Help students of all ages navigate efficient paths through the coursework and credentials needed to advance in their chosen careers.

Diversity, Equity, and Inclusion: Encourage the talent and contributions of all Maine people by removing barriers to education and employment for groups that have been traditionally underrepresented, including those facing generational poverty and new Mainers. Increase opportunities for paid experiences in STEM, research, and entrepreneurship programs to allow participation from all groups.

Online and Flexible STEM Programs: Create flexible and accessible opportunities for adult learners and professionals already in the workforce to upgrade

26 Black, Indigenous, and People of Color

their skills and credentials as new opportunities emerge.

Industry 4.0 Training: Expand training programs that teach interested workers and their employers how to use emerging technologies and real-time data to improve manufacturing and business operations.

Extracurricular Experiences: Support the important role of extracurricular experiences, such as festivals, STEM competitions, and field trips, in sparking interest in science and technology among young people and others exploring career options.

Measurement: Building on existing systems, MIEAB will monitor levels of educational attainment as reported by Educate Maine in its annual Education Indicators report.

AMP Fins

AMP Fins, based in Presque Isle, develops prosthetic fins that allow people who have lost limbs to engage in swimming and scuba diving. Designed and produced in Maine, these products are meeting the needs of amputees worldwide and promote inclusive access to physical activity.

Randy Lord, the catalyst for AMP Fins, lost part of his leg in an industrial accident. Longing to feel "whole" again, he and his wife Lori Lord began creating prototypes. Their first product, Custom Mold Fin, can be formed to meet each user's needs for all aquatic situations. AMP Fins' second product, the Mechanical Fin, was designed at the request of a clinical rehabilitation team at Walter Reed Military Medical Center and is now used in rehabilitation programs nationwide. With two designs for below- and above-knee amputees and video guidance for consumers, AMP Fins promotes inclusivity and accessibility.

Goal 4: Help businesses & communities thrive in the face of climate change

Summary: Maine industries and communities will face critical, even existential, challenges due to climate change. Some already are. Maine's R&D community must be a ready source of knowledge and innovation to help them adapt and thrive — helping farmers develop new crops and production methods, supporting Maine's forest products industry to meet global demand for climate-friendly forest products, expanding solar, wind and tidal energy generation and storage, helping marine industries adapt to changing oceans, and more.

Background: Climate change is having increasingly costly impacts on natural systems and human economies worldwide. Maine is seeing warmer temperatures, less winter snowfall, rising sea levels, and increasing annual precipitation, in conjunction with a shift toward more extreme weather events. These changes are affecting both terrestrial and marine environments, and have profound implications for human health and natural resources.

Over the past century, Maine's statewide average annual temperature has increased by about 3°F.[27] The average duration of winter (measured by temperature and snowfall) has declined by about two weeks, while summers have lengthened.[28] Maine's growing season is now sixteen days longer, on average, than in 1950.[29] Average annual precipitation has increased by about 6 inches since 1895.

Climate models show Maine could warm another 2-4°F by 2050 and by up to 10°F by 2100. Precipitation will increase, particularly during winter and spring.[30] And warming temperatures will further increase the potential for extreme weather, including heavy precipitation.

These temperature and precipitation changes will have tangible impacts on Maine residents and businesses, including:

- Health: The northward spread of invasive species and vector-borne diseases such as Lyme, and increased high heat-index days and heat-related illness
- Agriculture: A longer growing season and potential for new crop types, but increased evaporation and the exacerbation of drought or dryness, and introduction of new pests and crop diseases

27 Maine Climate Council (MCC) Scientific and Technical Subcommittee, "Scientific Assessment of Climate Change and Its Effects in Maine," 2020.

28 Birkel, S.D., Mayewski, P.A., 2018. Coastal Maine Climate Futures. Orono, ME: Climate Change Institute, University of Maine. 20 pp. Fernandez, I.J., Schmitt, C.V., Birkel, S.D., Stancioff, E., Pershing, A.J., Kelley, J.T., Runge, J.A., Jacobson, G.L., Mayewski, P.A., 2015. Maine's Climate Future 2015 Update. Orono, ME: University of Maine. 24 pp.

29 Fernandez, I.J., Birkel, S.D., Schmitt, C.V., Simonson, J., Lyon, B., Pershing, E., Stancioff, E., Jacobson, G., Mayewski, P.A., 2020. Maine's Climate Future 2020 Update. Orono, ME: University of Maine.

30 Easterling, D.R., K.E. Kunkel, J.R. Arnold, T. Knutson, A.N. LeGrande, L.R. Leung, R.S. Vose, D.E. Waliser, & M.F. Wehner (2017). Precipitation Change in the United states. In: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, D.C., U.S.A, pp. 207-230. https://doi.org/10.7930/J0H993CC

- Water: Reduction in water quality due to erosion, flooding, or algal growth, and drought-induced water scarcity
- Infrastructure: Threats to public infrastructure from weather-induced damage and sea level rise, capacity to handle increased seasonal energy demands, and increased demand for renewable energy systems and energy storage

Changes on land will be accompanied by changes at sea. The Gulf of Maine (GOM) is among the most rapidly warming regions of the global ocean,[31] and its marine ecosystem is losing its subarctic characteristics.[32] Climate models indicate the GOM's average annual sea-surface temperature could warm 1-3°F by 2050 and 1-7°F by 2100.

By the end of this century, sea level is projected to rise 3–5 feet based on an intermediate scenario of glacier melting. In its 2020 climate assessment report, the Scientific and Technical Subcommittee of the Maine Climate Council recommended planning for 1.5 feet of sea level rise by 2050 and 3.9 feet by 2100.[33] However, based on the large uncertainties in these projections, the subcommittee also suggested preparing for 3 feet of rise by 2050 and 8.8 feet by 2100.

A warming, rising ocean will have numerous impacts on Maine's marine industries and coastal communities, including:

- Significant changes to the GOM marine ecosystem, fisheries, and aquaculture
- Increased species migration pressures
- Ocean acidification caused by increasing CO_2 concentrations in the atmosphere
- Increased coastal flooding and erosion, threatening civil infrastructure
- Increased potential for saltwater intrusion of coastal drinking water aquifers; and
- Landward shifting of coastal beaches, dunes, salt marshes, and bluffs in response to erosion

In 2003, Maine became the first U.S. state to set a target for greenhouse gas (GHG) emissions, which it met when emissions were reduced to 10% below 1990 levels in 2012. In 2019, further legislation set the goal of reducing emissions 45% below 1990 levels by 2030 and 80% by 2050, and established the Maine Climate Council to guide achievement of these requirements. In 2019, the most recent year available, emissions were 23% below 1990 levels, meaning the state is continuing to progress toward its 2030 goal.[34] (Maine also has a statutory goal of achieving net-zero emissions by 2045.)

Building on this progress, the Maine Climate Council released a comprehensive climate action plan in 2020.[35] Its core goals are to reduce GHG emissions, avoid the impacts and cost of inaction, foster economic opportunity, and advance climate equity.

IDEXX

Artificial Intelligence (AI), the technological mimicry of human decision-making, has perpetrated many realms, including veterinary medicine. Large amounts of data can be tedious and sometimes impossible to analyze in a timely manner. The addition of AI methods in animal health not only conserves time, but promotes sustainability, is cost-efficient, and increases the overall level of care provided.

IDEXX Laboratories in Westbrook, Maine is a chief innovator in the animal healthcare industry. Its diagnostic and software products are used for the treatment of small companion animals, equine, and livestock, and in dairy markets. IDEXX is developing a suite of products and technologies that streamline veterinary medicine.

Part of IDEXX's incorporation of AI to improve workflow and pet care standards is a recent suite of analyzers. Veterinarians can use these tools to cut down lengthy process and analysis times, generating accurate results in minutes. For instance, IDEXX's ProCyte One Hematology Analyzer uses sensors to gather information from a blood sample that AI turns into graphical data and interpretive aids within minutes. This information gives clinicians what they need to help make treatment decisions quickly.

The development of AI tools in veterinary medicine goes beyond Maine and helps improve the quality of veterinary care globally.

31 Pershing AJ, Alexander MA, Hernandez CM, Kerr LA, Le Bris A, Mills KE et al. (2015) Slow Adaptation in the Face of Rapid Warming Leads to Collapse of the Gulf of Maine Cod Fishery. Science 350: 809–812.

32 MCC 2020.

33 Ibid.

34 Maine Department of Environmental Protection, "Ninth Biennial Report on Progress toward Greenhouse Gas Reduction Goals," July 2022.

35 Maine Climate Council, "Maine Won't Wait: A Four-Year Plan for Climate Change Action," December 2020.

Actions: Public, private, and nonprofit research institutions can be vital providers of innovation and expertise as Maine pursues these goals and adapts to climate change. Given the diverse, complex nature of this challenge, activities will look very different across the many sectors included in this plan. They include:
Clean Energy: Expand Maine's clean energy portfolio by catalyzing the creation of distributed and large-scale renewable energy facilities and energy storage, and modernizing existing energy infrastructure.

Local Food and Agricultural Resilience: Increase consumption of foods produced in state and promote climate-smart, high-tech agricultural practices.
Fisheries Resilience: Help Maine's fishing industry anticipate and adapt to the interactive effects of ocean warming, ocean acidification, and sea level rise.

Carbon Sequestration: Utilize Maine's forests and oceans to maximize carbon sequestration through strategic management and the creation of new products, while preserving their economic, environmental, and social value.

Artificial Intelligence (AI): Use AI to help advance climate-smart practices in agriculture, aquaculture, forestry, fisheries, and related sectors, and research ways to reduce AI's carbon footprint.

Measurement: Building on existing systems, MIEAB will monitor GHG emission levels reported biennially by the Maine Department of Environmental Protection.

Marin Skincare

Hiding between the rocks and seaweed of Maine's coast is a secret to fixing damaged skin: lobsters. Amber Boutiette and Patrick Breeding, co-founders of Marin Skincare, met in their first year at the University of Maine while studying biomedical engineering. While completing their studies, they worked with Robert Bayer, then professor of animal and veterinary sciences in the School of Food and Agriculture. Bayer was researching glycoprotein in American lobsters, *Homarus americanus*. Glycoproteins, molecules made of carbohydrates and protein chains, are responsible for the regenerative properties of echinoderms, crustaceans, and other marine groups.

Just as the properties of glycoprotein aid lobsters, they also can help repair our own damaged skin barriers, Bayer realized. Boutiette and Breeding jumped on the idea and the three collaborated to create a cream prototype for small-scale testing. Boutiette, who has eczema, used the serum with promising results. Marin Skincare launched in 2020.

Because of lobsters' role in Maine's economy and ecology, Marin Skincare prioritized the use of sustainable practices for their lobster products. Glycoproteins are sustainable, natural byproducts of lobsters. To increase efficiency and keep Marin Skincare local, Boutiette and Breeding partnered with Luke's Lobsters, a Maine-based lobster processor, to ethically collect glycoprotein.

With the support of Maine's start-up infrastructure, Marin Skincare has become a nationally recognized brand and shown that lobsters' regenerative properties are among the many secrets of Maine's ecosystems.

Goal 5: Strengthen Maine's R&D ecosystem

Summary: Maine's R&D ecosystem is the interdependent system of institutions, organizations, agencies, programs, and policies that collectively support research and development across the state. This goal aims to improve the effectiveness of this ecosystem, to increase interaction and collaboration, and to raise public awareness of R&D's role in economic development.

Background: Innovation encompasses a range of activities, from basic and applied research to commercialization and production. MIEAB recognizes that a transformative increase in R&D will require strategically aligning the efforts of state government, universities, the private sector, and nonprofit research institutions. All are necessary, supporting different innovation components, and must work together to achieve their full economic potential.

In 2007, the Maine Legislature created MIEAB to provide the leadership and coordination necessary to grow the innovation economy. The board is committed to this mission and prepared to fully execute its statutory duties.

Actions: MIEAB recommends the following actions to improve Maine's R&D framework:

Funding Predictability: Develop a clear schedule and strategy for biennial R&D bonding and state R&D appropriations.

Ecosystem Assessment: Map Maine's innovation support ecosystem to identify strengths, gaps, and opportunities to build a more fertile and nationally competitive environment for entrepreneurship, commercialization, and economic progress.

Centralized Information and Marketing: Develop, resource, and market a central repository of information about Maine's R&D assets. Establish a central repository and system for intellectual property (IP) protection, and a centralized data base of licensable IP.

Public Engagement: Increase public understanding of, and trust in, R&D's role in economic development and its value to Maine businesses and communities.

Measurement: MIEAB members will monitor progress toward this goal through their ongoing professional activities, and will report on this progress in future plans.

Gulf of Maine Ventures

Gulf of Maine Ventures (GMV) is the business development and impact investment arm of the Gulf of Maine Research Institute (GMRI). Its mission is to catalyze solutions to global ocean challenges by creating, scaling, and investing in innovative blue economy companies. By supporting and investing in companies that offer high-impact solutions, it aims to achieve a resilient, modernized 21st-century marine economy.

To date, GMV has helped two for-profit businesses develop, obtain seed funding, and launch successfully. The first, True Fin, buys high-quality seafood directly from Maine fishermen and delivers it to professional and at-home chefs nationwide. New England Marine Monitoring provides electronic monitoring systems, expert video review, technical support, and program management to New England fishermen. Today, both companies are generating over $2 million in annualized revenue and growing. Between them, they employ over 18 staff members.

Building on this success, GMV's work focuses on:

- Creating and incubating companies from within GMRI or partner research institutions
- Working with existing businesses that are implementing innovative solutions to refine their products and scale their business models in preparation for investment
- Investing in businesses that have demonstrated strong mission-impact and revenue potential through partnership with investment professionals at Bold Ocean Ventures

PRIORITY AREAS

This plan supports and advances the targeted technology sectors that have guided Maine's R&D investments since 1999. Agriculture, forest products, and aquaculture and marine fisheries are heritage industries that correspond directly to established target sectors. The high-growth target sectors, such as offshore wind and artificial intelligence, combine elements of multiple sectors in new and creative ways. In doing so, they build on Maine's historical comparative advantages to create new opportunities across multiple industries. This section presents the primary goals of R&D within each sector. See Appendix V for additional detail.

HERITAGE INDUSTRIES

Agriculture

As the world's population grows, and demand for sustainable food sources rises, Maine's natural resources and its location on the Eastern Seaboard create a unique opportunity for growth and innovation in agriculture. With strategic investments, Maine could lead the country in climate-smart practices, and significantly increase the amount of food consumed from in-state producers.

- Goal 1 Research Objective
  Prioritize research in four areas: 1) climate-smart agricultural practices including soil health, energy and water management, and crop breeding, 2) advanced technologies, 3) local food systems, and 4) pest and disease management.

- Goal 2 Enterprise Objective
  Increase in-state food consumption to 30% by 2030; strengthen local food supply chains while supporting more highly diversified farms that allow for the development of niche markets and specialty products.

- Goal 3 Workforce Objective
  Empower Maine farmers and farm workers to improve production practices by using climate-smart agricultural practices and advanced technologies (e.g., energy- and resource-efficient systems, decision support systems, drone technologies, remote sensing, precision agriculture).

- Goal 4 Climate Change Objective
  Increase in-state food consumption to 30% by 2030 and promote climate-smart agricultural practices.

Wyman's

Maine is known for its wild blueberry production. Wyman's, a family-owned Milbridge-based business, was founded in 1874 with the mission to help the world "eat more fruit." With the demand for fruit retail-products growing, Wyman's is developing new ways to engage the Maine community, create healthy consumer options, and be a leader in agroecosystem research.

In 2020, the company was named the largest retail brand for frozen fruit in the United States. Bruce Hall, Wyman's director of agroecology, says collaborations with the University of Maine were critical to this success. As demand for retail products grows, there's a need to consistently produce more wild blueberries. Wyman's partnered with the Maine Agricultural and Forest Experiment Station to create Wyman's Wild Blueberry Research & Innovation Center. This facility is the first collaboration between private and public research groups in the wild blueberry market and will lend itself to increasing hands-on educational opportunities for students and future industry leaders.

Continuing their focus on educational programs, Wyman's is funding two fellowship opportunities for graduate students. Their research will focus on quantifying carbon sequestration in blueberry agroecosystems and frost mitigation techniques.

"We may be best known at Wyman's for growing wild blueberries and selling fruit, but we are most proud of our positive impact on our local communities and environment," says Hall. "We have sowed the seeds of future collaborations with UMaine and, with them, push the bounds of stewardship and sustainability."

Aquaculture & Marine Fisheries

Seafood and its supporting marine-based industries are part of Maine's economic and cultural heritage. Changing economic conditions, environments, and regulations can impact Maine's aquaculture and fisheries sectors, threatening the resilience of Maine's working waterfronts. Research and innovation can help the communities affected by these changes anticipate and adapt to them, while reducing seafood trade deficits, increasing domestic food security, and increasing climate resilience and ocean health.

- Goal 1 Research Objective
  Advance the sustainable use of Maine's ocean and coastal resources for economic activity while preserving the health of these ecosystems.

- Goal 2 Enterprise Objective
  Expand sustainable aquaculture and fisheries operations along Maine's coast to help diversify coastal economies.

- Goal 3 Workforce Objective
  Preserve and grow a broad range of jobs within the seafood and marine bioproducts sector.

- Goal 4 Climate Change Objective
  Assist the industry, policymakers, consumers and natural resource managers in understanding and increasing coastal climate resilience through adaptation, mitigation, and decarbonization.

Forestry & Forest Products

Maine's forests can fuel a vibrant manufacturing industry while taking a lead role in the state's efforts to mitigate climate change. The vastness of this natural resource, combined with world-class research expertise, create a unique opportunity for Maine to be a leading source of climate-friendly, sustainable, and biobased products.

- Goal 1 Research Objective
  Improve tools to optimize forest management, and advance the development of climate-friendly and biobased alternatives in a variety of products and industries, including manufacturing, construction, and biochemicals.

- Goal 2 Enterprise Objective
  Catalyze the growth of a vibrant manufacturing industry that uses advanced technologies to create products that increase demand for a diversity of Maine tree species and grades of fiber.

- Goal 3 Workforce Objective
  Preserve and grow the forest industry workforce, and create new jobs at facilities making innovative wood-based products.

- Goal 4 Climate Change Objective
  Identify products and practices that mitigate the impacts of climate change on Maine's forests and the globe, reduce the carbon footprint of Maine's forest products industry, and help Maine reach its 2045 carbon-neutrality goal.

Peak Renewables

Three-fifths of Maine households use oil to heat their homes, more than any other state. Methane gas, a by-product of dairy production, is an alternative that could help Maine reduce carbon emissions and gain energy independence. Peak Renewables, a subsidiary of Summit Utilities, Inc., is researching how to do this.

The Maine dairy industry's 80,000 cattle produce over 1 million tons of cow manure annually. High methane emissions and contaminated runoff can cause significant environmental damage. With funding from MTI, the U.S. Department of Energy and others, Peak Renewables is turning cow excreta into pipeline-quality natural gas to fuel the state. The company broke ground at the first renewable natural gas (RNG) dairy digestion facility in Clinton in July 2022.

The digester heats and decomposes the manure, producing biogas. The gas is then cleaned to make it pipeline quality. Renewable energy credits will be sold to third parties that need them for their own decarbonization requirements. The gas itself will be purchased by Peaks Renewables' affiliate company, Summit Natural Gas of Maine, and used to provide service to its thousands of customers throughout the state. Carbon beneficial RNG is functionally identical to traditional natural gas and can be used for heating, cooking, and other processes. Peak Renewables estimates the facility will avoid emissions equivalent to 28,000 metric tons of dioxide each year of operation.

HIGH-GROWTH TARGET SECTORS

Aerospace

"New Space" is a fast-growing market, and Maine industries, from agriculture and forestry to aquaculture and fisheries, can improve their competitiveness using satellite data and other remote services. Maine has the research, education, and physical assets to excel in launching low-cost small satellites using small, low-cost launch vehicles.

- Goal 1 Research Objective
  Prioritize aerospace research with target areas identified by the Maine Space Grant Consortium (MSGC) ensuring alignment with Maine's emerging Spaceport initiative.
- Goal 2 Enterprise Objective
  Catalyze the development of an entrepreneurial space industry with a local supply chain, and provide data to support Maine's heritage industries.
- Goal 3 Workforce Objective
  Create training programs in advanced materials and other "new space" topics, and promote STEM curriculum at all levels, from computer science in PreK-12 to advanced mathematics doctoral programs.
- Goal 4 Climate Change Objective
  Advance the use of the Maine Space Complex to monitor the impact of climate change and the effectiveness of mitigation efforts. Identify products and practices that reduce the carbon impact of Maine's emerging aerospace industry.

Artificial Intelligence

Artificial intelligence (AI) has the potential to generate transformative solutions that enhance human life and societal well-being in Maine and beyond. Through innovative technologies and applications, AI can help Maine industries improve their operations and compete in the global economy.

- Goal 1 Research Objective
  Develop transformative AI-based solutions that enhance the social and economic well-being of the citizens of Maine and beyond. Priorities include making AI more efficient, ethical, and secure.
- Goal 2 Enterprise Objective
  Increase the number of Maine businesses and organizations using AI solutions to improve their products and operations.
- Goal 3 Workforce Objective
  Provide training and expertise to researchers and practitioners throughout Maine whose work could benefit from AI, and incorporate AI training into existing postsecondary programs in related fields.
- Goal 4 Climate Change Objective
  Use AI to help advance climate-smart practices and policies in agriculture, aquaculture, forestry, fisheries, clean energy, and related fields, and research ways to reduce AI's carbon footprint.

Advanced Building Products

Advanced, wood-based building products are a significant economic opportunity for Maine's forest products industry, and an important tool for carbon sequestration. Maine's vast forestlands position it for success in this growing field. Industry 4.0 (the application of information technology and real-time data to optimize processes and improve operations) is revolutionizing the manufacturing industry. Within construction, manufacturing-based production methods offer new ways to design and build affordable homes at scale.

- Goal 1 Research Objective
  Further develop innovative wood-based building products and construction practices, including wood fiber insulation and mass timber (engineered wood products that result in strong, large structural panels, posts, and beams), and innovative building techniques and technologies (such as prefabricated construction).
- Goal 2 Enterprise Objective
  Catalyze the development of an advanced building materials and techniques manufacturing cluster, including facilities for large-scale production of mass timber and wood fiber insulation.
- Goal 3 Workforce Objective
  Grow jobs within Maine's forest economy and create new jobs connected to the design, manufacture, delivery, marketing, and transportation of wood-based building products.
- Goal 4 Climate Change Objective
  Increase demand for carbon-sequestering products in long-lived buildings, encourage energy- and resource-efficient building products and processes, and encourage working forests that further sequester carbon.

Algae & Algal Products

Algae, from natural sources or grown in bioreactors, can fuel a vibrant independent industry, integrate into other industry sectors, and even help mitigate climate change. Maine's diversity of algal resources, combined with world-class research expertise, create a unique opportunity to be a leading source

of sustainable, algae-based products.

- Goal 1 Research Objective
  Improve tools to reduce the cost of algae cultivation and develop algae-based alternatives in a variety of products and industries, including biomanufacturing, biochemicals, biomedical research, and renewable energy.

- Goal 2 Enterprise Objective
  Catalyze the growth of a vibrant manufacturing industry that uses advanced technologies to lower the entry barrier to use of new and diverse algae-based products and processes.

- Goal 3 Workforce Objective
  Help the algae industry expand and diversify its workforce by creating new production and manufacturing jobs at facilities making innovative algae-based products.

- Goal 4 Climate Change Objective
  Identify and develop algae products and processes that reduce carbon dioxide emissions to help Maine reach its 2045 carbon-neutrality goal and increase exports of climate-friendly products and practices.

Biochemicals

Realizing the full potential of Maine's burgeoning bio-alternative industries requires continual research on its scientific underpinnings.

- Goal 1 Research Objective
  Continue industry-leading research on nanocellulose, biofuels, and bio-derived polymers (i.e., plastics and rubbers derived from plant and algae resources).

- Goal 2 Enterprise Objective
  Continue improving the production and properties of bio-alternatives for use in a wide variety of industrial applications.

- Goal 3 Workforce Objective
  Maintain world-class bio-alternative research facilities and educational programs to train the next generation of innovators.

- Goal 4 Climate Change Objective
  Increase demand for low-energy, carbon-sequestering products.

Biomanufacturing

Maine's forest can be a world-class source of nanocellulose — a plant substance with properties similar to plastic. This can fuel a vibrant manufacturing industry that combines advanced technologies with a renewable resource to create sustainable products.

- Goal 1 Research Objective
  Decrease the cost and energy-intensity of nanocellulose production, and enhance its properties as a manufacturing material.

- Goal 2 Enterprise Objective
  Move rural manufacturing — and the jobs it provides — toward an economically, environmentally, and socially sustainable future by advancing the use of nanocellulose in a wide variety of products and industries.

- Goal 3 Workforce Objective
  Sustain world-class additive manufacturing research and development facilities and educational programs to train the next generation of professionals and technicians.

- Goal 4 Climate Change Objective
  Advance the use of high-performance, low-energy, climate sequestering products in a variety of industries.

Biomedicine and Engineering Advances

Maine has nationally competitive expertise in basic biomedical research and a wide range of academic and healthcare institutions involved in basic, applied and translational research. Their collective strengths and accomplishments create a unique set of opportunities. Moreover, Maine's small population, served by a relatively small number of healthcare providers, suggests that collaboration and outreach will be necessary to engage patient populations in unique research initiatives.

- Goal 1 Research Objective
  Expand the application of precision medicine, biomedical data science, and genetic modeling of human disease.

- Goal 2 Enterprise Objective
  Continue generating the biomedical discoveries and expertise that have helped launch multiple spin-off companies in Maine.

- Goal 3 Workforce Objective
  Continue generating Maine expertise in the fields of cancer, genomics, neurobiology, host-pathogen interactions, computational biology and bioinformatics, aging, addiction, metabolism, and renal disease through postbaccalaureate, graduate and postdoctoral research training.

- Goal 4 Climate Change Objective
  Mitigate climate change enabled increased risk to infectious diseases (e.g, Lyme disease, West Nile virus)

Healthy Aging

Maine has one of the oldest populations in the U.S. In the coming decades, understanding how factors outside the healthcare setting influence the mental and physical health of older adults will be one of the state's major public health challenges.

- Goal 1 Research Objective
  Prioritize funding of research centers and individual projects focused on improving the mental and physical well-being of older adults and their caregivers.

- Goal 2 Enterprise Objective
  Encourage the creation of elder-appropriate technology solutions for older consumers, especially in the areas of AI, virtual and augmented reality, household technologies, and cybersecurity.

- Goal 3 Workforce Objective
  Prepare an age-capable workforce that can adequately identify and respond to the mental and physical health needs of older adults, especially in rural areas.

- Goal 4 Climate Change Objective
  Assess and mitigate the impact of climate change driven diseases of highest risk to the elderly.

Offshore Wind

Floating offshore wind is a strategic opportunity for Maine to meet its renewable energy targets and create a resilient Maine-made clean energy industry. With one of the nation's most robust offshore wind resources, and nearly a decade and a half of floating offshore wind innovation, Maine is poised to be a global leader in this burgeoning industry while preserving ocean access for historic uses.

- Goal 1 Research Objective
  Prioritize offshore wind research in three areas: 1) the technical aspects of engineering, manufacturing, installing, and operating floating wind turbines and farms in the Gulf of Maine, 2) their environmental and ecological impacts, and 3) the human dimensions and socio-economic impact of offshore wind development.

- Goal 2 Enterprise Objective
  Catalyze the development of a floating offshore wind farm in the Gulf of Maine, and support the development of a local supply chain that creates export opportunities for services, processes, and technology developed and patented in Maine.

- Goal 3 Workforce Objective
  Sustain world-class floating offshore wind research and development facilities and educational programs to train the next generation of offshore wind professionals and technicians.

- Goal 4 Climate Change Objective
  Expand Maine's clean energy portfolio by sourcing energy from Maine's abundant offshore wind resource, and catalyze the creation of a commercial floating offshore wind industry in Maine.

Tidal Energy

The Gulf of Maine, particularly the Western Passage between Maine and Canada, is one of the best tidal energy resources in the nation. With a successful ten-year history of R&D and commercialization that has advanced expertise in the field, Maine is strongly positioned to be a leader in tidal energy technology.

- Goal 1 Research Objective
  Prioritize tidal energy activities in four areas: 1) an inventory of potential tidal energy sites, 2) research on environmental impacts, 3) research on the human dimensions of tidal energy development, and 4) creation of a scaled tidal energy test site.

- Goal 2 Enterprise Objective
  Form a tidal energy cluster that encompasses research and design, manufacturing, installation, operation and maintenance, regulation, and site development.

- Goal 3 Workforce Objective
  Support the creation of a well-trained, well-paid tidal energy workforce, with opportunities for a diverse range of professionals, from engineers and managers to technicians and tradespeople.

- Goal 4 Climate Change Objective
  Expand Maine's clean energy portfolio by catalyzing the creation of a commercial-scale tidal energy operation in Maine.

CONCLUSION

Science and technology can be drivers of economic opportunity across Maine. Past investments in these areas – from both public and private sources – are the genesis of some of today's most successful businesses. These businesses employ thousands of people, spark further innovations, and feed a positive cycle of economic growth. A well-trained workforce fuels this growth and helps all Maine people share in the prosperity that it creates. This plan presents targeted research and development opportunities with the potential to yield results in the next three to five years. It acknowledges the significant investments made to date and affirms the potential to realize even greater gains by replicating the proven success of partnerships between Maine researchers and innovators and other stakeholders within Maine's R&D ecosystem.

APPENDIX I: MIEAB MEMBERS

The Maine Innovation Economy Advisory Board includes the directors of the Maine Technology Institute and the state's Office of Innovation, plus thirty individuals appointed by the Governor to represent Maine's private, public, and nonprofit research institutions, businesses, higher education, and venture capital. As of March 2023, members are:

Scott Bloomberg
Associate Professor of Law, University of Maine School of Law

Deborah Bronk
President/Chief Executive Officer, Bigelow Laboratory for Ocean Sciences

Denise Bruesewitz
Associate Professor of Environmental Studies, Colby College

Emily Christy
Consultant/Advisor, Tiny Barrel Ventures

Barry Antonio Costa-Pierce
President/Chief Executive Officer, Ecological Aquaculture Foundation and Professor of Biosciences & Aquaculture, Nord University, Norway

Patrick Cunningham
President/Chief Executive Officer, Blue Marble Geographics

Christopher Davis
Executive Director, Maine Aquaculture Innovation Center

Kate Dickerson
Executive Director, Maine Discovery Museum

Habib Dagher
Executive Director, University of Maine Advanced Structures and Composites Center

Michael A. Duguay
Executive Director, Harold Alfond Institute for Business Innovation/Vice President of Innovation, Thomas College

John Ferland
President, Ocean Renewable Power Company

Joan Ferrini-Mundy (Chair)
President, University of Maine and University of Maine at Machias
Vice Chancellor for Research and Innovation, University of Maine System

Patricia Hand
Senior Advisor to the President, MDI Biological Laboratory

Karen Houseknecht
Associate Provost for Research and Professor of Pharmacology, University of New England

Amber Lambke
Co-founder/Chief Executive Officer, Maine Grains

Emily B. Lane
President, Blue Lobster Consulting LLC

John M. Pavan
Chief Executive Officer, Pavan Enterprises, LLC

Joe Powers
Managing Director, Maine Venture Fund

Kris Sahonchik
Director, University of Southern Maine Research and Catherine Cutler Institute

Topaz Smith
Founder, EN-NOBLE

Dianne Tilton
Executive Director, Downeast Institute

Stephen Von Vogt
Chief Executive Office, Maine Marine Composites

Brian Whitney
President, Maine Technology Institute

APPENDIX II: MIEAP PROCESS

In February 2021, MIEAB directed Maine EPSCoR to begin gathering recommendations of priority research areas to be included in the 2023-2027 Maine Innovation Economy Action Plan. Over the course of the following two years, Maine EPSCoR invited dozens of researchers and stakeholders from a broad range of public, private, and non-profit institutions to submit their ideas and recommendations. It then invited additional stakeholders to review and comment on the submissions it received. Final recommendations were combined into a unified plan for statewide science and technology investments. A sub-group of MIEAB members reviewed early drafts of the plan in fall 2022, and the full board reviewed it in late 2022. Board members had opportunities to comment on, and request changes to, the plan during three meetings at which the plan was discussed, and to submit written comments via email and an online survey. Some board members also submitted written comments from colleagues. The final plan was approved by MIEAB on March 22, 2023.

MIEAB Meetings

October 27, 2021
December 22, 2021
January 6, 2022
May 26, 2022
July 14, 2022
November 21, 2022
January 26, 2023
March 2, 2023

MIEAB Plan Sub-Committee Meetings

September 20, 2022
November 2, 2022

Written Input Resubmitted by Individuals from the Following Institutions

(On the full plan and/or on relevant research areas, submitted via email or online survey)

Bigelow Laboratory for Ocean Sciences
Blue Lobster Consulting
Blue Marble Geographics
Colby College
Downeast Institute
Ecological Aquaculture Foundation
Governor's Energy Office
Governor's Office of Policy Innovation and the Future
LandVest
Maine Department of Economic and Community Development
Maine Discovery Museum
Maine Forest Service
Maine Governor's Energy Office
Maine Grains
Maine Marine Composites
Maine Space Grant Consortium
Maine Technology Institute
Maine Venture Fund
MaineHealth
MDI Biological Laboratory
Mook Sea Farms
National Renewable Energy Laboratory
Nord University, Norway
Ocean Renewable Power Company
Pavan Enterprises, LLC
Roux Institute at Northeastern University
Stonyfield Farm
The Jackson Laboratory
The Nature Conservancy
United states Department of Agriculture (Agricultural Research Service and Forest Service)
University of Maine
University of Maine School of Law
University of New England
University of Southern Maine

APPENDIX III: SUMMARY OF GOALS

Maine Innovation Economy Action Plan | 2023-2027

Vision: A resilient, innovation-driven economy that creates opportunities for all Maine people

Goal 1: Increase R&D to 3% of GDP while focusing on activities that directly support Maine industries

- Build on existing strengths and assets
- Expand R&D and commercialization capacity at post-secondary institutions
- Expand R&D tax credits
- Increase and stabilize public funds for R&D investments
- Increase support for companies and institutions pursuing federal grants
- Strengthen partnerships with national labs

Goal 2: Strengthen pathways to successful commercialization

- Increase support for start-ups
- Strengthen R&D and commercialization support for existing companies
- Increase incentives for commercialization at research institutions
- Foster the next generation of entrepreneurs and innovators

Goal 3: Prepare an innovation workforce

- Expand student research opportunities
- Increase awareness of science and technology careers
- Help both new and incumbent workers find career pathways
- Embrace diversity, equity, and inclusion
- Expand training on use of emerging technologies and real-time data in manufacturing (Industry 4.0)
- Support extracurricular STEM experiences

Goal 4: Help businesses & communities thrive in the face of climate change

- Expand Maine's clean energy portfolio
- Increase local food and agricultural resilience
- Support fisheries resilience
- Pursue strategic carbon sequestration opportunities
- Use artificial intelligence to advance climate-smart practices

Goal 5: Strengthen Maine's R&D ecosystem

- Develop a schedule for R&D bonding and state appropriations
- Create and market a central repository of information on Maine's R&D assets
- Increase public understanding of, and trust in, R&D's role in economic development

APPENDIX IV: ALIGNMENT WITH MAINE'S TARGETED TECHNOLOGY SECTORS

This plan supports and advances the targeted technology sectors that have guided Maine's R&D investments since state policymakers approved them in 1999. The "heritage industries" of agriculture, aquaculture and marine fisheries, and forestry and forest products correspond directly to individual target sectors. The "high-growth target sectors" combine elements of multiple sectors in new and creative ways. In doing so, they build on Maine's historical comparative advantages to create new opportunities across multiple industries. For each priority area of this plan, the grid below shows which of Maine's targeted technology sectors it most actively supports.

Maine's Targeted Technology Sectors

2022 MEAP Priority Areas

	Biotechnology	Composites & Advanced Materials	Environmental Technology	Forestry & Agriculture	Information Technology	Marine Technology & Aquaculture	Precision Manufacturing
Heritage Industries							
Agriculture (p28-29)				•			
Aquaculture & Marine Fisheries (p30-35)						•	
Forestry & Forest Products (p36-38)				•			
High-Growth Target Sectors							
Aerospace (p39-40)		•	•	•	•	•	•
Artificial Intelligence (p41-43)	•	•	•	•	•	•	•
Biobased Alternatives							
Advanced Building Products (p43-47)		•	•	•			
Algae and Algal Products (p48-49)	•		•			•	
Biochemicals (p49-53)		•					
Biomanufacturing (p53-56)		•		•			•
Human Health							
Biomedicine and Engineering Advances (p56-58)	•						
Healthy Aging (p59-60)	•						
Renewable Energy							
Offshore Wind Energy (p61-64)		•	•			•	•
Tidal Energy (p64-67)		•	•				•
Cross-Cutting Initiatives							
Enterprise Development	←	—	—	—	—	—	→
Workforce Development	←	—	—	—	—	—	→
Climate Preparedness	←	—	—	—	—	—	→

APPENDIX V: PRIORITY AREAS IN DETAIL

HERITAGE INDUSTRIES

Agriculture

As demand for sustainable food sources and the world's population grow, Maine's natural resources and its location on the Eastern seaboard create a unique opportunity for growth and innovation in agriculture. With strategic investments, Maine could lead the country in climate-smart practices, and significantly increase the amount of food consumed from in-state producers.

- Goal 1 Research Objective
  Prioritize research in four areas: 1) climate-smart agricultural practices, including soil health, energy and water management, and crop breeding, 2) advanced technologies, 3) local food systems, and 4) pest and disease management.

- Goal 2 Enterprise Objective
  Increase in-state food consumption to 30% by 2030; strengthen local food supply chains while supporting more highly diversified farms that allow for the development of niche markets and specialty products.

- Goal 3 Workforce Objective
  Empower Maine farmers and farm workers to improve production practices by using climate-smart agricultural practices and advanced technologies (e.g., energy- and resource-efficient systems, decision support systems, drone technologies, remote sensing, precision agriculture).

- Goal 4 Climate Change Objective
  Increase in-state food consumption to 30% by 2030 and promote climate-smart agricultural practices.

It is expected the world's population will reach 9.9 billion by 2050, requiring a 70% increase in the world's food supply. In addition, the global pandemic has accelerated the movement toward more local food options, given supply chain disruptions and price increases that exacerbated food insecurity and related negative health outcomes especially among disadvantaged communities. The increasing demand for affordable, safe, local protein and Maine's rich natural resources are ripe for innovation in agriculture. Additionally, Maine could lead the country in climate-smart agriculture practices and meet the goal in Strategy D (Grow Maine's Clean-Energy Economy and Protect Our Natural-Resource Industries) of the Maine Won't Wait Climate Action Plan by increasing the amount of food consumed in Maine from state food producers from 10% to 20% by 2025 and 30% by 2030 via local food system development. Related to the changing climate, Maine's Ten-Year Strategic Plan stated: "As markets and demand grow for sustainable food sources closer to markets, Maine has the opportunity to meet the significant consumer demand on the Eastern Seaboard, all within a day's drive of our state. From aquaculture to traditional seafood harvesting to value-added food production, growth is anticipated in these food industries and Maine can benefit greatly by growing our capacity to meet these markets." To accomplish these goals, Maine agriculture will need research, education, and outreach that the University of Maine is uniquely positioned to provide through the Maine Agricultural and Forest Experiment Station and Cooperative Extension. Agriculture has a direct impact on every county and every community throughout the state, through building the local economy, decreasing food insecurity, and addressing climate change.

Opportunity & Objective

There are 7,600 farms in Maine, more than any other New England state. Agriculture contributes $12.6 billion to the state's economy (4.9% of total gross domestic product). With 100,000 jobs currently in the industry, the need for a skilled workforce will continue to grow, but a focus on training for advanced technologies is important (e.g., decision support systems, drone technologies, remote sensing, precision agriculture). There is need for increasing focus on securing local supply chains and production, and need for more highly diversified farms that allow for the development of niche markets and specialty products, which could be promising opportunities for small farmers. Development of new crops, as well as seeking acreage of crops that are nationally being displaced due to climate change, offers additional market options. Prioritization of climate-smart production practices aligns well with many of Maine's current production practices (e.g., cover crops, crop diversification and enhanced biodiversity, agroecological practices, forestry and agricultural integrated operations, ecosystem service accounting). Increasing these practices will also contribute to Maine's climate goals.

Notable Maine Institutions & Organizations

- Agriculture Council of Maine
- Maine Beef Producers Association
- Maine Board of Agriculture
- Maine Climate Council
- Maine Dairy Industry Association
- Maine Department of Agriculture, Conservation and Forestry
- Maine Department of Economic and Community Development
- Maine Department of Environmental Protection
- Maine Farm Bureau
- Maine Landscape and Nursery Association
- Maine Organic Farmers and Growers Association

- Maine Pomological Society
- Maine Potato Board
- Maine Sustainable Agriculture Society
- Natural Resources Conservation Service
- Northeast SARE
- United States Department of Agriculture (NRCS, ARS)
- University of Maine (Natural Sciences, Forestry and Agriculture, Cooperative Extension, Maine Agricultural and Forest Experiment Station)
- Wild Maine Blueberry Commission

Current Research

- Farmers in a Resilient Rural Economy — This research has at its core the mission of conducting capacity research to support and enhance agriculture and rural life in the state of Maine.
- Soil Health & Chemistry Research — Natural climate solutions, including increasing levels of organic matter to sequester soil carbon, are being emphasized at the federal and state levels.
- Horticultural Practices Research — Addressing needs related to sustainability in the U.S. horticulture industry in the context of a broader multistate project on sustainable practices, economic contributions, consumer behavior, and labor management in the horticulture industry.
- The Maine Food System — Research focused on agricultural sustainability and interrelated work in policy, research, production, processing, commerce, nutrition, food security, and food safety.

Future Priority Areas

- Continued emphasis on soil health, with expanded capacity for: training of certified soil scientists and overall expansion of certified soil and crop advisors; PFAS and other contaminants coupled with research focused on broad remediation techniques; quantification of soil carbon sequestration to be ready to respond to carbon markets.
- Precision agriculture development for Maine farms: focus on technologies that are applied at small scales and low cost (e.g., chaff sensors and satellite hyperspectral imaging); decision support systems specifically developed for Maine crops that focus on efficient application of water and nutrients and their interaction; early crop stress sensing and intervention management.
- Technology development: Precision agriculture driven development of planting, management, harvesting, etc. machinery. Includes the development of precision application of water, nutrient, and weed control; yield monitoring; soil EC and other sensing to determine best practices for nutrient applications; development of scalable equipment to address diversified Maine farms.
- Model Maine Diversified Farm of the Future: capitalizing on the UMaine Experiment Station farm network, develop research focal areas that develop and assess an integrated, resilient, and diversified farm operation in different state regions.
- Expanded crop breeding programs for Maine farms: using the model of the successful potato breeding program, establish additional breeding programs to develop regionally adapted germplasm for Maine. Breeding programs should rely on research facilities that use high throughput phenotyping and an appropriate mix of genomic and traditional breeding techniques.
- Landscape-scale water management research: over the next decade, Maine's water resources will be critically impacted as more population and more food production moves nationally toward the Northeast. Research is crucially needed to develop watershed, subregional, field, and microscale agricultural water management (quantity and quality) techniques for efficient use and preservation of water resources. This includes surface and subsurface sources of water and could include research on policies related to water access and allotment.
- Increasing capacity to create a safer, healthier, more accessible, and increasingly productive food system.

Economic Impact

Expanded food system will create new businesses, add jobs, increase property values, generate new revenues and contribute to increasing rural communities throughout the state.

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Aquaculture

Maine has an opportunity to lead the nation in sustainable aquaculture innovation and technology. Achievements in this field support the national effort to reduce seafood trade deficits while increasing food security and supporting a new Blue Economy that increases climate resilience and ocean restoration.

- Goal 1 Research Objective
  Prioritize research in six areas: 1) aquatic veterinary services and products, 2) alternative feed technologies, 3) technology-based innovations, 4) marine and freshwater culture systems, 5) decision-support tools, and 6) triple-bottom-line sustainability.

- Goal 2 Enterprise Objective
  Expand sustainable aquaculture operations along Maine's coast and help diversify coastal economies.

- Goal 3 Workforce Objective
  Sustain world-class aquaculture research facilities and educational programs to create a skilled aquaculture workforce.

- Goal 4 Climate Change Objective
  Assist the aquaculture industry, policymakers, consumers and natural resource managers in understanding and increasing coastal climate resilience through adaptation, mitigation, and decarbonization.

In 2019, at the national level, freshwater and marine aquaculture was valued at $1.5 billion, which is 24% of the value of domestic seafood products. In New England, aquaculture is the third most valuable fisheries sector. These operations are supported by a world-class research and technology sector. In Maine, aquaculture is one of seven targeted technology areas as detailed in the 2010 Maine Science and Technology Action Plan. In the past ten years, the state has experienced rapid growth in interest with investments in Recirculating Aquaculture System (RAS) companies and the shellfish and seaweed sectors. Along with this rapid development potential comes an opportunity for Maine to lead the nation in sustainable aquaculture innovation and technology that can both support the national effort to reduce seafood trade deficits while increasing food security, as well as supporting a new Blue Economy that increases climate resilience and ocean restoration while it reduces inequity in the sector.
The 2010 Science and Technology Plan listed Marine Technologies and Aquaculture as one of the seven targeted research sectors without much specificity in the research priorities. In the past ten years, extensive collaborative projects funded through Maine EPSCoR, USDA and NOAA, such as SEANET, RAS-N, SAS2 and the Maine Aquaculture Hub, have identified new research themes as the ecosystem and industry have evolved. More recently, these themes have been prioritized in-state and federal RFPs and are of growing interest to investors and consumers. To incorporate these priorities into this chapter, we have separated aquaculture from marine technology and subdivided the suggested research into six broad areas: aquatic veterinary services and products, alternative feed technologies, technology-based innovations, marine and freshwater culture systems, decision-support tools and research in triple bottom line sustainability. In addition to these research priorities, other initiatives have called attention to infrastructure and related research that supports Maine Aquaculture. For example, Maine Innovation Economy Action Plan calls for the general improvement of research infrastructure, the Maine Won't Wait Climate Plan highlights climate resilience in the marine sector, and the Maine aquaculture Roadmap recommends increasing research coordination and planning capacity. The Maine Economic Development Plan as well as other state and federal workforce initiatives point to the aquaculture cluster as an area to increase training for high-quality jobs.

With 3,500 miles of tidal shoreline, Maine has incredible potential to expand existing farmed species along the coast. For example, with considerable research contributions from the research community, eastern oyster aquaculture has expanded from approximately $1 million in landed value in 2011 to $9.6 million in 2019. Most of this industry's growth has occurred on the Damariscotta River, but new tools (such as satellite prospecting for new growing areas) are identifying areas for expansion. Additionally, sea vegetables, sea scallops, razor clams, soft shell clams, and mussels could become viable species for those looking to diversify their income. Mussel aquaculture revenue has almost quadrupled between 2011 and 2019, and between 2018 and 2019 the value of the marine algae harvest has also quadrupled. However, shellfish and seaweed aquaculture are still a cottage industry with great potential for growth. The opportunity for Maine to be a part of a global expansion of aquaculture and the national effort to reduce seafood trade deficits is underexploited, and the need for investment in research that increases sustainable aquaculture growth in the region is indisputable.

Opportunity and Objectives

- Maine's aquaculture sector annually contributes $80 million-$100 million farm gate and $153 million economic impact to the state's economy (Maine Aquaculture Association, 2020).
- Aquaculture growth has the potential to meet multiple economic and social objectives.
- Blue Carbon as it relates to aquacultured species, especially macroalgae, has the potential to play a role in Maine's goal for carbon neutrality by 2045.
- Increased R&D Infrastructure (e.g., pilot-scale RAS systems, pilot-scale shellfish and seaweed

hatcheries, marine-based experiment stations, pilot-scale seafood processing facility) would add resilience, flexibility, knowledge support, and value to Maine's entire seafood sector.
- The Gulf of Maine has warmed faster than 99% of the world's oceans and these warming trends will affect marine species' productivity, stock resilience, and disease prevalence in ways that have not been fully evaluated. Therefore, developing multi-use predictive tools will strengthen the resilience of Maine's fisheries in general, as well as help quantify impacts for other coastal sectors and infrastructure.
- Maine's reliance on its lobster fishery, which in 2021 represented 82% of the value of all fisheries landings, has created a need for a diversity of other working waterfront opportunities and aquaculture offers a significant share of that potential.

Notable Maine Institutions & Organizations

- Bates College
- Bigelow Laboratory for Ocean Sciences
- Bowdoin College
- Coastal Enterprises Inc.
- Colby College
- College of the Atlantic
- Downeast Institute
- Gulf of Maine Research Institute
- Hurricane Island Center for Science and Leadership
- Island Institute
- Maine Aquaculture Association
- Maine Aquaculture Innovation Center
- Maine Department of Inland Fisheries and Wildlife
- Maine Department of Marine Resources
- University of Maine (Aquaculture Research Institute, Center for Cooperative Aquaculture Research, Cooperative Extension, College of Natural Sciences, Forestry and Agriculture, Cooperative Extension, Darling Marine Center, Maine Sea Grant)
- University of New England
- University of Southern Maine
- USDA-ARS National Cold Water Marine Aquaculture Center

Past Research Activities

- Ten-year Aquaculture Economic Development Plan 2010
- NSF EPSCoR Sustainable Ecological Aquaculture Network (SEANET) (2014-2019)
- Maine Aquaculture Economic Impact Analysis (2016)
- Recirculating Aquaculture Salmon Network (RAS-N) is a multistate Sea Grant Aquaculture Hub that supports a growing domestic land-based Atlantic salmon industry by addressing the barriers, bottlenecks, and needs of commercial RAS production (2018-2022)
- Aquaculture R&D Survey Report 2017 & 2020
- Aquaculture Workforce Development Needs Report 2020
- Maine Won't Wait Climate Action Plan 2020
- Maine Economic Development Strategy 2020–2029
- Edible Seaweed Market Analysis 2020
- Maine Aquaculture Roadmap (2022-2032)

Current Research Activities

- NSF EPSCoR Maine-eDNA is a statewide, multi-institutional initiative establishing Maine as a national leader in environmental monitoring, ecological understanding, and sustainability of coastal ecosystems and fisheries, including aquaculture. (2019-2024)
- Sustainable Aquaculture Systems Supporting Atlantic Salmon SAS2 is a U.S./global partnership between academia and industry that will use a transdisciplinary, integrative systems-approach to foster the development of transformative, environmentally sustainable and economically feasible Atlantic salmon farming in the U.S. (2021-2025)
- Marine Rearing of Adult Atlantic Salmon will employ a novel rearing method to produce mature Atlantic salmon and deliver them to underutilized, priority habitat within the Penobscot River. This work cultivates a new partnership between Cooke Aquaculture, USDA, USFWS, NOAA, ARI, and the Penobscot Nation.
- Coast to Cow to Consumer: Marine Algae Use to Enhance Milk Production, Mitigate Greenhouse Gas Emissions, and Recover Nutrients aims to sustainably intensify U.S. dairy production by developing marine algae-based feed supplements for cattle. These additives can also reduce environmental impacts of dairy production by recapturing nutrients and reducing greenhouse gas emissions. (2021-2025)
- Sea Grant Maine Aquaculture Hub is a multi-institutional Maine collaborative formed to help the aquaculture industry in Maine overcome barriers to growth through industry engagement, training, R&D funding and road map development. (2018-2024)
- SEAMaine (Seafood Economic Accelerator for Maine) is an industry-led initiative bringing together leaders in Maine's commercial fishing, aquaculture, and seafood economy. Funded by the U.S. Department of Commerce Economic Development Administration, with match funding from the Maine Technology Institute and FocusMaine, the statewide initiative is developing a road map and action plan for economic growth, market and workforce development, and greater resiliency in Maine's seafood economy. (Ongoing)
- USDA ARS Non-Assistance Cooperative Agreement: Through this federal partnership, ARI works with the USDA ARS National Cold Water Marine Aquaculture Center in Franklin and Orono on the Genetic Improvement of North American Atlantic salmon and the eastern oyster for aquaculture production.
- Aquaculture Economic Impact Report: Maine

Aquaculture Association (MAA) will update the Maine Aquaculture Economic Impact Analysis of 2016 to reflect recent growth. (2022)
- Aquaculture Occupational Standards: The occupational standards are intended to present education and training providers with a clear and comprehensive understanding of the specific technical skills and knowledge that are critical for the most common careers in each sector, standardize workforce training in the state, and establish an industry-led process to align training with workforce needs as the industry, and workforce needs, evolve. (Ongoing)
- Maine Aquaculture R&D Survey Report: MAIC, in collaboration with ARI, MAA, and MSG, has conducted an online R&D survey with a broad group of participants in the aquaculture sector for three biannual cycles. The survey guides the development of the Maine Aquaculture R&D and Education Summit. (2022)

Mid- and Long-Range Research Priority Areas

- Aquatic veterinary services and products (e.g., vaccines, biosecurity, probiotics): advancing novel research to develop aquatic animal health products, assisting Maine's biotech companies to meet key commercialization objectives and improving aquatic animal health and genetics.
- Alternative feed technologies (e.g., algal feeds, micro-encapsulation, alternative proteins): advancing sustainable feeds that rely less on wild caught fisheries or unsustainable land-based feeds for more efficient delivery, production, and nutritional value.
- Technology based innovations (e.g., land-based system designs, hatchery technology, AI applications, nanocellulose, sensor technology, nanobubble): developing technologies that increase energy and labor efficiencies, decrease waste output and increase resilience in the face of environmental change.
- Marine and freshwater culture systems (e.g., multi-trophic aquaculture systems, co-location with offshore wind, land-based, closed pen): diversifying and improving systems that increase where and how aquatic products can be grown to reduce environmental impacts, increase labor efficiency, reduce waste outputs, and maximize food safety.
- Decision-support tools (e.g., eDNA monitoring, ecosystem services, nearshore monitoring systems, ecosystem models): assisting managers and policymakers in understanding resource trends, farm siting and permitting, carrying capacity and environmental uncertainty.
- Triple bottom line sustainability research (e.g., ecosystem services, community acceptance, environmental impacts, cultural diversity, economic and rural development research and climate resilience): preparing and adapting aquaculture to changing social, economic and environmental parameters while quantifying and improving diversity within the sector, ecosystem services, and restorative practices.

Economic Impact

- FocusMaine predicts Maine aquaculture exports will net $230 million–$800 million by 2025.
- Valuation of blue carbon storage potential and other ecosystem services leads to greater additive economic impacts.
- Multiplier effects from marine research sector
- Development of the Maine sustainable seafood brand will increase demand across the seafood sectors.
- Increased rural community and tribal career opportunities.
- World-renown research capacity attracts international investment.
- More resilient coasts decrease potential economic impacts of climate change and changes in other fisheries.

Marine Fisheries

Maine's marine fisheries are part of its economic and cultural heritage, and an important source of commercial activity. Climate change is placing them in a vulnerable position. Researchers can help the individuals and communities most affected by these changes anticipate and adapt to them, preserving fisheries as a sustainable Maine industry.

- Goal 1 Research Objective
  Prioritize research that protects and advances the sustainable use of Maine's ocean and coastal resources, preserving the health of ocean and coastal ecosystems to enable economic activity.

- Goal 2 Enterprise Objective
  Work with the fisheries industry and managers to achieve long-term economic resilience by anticipating and adapting to climate change.

- Goal 3 Workforce Objective
  Sustain Maine's seafood industries to preserve the full diversity of jobs from fishing to processing and distribution.

- Goal 4 Climate Change Objective
  Work with the fisheries industry and managers to collectively understand and respond to the interactive effects of ocean warming, ocean acidification, sea level rise, and other climate factors.

Fisheries were not identified as a target technology area in the 2017 Maine Science and Technology Action Plan. Yet, Maine's fisheries-based economy, and the coastal and inland communities it supports, has a direct value exceeding $1.2 billion annually. Freshwater recreational anglers in Maine's inland waters contribute roughly $319 million annually to the state's economy (2014). Freshwater fisheries range from coldwater (brook, brown, and lake trout, landlocked salmon, and whitefish), warmwater game fish (large and small mouth bass, northern pike, white perch) and others (alewife, American eel). Marine commercial landings exceeded $890 million in 2021. The top five species in 2021 were lobster ($730 million in 2021 — 82%), softshell clam ($27 million), and American eel elvers ($18 million). Lobster represents the most valuable single-species fishery in the United States, and 80% of it is harvested in Maine. Commercial fisheries in Maine include groundfish, oysters, menhanden, scallop, bloodworms, among many others. Other important recreational and commercial harvest include tuna, swordfish, squid, bluefish, and pollock.

Ocean warming has played a key role in changing distributions of commercial and noncommercial species. Maine is losing its boreal and subarctic species while non-native temperate species from the south are on the increase (Arnold et al. 2020). These shifts present challenges and opportunities for fisheries managers. The interactive effects of warming, ocean acidification, and sea level rise on coastal ecosystems are not well understood and recent evidence indicates that extreme climate events reduce regional catch and revenue in the fishing sector, ultimately affecting wages and employment of harvesters (Oremus, 2019).

The combined effects of increasing river discharge and declining influence of the cold, nutrient-rich, Labrador Current from North Atlantic are altering Gulf of Maine circulation, diminishing ecosystem productivity, and making more vulnerable the communities dependent on wild-harvest fisheries. Estimated sea level rise and resulting coastal erosion and habitat losses may mean $34 million and $104 million in lost ecosystem services by 2030, and between $103 million, and $260 million in losses by 2100 (Arnold et al. 2020). Direct value loss to fisheries and aquaculture are estimated near $700 million annually (and more in supporting businesses) are at risk from warming and acidifying ocean waters. Some projections suggest lobster abundance in the Gulf of Maine could decline 45% by 2050 (LeBris et al, 2018), potentially decreasing Maine's GDP by approximately $800 million over 30 years and reducing the state's economic output by $1.3 billion.

Apart from the direct effects of a changing climate to fisheries, but still related to it, offshore wind energy development and fishing gear regulations protecting the North Atlantic right whale pose what many in the fishing industry see as an existential threat. Through federal regulation, fixed gear fishers, primarily the lobster, crab and gillnet fisheries, are facing the prospect of dramatically changing how, where, and when they fish to sustainably co-exist with both the endangered North Atlantic right whale and offshore wind energy development.

Opportunity & Objective

- Maine people depend on its freshwater and marine resources through ecotourism, recreational, and commercial practices.
- Maine's Blue Economy includes the sustainable use of ocean and coastal resources for economic growth, improved livelihoods, and jobs, while preserving the health of ocean and coastal ecosystems.
- Maine's fisheries are in a vulnerable state with increasing temperatures, longer summers, and shorter winters, changing precipitation patterns and hydrology, and ocean acidification all changing ecosystem dynamics of freshwater and coastal systems.
- The primary objective is sustainable fisheries, with better quantification and support of ecosystem services, such as recreation, biodiversity, and attention to cultural values.

Notable Maine Institutions & Organizations

- Bigelow Laboratory for Ocean Sciences
- Downeast Institute
- Gulf of Maine Research Institute

- Maine Department of Marine Resources
- Maine Sea Grant College Program
- Maine-eDNA
- Southern Maine Community College
- University of Maine System
  - Darling Marine Center
  - Marine Aligned Research, Innovation, and Nationally Recognized Education (MARINE) Initiative
  - School of Biology and Ecology
  - School of Marine Sciences
  - University of Maine at Machias Division of Environmental and Biological Sciences
  - Wildlife, Fisheries, and Conservation Biology
- University of Southern Maine

Other involved organizations and research partners include Maine Center for Coastal Fisheries; Maine Coast Fishermen's Association; Maine Lobstermen's Association; Ready Seafood Co.; EAMaine - Seafood Economic Accelerator for Maine; Island Institute; The Nature Conservancy; NOAA National Marine Fisheries Service - Northeast Fisheries Science Center.

Past Research Activities

- Considerable investment from NOAA, especially through Sea Grant and Saltonstall-Kennedy and cooperative agreement programs has supported study of the influence of the ocean's physical and biotic environment on the population dynamics and distribution of marine organisms, integrates ecology, oceanography, and fishery science toward a better mechanistic understanding of marine populations and communities. A long-standing research program on the American lobster, for example, has developed predictive tools for population trends through an understanding of the influence of environmental factors, such as temperature, currents, predators, and disease, on larval transport, settlement, and post settlement processes. Additional research has been funded to support development of fisheries assessment methods and techniques that have been applied by governing authorities.
- Study of highly migratory species like tuna, billfish, and sharks undertaken to understand basic biology and life history parameters that are critical components of stock assessment models and essential pieces of information that reduce uncertainty and allocate scientifically based appropriate levels of catch. Projects engage commercial and recreational stakeholders to provide more robust estimates of stock status and ensure the long-term sustainability of these top predators.
- Maine Department of Marine Resources Lobster Research Collaborative research projects focused on lobster distribution, shifts in lobster habitat, and the changing environment. Projects were completed in 2021 with consensus that meaningful research collaborations with each sector of the lobster industry are crucial to the success of lobster research in support of fishery management. Participants also highlighted the need to understand the complex impacts of climate change on all lobster life stages and the Maine fishery. These priorities are being used to inform the development of lobster research projects, funding opportunities, and collaborations.

Current Research Activities

- NSF EPSCoR investment in eDNA research is exploring how DNA present in the water column, sediments and fish diets can be used to better understand the distribution, abundance, spawning activity, and foodweb interactions of highly valued marine and freshwater species, such as alewife, lobster, scallop, and other shellfish. In turn, partnerships among scientists, government agencies and the fishing industry in the region are developing a cooperative framework for ecosystem-based management of Maine's aquatic and marine natural resources (Maine-eDNA) - NSF EPSCoR Track 1.
- SEAMaine — Seafood Economic Accelerator for Maine, is an industry-led initiative bringing together leaders in Maine's commercial fishing, aquaculture, and seafood economy. Funded by the U.S. Department of Commerce Economic Development Administration, with match funding from the Maine Technology Institute and FocusMaine, the statewide initiative is developing a road map and action plan for economic growth, market and workforce development, and greater resiliency in Maine's seafood economy.
- American Lobster Initiative, funded by the National Oceanic and Atmospheric Administration's National Sea Grant College Program, is addressing critical knowledge gaps about American lobster and its iconic fishery in a dynamic and changing environment. The initiative started in 2019, supporting both scientific research and a regional Sea Grant extension program. Together, the research and extension components of this initiative will develop and share new knowledge and understanding with industry stakeholders and resource managers from Maine to New York, with the goal of increasing the American lobster industry's resilience to the biological, economic, and social impacts of ecosystem change in the Gulf of Maine and Georges Bank, and southern New England.
- The mission of the UMaine Lobster Institute is to foster collaboration and communication in support of a sustainable and profitable lobster industry in the northeast U.S. and Canada. It strives to maximize the engagement of UMaine faculty, students, and facilities with stakeholders in this iconic fishery on both sides of the border. Toward the goal of improving cross-border collaboration, the Lobster Institute recently partnered with Maine Sea Grant to form the U.S.-Canada Climate and Fisheries Futures Collaborative.
- American Lobster Settlement Index is an annual

monitoring program that quantifies the pulse of newly settled lobsters that repopulate rocky coastal nursery grounds in New England and Atlantic Canada. It is supported by participating marine resource agencies and industry partners in the U.S. and Canada. Quantifying this early segment of the life history is a pivotal life stage that both sheds light on the ocean processes that deliver larvae to nurseries, and is useful as a predictor of future trends in subsequent recruitment to the fishery.
- HMS initiatives — The Pelagic Fisheries Lab in the School of Marine Sciences at the UMaine is dedicated to improving the status and sustainability of highly migratory species in the Atlantic Ocean, including the Gulf of Maine. This includes sampling programs to supply federal and international agencies with accurate information on species biology and estimation of life history parameters used to inform stock assessment models and quota allocation. This includes new partnerships with Maine DNR to actively monitor the life history of pelagic fish in the Gulf of Maine.
- Groundfish — NOAA and Maine-New Hampshire Inshore Trawl Surveys. ME-NH surveys are resource assessment surveys performed along the coastal waters of Maine and New Hampshire. Biannual surveys, spring and fall, have been conducted since fall 2000. This survey is a collaborative research project using a commercial fishing vessel as the platform. The boat owner, captain, and crew have been actively involved in the design and implementation of this survey. These data are used for research and management purposes.

Future Objectives & Needs

- More monitoring and projection of marine conditions including pairing of biological and physicochemical parameters to better forecast future management activities, potential ecosystem services, and new species opportunities.
- Understanding fisheries carbon footprint and potential for efficiencies in the supply chain lead to reductions in GHG emissions. Support advances in attribution science to link changes in carbonate chemistry in the Gulf of Maine to specific carbon emitters.
- Increased availability of data and analyses related to the marine ecosystem threats, including social and economic viability strategies.
- Improved decision-support tools and technical services to assist both managers and policymakers to understand current resource trends, potential trajectories based on alternative futures, and uncertainty.
- Better capacity for assessing ecosystem services value based on current availability, market demands, and future potential supply.
- Regular assessment of rural community resilience through a variety of spatially explicit metrics and indicators.
- Recognize the critical roles that municipalities, fishermen, aquaculturists, and others are playing and will play to address ocean climate change, and ensure adequate opportunities to engage them in strategy development and action planning.
- Sustainable fisheries management strategies need to reflect and react to the complexity and nonlinearity of the marine ecosystem response to changing oceans and the rapid rate of warming in the Gulf of Maine.
- Greater U.S.-Canada collaboration, and in particular between Maine and the Atlantic provinces, to coordinate research and management of our shared fishing resources and endangered species.

Economic Impact

- Better understanding of the current and future inland and marine resources for planning.
- Potential for integrated freshwater and ocean management to meet multiple objectives.
- Sustainable flow of seafood and other ecosystem services.
- More efficient supply chains.
- Improved workforce, coastal, and rural community resilience.
- More resilient aquatic systems to minimize potential impacts of climate change and associated threats of shifting ecosystems.

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Forestry and Forest Products

Maine has an opportunity to effectively decarbonize statewide by investing in natural climate solutions and utilizing climate-smart renewable resources provided by the forest, while supporting additional ecosystem services such as recreation, watershed health, biodiversity, and cultural values.

- Goal 1 Research Objective
  Prioritize forestry research in two areas: 1) improving monitoring and projections of forest conditions, threats, supply, and demand; 2) improving decision-support tools to assist land managers and policymakers in understanding current trends and projections, and assessing ecosystem services value.

- Goal 2 Enterprise Objective
  Develop innovative biobased products and chemicals that increase demand for a diversity of Maine tree species, particularly applications dependent on low-grade fiber.

- Goal 3 Workforce Objective
  Help the forest industry sustain its workforce through ongoing education and training, and by promoting "green collar" job opportunities.

- Goal 4 Climate Change Objective
  Identify policies and practices that mitigate the impacts of climate change on Maine's forests and reduce the carbon impact of Maine's forest products industry, and utilize them to help Maine reach its 2045 carbon-neutrality goal.

Maine's forest-based economy and the rural communities it supports are rapidly changing as a result of a variety of complex and interactive factors. In the last few years, there has been the loss of an important paper mill in Jay, an estimated 30%-40% decline in available wood markets, reduced harvesting, and a shift in the use of paper, resulting in a 19% decrease in revenue for the remaining paper mills, which has had direct implications for surrounding rural communities. In addition, a majority of Maine's forest itself has reached a critical biological tipping point related to decreased management due to this current lack of robust fiber markets (Woodall and Weiskittel 2021). The forest is also threatened by a potential spruce budworm outbreak occurring in Canada (MacLean et al. 2019) and the ongoing challenges created by climate change, which include invasive species, disruptions to necessary infrastructure or operations, forest health declines, and general worker safety due to the rapid increase as well as prevalence of tick-borne human diseases and heat stress throughout the state (Soucy et al. 2020). Finally, an important change has been to the actual workforce that sustains the forest-based economy, particularly given recent economic conditions (Kingsley 2022). By 2030, more than 26% of the current forest industry workforce in Maine will have reached retirement age and this value continues to increase over the coming decade at a much higher rate than similar sectors (Wallace et al. 2021). To address all these challenges, research indicates that initiatives to reevaluate existing policies, expand incentives for science-informed decision-making, integrate adaptation and mitigation efforts, and increase communication and outreach are needed (Soucy et al. 2021), while seeking strategic workforce development opportunities such as promotion of green collar careers (Wallace et al. 2021).

Given the state's objective of achieving net-zero emissions by 2045, Maine is experiencing accelerating momentum toward effective statewide decarbonization with sustainable management and utilization of climate-smart renewable resources. In Maine, these opportunities are dominated by the forest. Currently, the forest and associated products it generates offset 60%-75% of Maine's greenhouse gas emissions (Bai et al. 2020) with a potential to offset significantly more through natural climate solutions, such as improved management and innovative bioproducts (Daigneault et al. 2021). In particular, high mitigation potential is achievable by implementing a mix of intensive forest plantations, naturally regenerated stands, and 10%-20% of forest area permanently reserved from harvesting. Continuing to Identify potential strategies, policies, and incentives for Implementing a mix of natural climate solutions across the state could help make Maine carbon neutral or net-zero by 2045 or earlier, and possibly go beyond these goals. However, a better understanding of current and future forest resource trends, potential utilization, and additional opportunities is needed to make strategic investments.

Opportunity

- Maine's forest and the associated products it generates offset 60%-75% of Maine's greenhouse gas emissions.
- Annually, Maine's forest products sector annually contributes $8 billion-$10 billion to the state's economy, which account for 5%-7% of the state's GDP (one of the highest proportions in the U.S.).
- Maine's forest resource is vulnerable due to the current density and lack of robust fiber markets, while being threatened by a potential spruce budworm outbreak occurring in Canada and the ongoing challenges created by climate change.
- The state's forests have the potential to sequester significantly more carbon through improved management and innovative products, playing an even larger role in Maine's goal for carbon neutrality by 2045 while enhancing workforce development.
- Maine has a diversity of potential fiber markets with a range of species present, which could support the development of novel biobased products and chemicals.
- Maine's diverse working forest has the potential to be managed for effective climate mitigation and increased carbon sequestration.

Primary Objective

To effectively decarbonize statewide by investing in natural climate solutions and utilizing climate-smart renewable resources provided by the forest, while better quantifying and supporting additional ecosystem services such as recreation, watershed health, biodiversity, and cultural values

Notable Maine Institutions & Organizations

- FOR/Maine
- Forest product sector
- Maine Climate Council
- Maine Forest Service
- Nonprofit organizations
- Northern Borders Regional Commission
- Private landowners
- Spruce Budworm Task Force
- University of Maine Center for Research on Sustainable Forests
- University of Maine Cooperative Forestry Research Unit
- University of Maine School of Forest Resources

Past Research Activities

- Strategic assessment and planning for future forest economy by FOR/Maine
- Natural climate solutions assessment by UMaine (Daigneault et al. 2021) and The Nature Conservancy (Fargione et al. 2018; Cook-Patton et al. 2021)
- State carbon budget completed by UMaine
- Wood supply assessments and projections by FOR/Maine, UMaine, and Maine Forest Service
- Spruce budworm mitigation plan by Maine Spruce Budworm Task Force (Wagner et al. 2016)
- Carbon profile of forest products sector (Gunn and Buscholz 2018)
- Climate mitigation potential assessment (Williams et al. 2021)
- Forest industry workforce needs assessment (Bernsen et al. 2020) and development strategy (Wallace et al. 2021)
- Other academic research contributions

Current Research Activities

- Statewide land cover and forest carbon mapping by NOAA/University of Maine
- Revised state carbon budget by Maine DEP/ University of Maine
- Evaluation of management strategies for improving carbon sequestration by University of Maine and Forest Carbon for Commercial Landowners
- Forest Carbon Task Force policy recommendations
- Monitoring of spruce budworm populations
- Assessing rural community resilience indicators

Future Research Objectives & Needs

- More near-time monitoring and projection of forest conditions to better forecast future management activities, potential carbon sequestration, and wood supply opportunities. (Currently, the best source of information on Maine's forest is the U.S. Forest Service's Forest Inventory & Analysis, but the data often takes one to two years after collection to become publicly available.)
- Improved decision-support tools to assist both land managers and policymakers to understand current resource trends, potential trajectories based on alternative futures, and uncertainty.
- Increased availability of data and analyses related to forest threats that would include refined maps of occurrence, levels of defoliation or mortality, and future projection of conditions.
- Better capacity for assessing ecosystem services value based on current availability, market demands, and future potential supply.
- Regular assessment of rural community resilience through a variety of spatially explicit metrics and indicators.
- Refined utilization of remote sensing technology for forest assessment, monitoring, and projections.

Economic Impact

- Better understanding of the current and future forest resource for planning.
- Potential to improve forest management to meet multiple objectives at the landscape-scale.
- Sustainable flow of timber and other forest ecosystem services.
- Improved workforce development and rural community resilience.
- More resilient forest to minimize potential impacts of climate change and associated threats like spruce budworm.

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HIGH-GROWTH TARGET SECTORS

Aerospace

"New Space" is a fast-growing market, and Maine industries, from agriculture and forestry to aquaculture and fisheries, can improve their competitiveness using satellite data and other remote services. Maine has the research, education, and physical assets to excel in launching low-cost small satellites using small, low-cost launch vehicles.

- Goal 1 Research Objective
  Prioritize aerospace research in six areas: 1) satellite-generated "big data" analytics and management, 2) quantum computing and storage, 3) navigation, tracking, and communication, 4) satellite and small launch vehicle manufacturing, 5) satellite and constellation design, and 6) geospatial informatics and remote sensing.

- Goal 2 Enterprise Objective
  Catalyze the development of an entrepreneurial space industry with a local supply chain, and provide data to support Maine's heritage industries.

- Goal 3 Workforce Objective
  Create training programs in advanced materials and other "new space" topics, and promote STEM curriculum at all levels, from computer science in PreK-12 to advanced mathematics doctoral programs.

- Goal 4 Climate Change Objective
  Advance the use of the Maine Space Complex to monitor the impact of climate change and the effectiveness of mitigation efforts. Identify products and practices that reduce the carbon impact of Maine's emerging aerospace industry.

"New Space" Economy

Historically, space has been the domain of large government-funded projects executed by a handful of aerospace and defense contractors. Over the past two decades, this paradigm has shifted, and the commercial industry now launches more satellites than government. Evolving hardware and software have significantly increased performance and reduced the cost and size of spacecraft development. This evolution has unlocked the value of creating smaller satellites and corresponding micro launch vehicles, reducing the cost of launching payloads into space. This new cost-effective technology has, in turn, lowered barriers to entry, attracting a wave of commercial participants into the industry, spurring innovation, and attracting private capital to finance research and development. "New Space" is one of the fastest-growing, high-tech future-forward industries emerging this century. Small satellites such as CubeSats that are the size of a bread loaf are among the fastest growing and most dynamic aerospace markets, attracting a high level of venture capital and federal attention. This market was valued at $4 billion in 2020 and is projected to grow to $25 billion by 2030.

Maine's "New Space" Assets

Maine has the assets to capture a meaningful share of the growing global new space economy and the small-satellite market. Its geographic location allows for the safe launch of satellites into polar orbit without endangering population centers, and its former military bases are unique physical assets. Building on these, Maine has R&D, education, and physical assets at UMaine, USM, the Roux Institute, and other institutions; proximity to academic and business centers in the Northeast region; aerospace and manufacturing supply chains; and companies directly involved in space exploration and development such as VALT Enterprises, blueshift Aerospace, and Fiber Materials.

Maine Space Complex

In April 2022, the Legislature enacted and the Governor signed into law a bill to establish the Maine Space Corporation, a quasi-state body to manage the development and growth of the geographically distributed, shared-resource based, Maine Space Complex as the aspiring vision for a coordinated effort to leverage these assets, build capability and facilitate growth throughout the new space economy value chain. Maine is now positioned to become a leader in the emerging and fast-growing market of launching low-cost small satellites into polar orbits using small, low-cost launch vehicles. The three business units of the Maine Space Complex are:

- Maine Space Data & Advanced Analytics Center. The Space Data & Advanced Analytics Center will be a cloud-based, digital platform resourced to import/downlink, store, cleanse, manage, and analyze satellite data in concert with terrestrial data to solve local business public policy issues in innovative ways. This will be a distributed network of nodes, offering portals from various locations (e.g. Roux Institute, University of Maine, Governor's Office, etc.) to access satellite data (and other relevant data sets) for data science applications, such as machine learning and artificial intelligence. It will be resourced with human capital that can specialize in satellite data and advanced analytics to drive the application of data toward the advancement of local industry and policy use cases, and provide support and mentorship to data-centric start-ups and companies. It will require a cloud configuration with a network equipped with the hardware and software to import/downlink, store, cleanse, manage, and analyze satellite data in concert with terrestrial data to solve business and public issues in innovative ways and support the development of data-focused

start-ups creating new data products and services.
- Maine New Space Innovation Hub. To be located at Brunswick Landing, with a spoke at Loring Commerce Centre, the Hub is envisioned as a knowledge and innovation hub for new business incubation and acceleration, hardware and materials component development facilities, and satellite and launch vehicle manufacturing and testing. The shared space will contain specialized equipment to facilitate R&D, academic and scientific inquiry. It will also house joint academic-industry research initiatives, an office of tech transfer, administrative office space for businesses, and conference facilities to host national/international events to draw users and attention to the Maine space industry. It will also act as an educational center providing classrooms for in-person and remote PreK-12 and higher education learning opportunities and events.
- Maine Launch Sites and Services. This unit will include both vertical launches at one or more sites along the coast of Maine, as well as horizontal launch capabilities from aircrafts that leverage the long runways at Brunswick Landing and Loring Commerce Centre. Both launch venues will be low-cost and provide accessibility to low Earth orbit polar orbit launch site for small satellites with superior customer service to serve the commercial, academic/scientific, and government sectors. The sites will create a need for credentialed and highly skilled technical jobs, and offer workforce retraining opportunities. Launch capabilities will spur the development of a knowledge cluster, creating a foothold to capture prospects as the industry matures and develops. The sites will also leverage Maine's current rocketry, data, and geospatial analytics capabilities to become a more visible national and international aerospace industry destination.

The Maine Space Complex is about more than simply launching small satellites on small rockets. It is about engaging students, researchers, businesses, state and local governments, and communities across the three segments of the new space economy value chain, and the underlying infrastructure needed to support these segments. The upstream segment is research, manufacturing, and ground systems; all include basic and applied research activities, scientific and engineering support activities, materials and components supply, manufacturing of space systems, subsystems, equipment, telemetry, tracking, and command stations. The downstream segment is space operations for terrestrial use and products and services which rely on satellite technology, signal, data to function (e.g., satellite broadcasting, selected GIS, Global navigation satellite system-enabled devices). The space-related segment includes space applications, products, and services from spin-offs or technology transfer from the space sector, that use satellite technology, but do not depend on it.

Notable Maine Institutions & Organizations

- Educate Maine
- Loring Commerce Centre
- Maine Composites Alliance
- Maine Department of Transportation
- Maine International Trade Center
- Maine Space Corporation
- Maine Space Grant Consortium
- Manufacturers Association of Maine
- Midcoast Regional Redevelopment Authority
- The Roux Institute at Northeastern University
- University of Maine
- University of Southern Maine

Economic Impact

A 2022 economic impact analysis of the Complex by the University of Southern Maine's Center for Business and Economic Research based on four revenue and market share scenarios, and forecasts for space complex business components, and using an economic model developed by Regional Economic Models Incorporated (REMI), projected that a new space economy in Maine could contribute:

- Between $550 million and $1.1 billion per year to the state GDP by 2042 (in 2022 dollars),
- Between 2,800 and 5,500 well-paying jobs annually by 2042, and
- A significant source of new tax revenues across the state.

These simulations represent the potential impacts of a new space economy that emerges in line with market forecasts and according to the various scenarios simulated in the analysis.

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Artificial Intelligence

Artificial intelligence (AI) has the potential to generate transformative solutions that enhance human life and societal well-being in Maine and beyond. Through innovative technologies and applications, AI can help Maine industries improve their operations and compete in the global economy.

- Goal 1 Research Objective
  Develop transformative AI-based solutions that enhance the social and economic well-being of the citizens of Maine and beyond. Priorities include making AI more efficient, ethical, and secure.

- Goal 2 Enterprise Objective
  Increase the number of Maine businesses and organizations using AI solutions to improve their products and operations.

- Goal 3 Workforce Objective
  Provide training and expertise to researchers and practitioners throughout Maine whose work could benefit from AI, and incorporate AI training into existing postsecondary programs in related fields.

- Goal 4 Climate Change Objective
  Use AI to help advance climate-smart practices and policies in agriculture, aquaculture, forestry, fisheries, clean energy, and related fields, and research ways to reduce AI's large carbon footprint.

With the advancement in computing technology and change in market demand, computing systems are now employed for performing complex and involved tasks. Developing algorithms to solve complex problems is not always easy; hence, techniques were developed to have the algorithm itself learn from observing the raw data. These learning techniques and other rule-based techniques for solving complex problems gave rise to a new computing paradigm called Artificial Intelligence (AI). Today in the U.S. and worldwide, AI techniques are employed in diverse domains such as:

- Home Automation: AI-based automation techniques are used to optimize power utilization in different appliances around the house and automated home security systems routinely rely on AI techniques to detect anomalies and predict future consumption.
- Intelligent Transport System: From traffic control algorithms to self-driving cars, many transport system applications use some form of AI to improve efficiency, control device behaviors and make decisions that have social and economic consequences.
- Environmental Protection: Pollution prediction systems and wildlife monitoring techniques use AI to improve accuracy and coverage.
- Cybersecurity: AI-based methodologies are increasingly used for predicting system vulnerabilities, detecting fraud, and detecting intrusions.
- Medicine: AI is widely used in the medical domain to monitor patients, develop pharmaceutical products, and remote robotic surgeries and other tasks.
- Precision Agriculture: Drone-based crop monitoring, satellite image-based yield estimation, and automated farming systems are all using AI.
- Industrial Automation: AI is also used in industrial settings to automate the pipeline, operate warehouse robots, and perform quality control.
- Retail Automation: Smart carts and automatic item detection techniques are also being introduced into the retail world with the help of AI techniques.

AI has penetrated nearly all U.S. markets and AI applications are only predicted to grow.

Challenges Facing Artificial Intelligence Growth

Artificial Intelligence has come a long way from simple rule-based expert systems to deep neural networks. AI is now widely used in diverse cyber-physical systems (CPS) for solving real-life problems. Although the ability to solve complex problems using AI techniques has increased dramatically in recent years, there are several existing challenges to implementing reliable and accurate AI systems:

- Ethical Issues and Bias: AI models are susceptible to undesirable bias if proper training methodologies are not followed and guardrails are not implemented. Also, relying on certain data features for generating a prediction can lead to unfair or unjust outcomes.
- Inefficient Implementation: Techniques to implement AI in real systems are far from perfect. Model accuracy in lab settings must translate to the real world to make an impact. Standards must also be developed for these techniques to ensure reliability.
- Lack of Data Privacy and Security: Data mining, processing, and collection of data for training AI models is a topic of strong public interest and debate. While compliance standards are increasingly adopted and enforced, there are additional steps that need to be taken to ensure high privacy and security standards are adhered to.
- Inefficient Data Storage and Access: AI systems require the storage and rapid access of a very high volume of data for different purposes. Innovations are required to ensure efficient data management in connected systems and the cloud.
- High Carbon Footprint: Training/using AI models often requires a high amount of computation, which indirectly leads to negative environmental outcomes.

Solving these core issues in AI can lead to better AI-driven systems and a wider appeal.

The Roux Institute at Northeastern University

In 2020, Northeastern University launched the Roux Institute in Portland, Maine, an ambitious initiative to grow talent in AI and other advanced technologies. The institute, made possible by the vision and philanthropy of David and Barbara Roux, is partnering with Maine companies to advance workforce skills through graduate education and research opportunities. It seeks to transform Portland into a hub for innovation.

Davis Institute for Artificial Intelligence at Colby College

Established in 2021, the Davis Institute for Artificial Intelligence at Colby College explores applications of AI and machine learning grounded in the liberal arts. Its target outcomes include both education and enterprise development.

University of Maine Artificial Intelligence Initiative (UMaine AI)

The UMaine AI initiative, founded to promote AI research activities in the university, and has more than 40 affiliated faculty members (seven steering committee members). UMaine AI strives to create strong collaborative ties with other universities, government, industry, and broader community. This initiative has also led to different outreach activities, including monthly education webinars attracting over 1,200 participants.

Key Past & Current AI-Related Research Activities at the University of Maine

The University of Maine has fostered, developed, and perfected different technologies involving diverse AI techniques. Some of the research groups working in the area of AI and cyber-physical systems are listed below:

- MaineSAIL: The Software Agents and Artificial Intelligence Laboratory (led by professor Roy M. Turner) at UMaine focuses on developing multiagent systems empowered with AI. Several interesting innovations such as ORCA, CODA, and ACRO were made possible through the involvement of this research team.
- Advanced Structures and Composites Center: With more than 200 patents and 700+ publications, this research group (led by professor Habib Dagher) focuses on developing innovative technologies in diverse domains, such as material sciences, advanced manufacturing, and composites. Such technologies also involve the development of cyber-physical systems such as the DeepCLiDAR.
- VEMI Lab: This lab was co-founded by Richard Corey and professor Nicholas Giudice, who lead the lab with professor Caitlin Howell. This research team specializes in developing human-computer interaction (HCI) technologies.
- Sekeh Lab: Professor Sekeh and her team at UMaine contribute to diverse areas of AI. This group has worked toward developing novel AI algorithms, improving deep learning model efficiency, securing AI models, and many other innovations.
- WiSe Net Lab: Established in 2005, this lab, led by professor Ali Abedi, has engineered and innovated several technologies in the areas of wireless sensor networks and space applications. AI and smart sensing play an important role in many of these technologies.
- MIM Lab: The Multisensory Interactive Media Lab focuses on developing innovative technologies in the domains of virtual reality and augmented reality, with AI playing an important role in such innovations.
- SKAI Lab: The Spatial Knowledge and Artificial Intelligence Lab, led by professor Torsten Hahmann, innovates in diverse areas of AI such as formal space representations, automated ontology modularization, and integration of high-level knowledge with low-level data.
- Climate Change Institute: The hub of climate change research at the University of Maine. Some of the technologies employ cyber physical systems and AI for climate monitoring, climate prediction, and information transfer.

The University of Maine has a long history of innovating in diverse areas of AI. It has led research initiatives to advance the theoretical understanding of AI and machine learning while also developing innovative technologies, utilizing AI, that can make a real difference in the world.

Future Research Objectives

The University of Maine will leverage existing resources and past research experiences to solve different core problems of AI, apply AI to solve novel real-world problems, and continue to innovate in the space of cyber-physical systems. The following are some of the suggested research activities in the areas of AI and cyber-physical systems:

- Green AI: Innovation is required to make AI training, inferencing, and architecture search more energy efficient. Future works should also focus on efficient implementations of AI in cyber-physical systems with greenhouse gas emissions in mind.
- Ethical AI: Although some work has been done in this domain, scientists are far from creating truly unbiased (in terms of irrelevant features) AI models. More research is required in this domain to make AI more trustworthy in the future.
- Toward Efficient Hardware Implementation: Efficient implementation of AI models in real systems is a challenging task due to real-world constraints that may have been overlooked in a lab setting. Research is required to bring real system implementation constraints into the loop while developing AI models.

- Secure AI: The security of the data being processed by an AI model and the security of the AI model itself is crucial to building trust among the user communities. UMaine has past contributions in this area and will continue to drive research innovations to solve these issues.
- Efficient Data Management for AI: Efficient data handling in connected devices (edge) has emerged as a new challenge in recent years. Innovations in this area are required to make AI-driven connected systems more efficient in the future.
- New Frontiers: University of Maine ECE has hired two new faculty members (Dr. Tonkoski and Dr. Chakraborty) for creating potential research thrusts in the areas of applied AI for cybersecurity and sustainable energy.

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SKAI Lab, https://ai.umaine.edu/skailab

Climate Change Institute, https://climatechange.umaine.edu

Advanced Building Products

Advanced, wood-based building products represents a significant economic opportunity for Maine's forest products industry, and an important tool for carbon sequestration. Maine's vast forestlands position it for success in this growing field. Industry 4.0 (the application of information technology and real-time data to optimize processes and improve operations) is revolutionizing the manufacturing industry. Within construction, manufacturing-based production methods offer new ways to design and build affordable homes at scale.

- Goal 1 Research Objective
  Further develop innovative wood-based building products and construction processes, including wood fiber insulation and mass timber (engineered wood products that result in strong, large structural panels, posts, and beams), and innovative building techniques and technologies (such as prefabricated construction).

- Goal 2 Enterprise Objective
  Catalyze the development of an advanced-building materials and techniques manufacturing cluster, including facilities for large-scale production of mass timber and wood fiber insulation.

- Goal 3 Workforce Objective
  Safeguard jobs in Maine's forest economy and create new jobs connected to the design, manufacture, delivery, and marketing of wood-based building products.

- Goal 4 Climate Change Objective
  Increase demand for carbon-sequestering products in long-lived buildings, encourage energy- and resource-efficient building products and processes, and encourage working forests that further sequester carbon.

MASS TIMBER

Mass timber (engineered wood products that result in exceptionally strong, large structural panels, posts, and beams) represents a significant economic opportunity for Maine's forest products industry, and an important climate change mitigation tool. Maine's vast forestlands, and over two decades of research experience, position it for success in this growing field.

Mass timber is a family of engineered wood products, including glue-laminated timber (glulam), nail laminated timber (NLT) and cross-laminated timber (CLT), among others. These three products use dimension ("2-by") lumber as its primary feedstock, sustainably produced by five large sawmills in the state today with over 500 million board feet (MMBF) of annual production of spruce-pine-fir south (SPFs) lumber. Maine, being the most heavily forested state in the nation by percentage of

land area (89%), is ideally situated for a mass timber manufacturing facility, sitting atop the Eastern U.S. seaboard, one of the most populated areas on the planet. Maine's vast forests and rural economies could feed the exponentially growing demand for mass timber in urban centers, such as Boston, New York, Philadelphia, Washington D.C. and beyond.

Opportunity & Objective

- The University of Maine has already established itself as a leader in R&D and commercialization of engineered wood products. The 100,000-square-foot Advanced Structures and Composites Center (ASCC) is known nationally and internationally in this field, working closely with the university's School of Forest Resources, as well as many of Maine's forest products industries. A planned expansion will nearly double its size with a mass timber addition in 2023.
- The opportunities are many, with ASCC being an important piece of the puzzle when attracting businesses to the state that seek development of innovative products and processes. The objectives include:
  - Continuing innovative wood product development to support Maine's forest products industries.
  - Foster not only supply-side issues, but also increase interest and demand in mass timber products, which sequester carbon in long-lived buildings and encourage working forests that will continue to further sequester more carbon.
  - Attract a mass timber producer to the state, which will bolster Maine's sawmills and create new jobs in rural communities.
  - Training Maine's future workforce in state-of-the-art facilities, working with many of the state's forest product industrial partners.
  - Showcase CLT in large buildings through use of mass timber in ASCC's planned 90,000+ square foot Green Engineering & Materials (GEM) Factory of the Future (FoF).

Notable Maine Institutions & Organizations

- Advanced Structures and Composites Center at the University of Maine has conducted research on mass timber since 1996, including over 275 industrial trials with clients from Maine and beyond.
- American Wood Council: A nationally recognized technical authority and advocate for the sustainable wood building products industry in the codes, standards, legislative, regulatory, and climate policy areas.
- FORMaine: Maine's Forest Opportunity Roadmap: An EDA-funded effort to revitalize Maine's forest products industry and grow from $8.5 billion to $12 billion annually.
- Maine Forest Products Council: A coalition of Maine forest products industry companies.
- Maine Mass Timber Commercialization Center: An EDA-funded effort from 2017-2020 to attract a mass timber manufacturer to Maine. Research component included testing all ten species in the SPFs lumber grouping to ensure suitability for CLT production.
- Northeastern Lumber Manufacturers Association: The agency that oversees most lumber producers in the region.
- Northern Forest Center & Northern Borders Regional Commission: An advocate for revitalization of the Northern forest region.
- WoodWorks: A nonprofit trade organization promoting use of wood products.

Research Activities

- An EPSCoR grant allowed for the establishment of the Advanced Engineered Wood Composites (AEWC) Center in 1996. Research in early years focused on reinforcing glulam beams with fiberglass. This funding allowed for the growth that has turned the center (now known as the Advanced Structures and Composites Center) into the largest R&D facility in the state of Maine.
- EDAT — In 2016, following closures of five major paper mills in Maine, an Economic Disaster Assessment Team (EDAT) was formed and sent to Maine. Priority "E" of the EDAT report stated: "Invest in the research, development and commercialization of emerging wood technologies." In particular, the EDAT report singled out the unique opportunity that exists for development of Mass Timber (e.g., cross-laminated timber) production in Maine: "Cross-Laminated Timber (CLT) research at the University of Maine is linked to several potential manufacturing facilities seeking east coast locations. Immediately form a collaboration of appropriate parties to promote the siting of a CLT facility in Maine and identify recommendations to incentivize wider use of CLT and possible demonstration projects."
- EDA MMTCC — In response to the EDAT suggestion, the ASCC won a competitive Economic Development Administration (EDA) RIS i6 award. This $450,000, three-year award created the Maine Mass Timber Commercialization Center (MMTCC). This Center included establishment of an advisory board, consisting of more than 50 entities in Maine and the region interested in attracting a CLT supplier to Maine. The MMTCC also created an attraction package "Why Maine for CLT Production," which can be downloaded from the link found in the references below. This grant also included R&D work, including assessing the bondline durability of all ten species in the SPFs lumber grouping found in Maine and the region. The "Maine Mass Timber Event" was held in Orono, ME, bringing together 180 interested parties to roadmap the future of mass timber in Maine. Finally, the advisory committee worked with the Maine Uniform Building and Energy Code (MUBEC) committee to get Maine to early-adopt the tall wood building provisions included in the 2021 International Building Code (IBC). A

website for the MMTCC contains several reports for download: https://composites.umaine.edu/key-services/wood-composites/maine-mass-timber-commercialization-center/

- USDA NIFA — This research project sought to make Maine-made CLT more competitive against regions with timber resources with higher properties. Hybrid CLT was produced, incorporating SPFs lumber with laminated strand lumber, a wood composite product manufactured by Louisiana Pacific Corp. in Houlton, ME. The research found that using LSL in the core increased panel capacity by 26%.
- USDA ARS — Several Agricultural Research Service (ARS) funded R&D programs have been carried out recently on mass timber including:
  - New grades of CLT using Maine lumber. Two new grades of "E-rated" (using machine stress rated lumber) grades were produced by a partner CLT producer, tested and qualified at the ASCC. These grades have among the highest design values of all CLT grades published in ANSI PRG-320, which governs CLT. This makes Maine immediately more attractive from a mechanically competitive standpoint.
  - CLT with gaps. A 2-year project was carried out looking at the effects of gaps on CLT properties. 1/8 inch, 3.5 inch and 7.25 inch gaps were introduced into the panels' minor axis layers. Additionally, the remaining boards in the minor axis were replaced with LSL which compensated for the lost shear capacity due to the lost cross section created by the gaps. The gapped panels with LSL cores performed equally to the solid members without gaps, showing promise for this product, whose gaps could be used for post-tensioning rods, electrical or plumbing chases, or filled with thermal or acoustical insulating materials.
- USDA Wood Innovations Grants — Blast testing of CLT. Two programs (2017 and 2022) were conducted at the University of Maine testing CLT and reinforced CLT for blast applications, such as CLT used in hotels in Army bases (several have already been constructed).

Current Activities

- EDA FOR/Maine — Seeks to increase demand for forest products in Maine from $8.5 billion in 2018 to $12 billion by 2025. One of the priorities is the attraction of a CLT producer to Maine.
- EDA NFC — In 2022 the Northern Forest Center (NFC) notified the University of Maine of its award to fund the acquisition, installation and commissioning of a wood fiber insulation (WFI) pilot line at ASCC. A concurrent USDA Wood Innovations Grant will optimize this line, allowing for creation of products such as wood fiber insulated CLT.

Suggested Future Research

- Funding for the MMTCC (2017-2020) expired in October 2020. Further funding to support full-time staff to manage, grow and revitalize this center and its advisory committee is needed. As a business attraction opportunity, this should be led by economic development departments.
- Support is critical to ensure that the GEM FoF project is built, as intended, with mass timber. This demonstration building will be a model for others considering use of mass timber in construction projects throughout Maine and the region. Such a building minimizes the risk of future projects by allowing contractors and code officials familiarity with the product and systems.

Economic Impact

Many of the potential economic impacts of a mass timber production facility in Maine can be found in the Maine Mass Timber Attraction package, available at: https://composites.umaine.edu/wp-content/uploads/sites/20/2020/01/MMTCC-Attraction-Package-ver-01_07_2020-abridged.pdf

A single CLT facility in Maine would likely consume approximately 50 MMBF/year of SPFs lumber. This represents about 10% of current production, which all mills spoken to say can easily be sustainably produced. The attraction package referenced above includes a survey by the James Sewall Corporation detailing the availability and sustainability of increasing spruce-fir harvests for mass timber production.

As demand for greener, carbon sequestering, sustainable building materials increases, the contribution of mass timber to mitigation of climate change should not be underestimated. A report by Meridian (that the University of Maine participated in) outlining these opportunities can be found at: https://s31207.pcdn.co/wp-content/uploads/2021/07/Final-Mass-Timber-Report.pdf

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WOOD FIBER INSULATION (ADVANCED BUILDING MATERIALS CONTINUED)

The global insulation market size was estimated at USD 52.18 billion in 2018 and is expected to expand at a compounded annual growth rate (CAGR) of 5.7% over the forecast period of 2019-2024. Increasing consumer awareness regarding energy conservation is estimated to propel the growth. In the EIA 2019 Annual Energy Review, residential energy consumption was estimated at 11.9 quadrillion BTUs, accounting for 16% of the country's total energy consumption, with a residential unit (on average) using over 50% of its total energy on space heating and air conditioning. The EPA EnergyStar program has identified that approximately 90% of homes in the U.S. are under-insulated (representing approximately 100 million housing units), and estimates that insulating existing homes to meet the 2012 International Energy Conservation Code requirements and reducing air infiltration by 25% would lower the national total average residential energy cost by 11%.

Wood fiber insulation (WFI)-based products have been produced and used in European countries, mainly in Germany, Austria, and Switzerland, since the mid-1990s. WFI is made in three forms, 1) loose-fill, 2) batts, and 3) rigid boards. WFI, which has grown into a 0.7 billion USD market in Europe, is currently being imported into the U.S., but high shipping costs have kept it an expensive niche product. Emerging domestic manufacturing is projected to make WFI a cost-neutral, drop-in replacement for fossil-based insulation boards, such as extruded/expanded polystyrene foam (XPS/EPS). Wood fiber insulation has better ecological credentials, as well as several performance advantages over the fossil-based conventional insulation materials, including better sound attenuation, and vapor openness. WFI also can utilize a wide range of species, providing a critical outlet for lower-value, underutilized species which can have a positive impact on overall forest health. Finally, WFI is a prime potential consumer of residuals, which for many regions have found their traditional outlets disappearing (e.g., paper chips, pellets, biomass energy plants).

Inclusion of WFI into modular, panelized systems holds great promise as an environmentally friendly, energy-efficient, and cost-effective building solution. Panelized construction is a building practice whereby pre-engineered wall sections are produced in factory-controlled conditions, then shipped complete to the building site for final construction. Recently, the National Association of Home Builders reported that complete home panelization is the fastest growing segment of new residential construction. Indeed, the Prefabricated Modular Construction (PMC) market is projected to grow at a 6.9% CAGR from 112.4 billion USD in 2019 to 153 billion USD by 2023. Not limited to only metal building manufacturing, prefabricated wood building in the United States brought in just over $2 billion USD in annual revenue in 2011 and is expected to surpass $4 billion USD in 2020.

Related to prefabricated and panelized construction, the use of WFI is predicted to be a key component in energy retrofit applications. The global energy retrofit system market size was valued at 132.8 billion USD in 2019 and is anticipated to grow at a CAGR of 4.1% from 2020 to 2027. The residential segment, in particular, is anticipated to grow at a substantial rate over the forecast period. Retrofitting helps homeowners control their energy bills, while encouraging adoption of renewable energy retrofit systems, positively impacting the efforts to lower the carbon footprint. The scale of the problem with existing homes is staggering. Sixty-eight percent of the current housing stock was built before 1990 when more robust energy efficiency requirements began appearing in building codes around the U.S. It is estimated that 34.5 million homes have wood-framed wall cavities with no insulation at all; millions more have only 4 inches of insulation in 2×4 walls. Air leakage is also a huge problem with 71% of homes with leakage rates above 10 air changes per hour at 50 Pa (ACH50). For comparison, a new code-built home might be 4-5 ACH50, while zero energy homes routinely reach 1 ACH50.

GO Lab, Inc., a building products manufacturer based in Belfast, Maine, is currently building the first WFI manufacturing facility in the U.S. in Madison to demonstrate the market. Their wood fiber insulation is to be comprised of greater than 90% softwood fiber, will be renewable, recyclable, and nontoxic, and is expected to meet all performance requirements of common commercial construction insulations. GO Lab staff attest their WFI will be marketed and distributed at a cost-competitive price. Once running at capacity, GO Lab's production facility in Maine will consume approximately 100,000 green tons of softwood chips annually, while addressing just 0.6% of the U.S. insulation market. Within ten years, GO Lab, Inc. hopes to expand, adding ten to fifteen additional plants throughout the U.S. located near major markets. With this expansion they project, conservatively, that they will be able to attain 8%-10% market share.

Notable Institutions & Organizations

- Advanced Structures and Composites Center (University of Maine)
- GO Lab Inc.
- Northern Forest Center
- University of Maine School of Forest Resources

Research Activities

Past

- GO Lab has previously partnered with the University of Maine's Advanced Structures and Composites Center on the research and development of wood fiber insulation. An objective of previous work by GO Lab and the ASCC, conducted in 2018-2019 was simply to produce a low-density fiberboard prototype as good as commercial European products from locally sourced sawmill residuals using different techniques and resins. Those efforts were considered a success; mechanical properties and thermal conductivity of prototype products were comparable to European commercial LDF products.
- Since that time, GO Lab and the University of Maine have partnered at several other R&D programs evaluating the effect of various manufacturing parameters, adhesives (including biobased adhesive) type and loading on mechanical and physical properties of wood fiber insulation as part of an EPA SBIR-sponsored project.
- The University of Maine's Laboratory of Renewable Nanomaterials has also partnered with Go Lab on several projects. In one, comparable WFI panels were produced using cellulose nanofibrils (CNF) as binder to replace synthetic adhesives. The produced panels had comparable properties as well as higher compressive strength. In another current project, Go Lab is supplying raw materials to produce low-density insulation packaging materials.

Current

- Monitoring the hygrothermal performance and energy requirements of CLT/WFI school annex in Belfast, Maine (USDA - ARS)
- Preliminary R&D of prototype wood fiber insulated panels (WIPs) (USDA - ARS)
- Testing to substantiate the effectiveness, efficiency, and safety of GO Lab Wood Fiber Insulation (USDA – FS)
- UL testing of sample board and batt (fire, smoke, R-value)
- UL testing of wall and ceiling assemblies (fire, smoke, R-value)
- Acoustic testing
- Compressive strength
- Vapor permeability
- Installation, commissioning, and optimization of pilot-scale fiberboard line at the ASCC (USFS - FS, EDA)
- GO Lab's mill construction in Madison to be the first North American manufacturer of WFI

Future

- Acceptance of WFI in the model building codes
- Use of biobased adhesives in WFI
- Improved flame-resistance of WFI
- Alternate construction techniques of WFI attachment to substrates
- Quantify hygrothermal performance and energy consumption of structures constructed with WFI
- Developing low density, insulation/protective packaging materials to replace Styrofoam

Economic Impact

Once running at full production, it is predicted that GO Lab (Timber HP) will be able to produce some $100 million worth of insulation a year and employ roughly 100 people at its Madison production headquarters. In addition, for every direct forest-manufacturing job in Maine, another 17 jobs are created indirectly according to Scott Dionne, Chief Marketing Officer, GO Lab.

Algae & Algal Products

Algae, from natural sources or grown in bioreactors, can fuel a vibrant independent industry, integrate into other industry sectors, and even help mitigate climate change. Maine's diversity of algal resources, combined with world-class research expertise, create a unique opportunity to be a leading source of sustainable, algae-based products.

- Goal 1 Research Objective
  Improve tools to reduce the cost of algae cultivation and develop algae-based alternatives in a variety of products and industries, including bio-manufacturing, biochemicals, biomedical research, and renewable energy.

- Goal 2 Enterprise Objective
  Catalyze the growth of a vibrant manufacturing industry that uses advanced technologies to lower the entry barrier to use of new and diverse algae-based products and processes.

- Goal 3 Workforce Objective
  Help the algae industry expand and diversify its workforce by creating new production and manufacturing jobs at facilities making innovative algae-based products.

- Goal 4 Climate Change Objective
  Identify and develop algae products and processes that reduce carbon dioxide emissions to help Maine reach its 2045 carbon-neutrality goal, and increase exports of climate-friendly products and practices.

Curiosity-based algal science has enabled many significant scientific and societal advances. For example, algal germplasms serve as a living library and have been instrumental in understanding evolutionary relationships among algal lineages (e.g., Brawley et al., 2017; Caron et al. 2016; Sexton and Lomas, 2018). Access to these germplasm collections allows researchers to reevaluate old questions using new knowledge and tools, such as the previously underappreciated role of virus-mediated gene flow in microalgae evolution (Nelson et al. 2021). Collection holdings allow a revised look at mechanisms underlying the rise of multicellularity in marine algae, in comparison to mechanisms in plants and animals (Bringloe et al. 2020; Cock et al. 2010). Furthermore, algae are increasingly seen as contributors to solutions-based research, such as sequestering carbon dioxide through blue carbon storage (e.g., Krause-Jensen et al. 2018), amending livestock feed to reduce enteric methane production (e.g., Roque et al., 2019), remediating domestic waste streams (e.g., Cole et al., 2016; Li et al. 2019), and as sources of natural products for pharmaceuticals and industrial applications (e.g. Chu, 2012; Raposa et al. 2013). Living collections of algae are the cornerstone of this basic science, education and innovation infrastructure, which will inevitably lead to job growth in this and related sectors (National Academies of Sciences, 2020), and make it possible to address current scientific challenges of global importance. More importantly, these resources create the foundation for future research and discovery.

Opportunities & Objectives

- Potential to meet multiple economic and social objectives.
- Blue Carbon as it relates to algae, has the potential to play a role in Maine's goal for carbon neutrality by 2045.
- Microalgae has the potential to replace wild-harvest "fish meal, oil, and beneficial compounds" when it comes to producing feed for finfish aquaculture.
- Algae have the potential to revalorize domestic and industrial waste streams through bioremediation, and thus producing lower cost "biomass" for bioenergy.
- Algae have the potential to produce bio/chemicals that replace synthetic chemicals and novel chemicals for a wide range of food system, nutraceutical, cosmeceutical, and pharmaceutical applications.

Notable Maine Institutions & Organizations

- Algae Foundation
- Bigelow Laboratory for Ocean Sciences (National Center for Marine Algae and Microbiota, Center for Seafood Solutions, Center for Algal Innovations)
- PhytoSmart LLC
- Running Tide
- University of Maine School of Marine Sciences

Current Research

- Finfish and shellfish feed replacements/improvements
- Algal-based bioplastics
- Domestic wastewater remediation (microplastics and nutrients)
- Novel biochemicals, including algae as a novel source of biochemicals
- Carbon dioxide remediation processes including monitoring, reporting, and verification (MRV)
- Technology/hardware innovation to reduce cost of microalgae production

Future Priority Areas

- Scalable production in Maine
- Integration of algae as part of circular economies around other targeted technology sectors
- Development of sustainable replacement products/processes leading to carbon neutrality
- Life cycle assessment of microalgae production

Economic Impact

- Commercial microalgae biomass production for food systems, currently dominated by production of Spirulina, supports $0.5 billion in global direct-use business due to the greater value per unit biomass.
- The global omega-3 fatty acid market derived from cultured microalgae is roughly $3.5 billion.
- Into the future, this diverse array of algae-based science and application research will likely continue to expand in both production volume and economic value through creation of new companies as has been seen in Europe upon their increased focus on algae.

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Biochemicals

Realizing the full potential of Maine's burgeoning bio-alternative industries requires continual research on its scientific underpinnings.

- Goal 1 Research Objective
  Continue industry-leading research on nanocellulose, biofuels, and bio-derived polymers (i.e., plastics and rubbers derived from plant and algae resources).

- Goal 2 Enterprise Objective
  Continue improving the production and properties of bio-alternatives for use in a wide variety of industrial applications.

- Goal 3 Workforce Objective
  Maintain world-class bio-alternative research facilities and educational programs to train the next generation of innovators.

- Goal 4 Climate Change Objective
  Increase demand for low-energy, carbon-sequestering products.

BIOFUELS

Developing forest biorefineries to produce advanced biofuels and biomaterials would help sustain Maine's existing and emerging forest products sector by maximizing the utilization of the whole tree to increase total profitability of Maine's sustainable forest harvest. The growth of forest biorefineries in Maine benefits other economic sectors, especially agriculture and aquaculture. Synergies between emerging recirculating aquaculture systems and forest biorefineries will minimize the environmental burden of producing advanced biofuels and aquaproducts, and maximize the revenue and positive climate impacts of both biorefineries and land-based aquaculture systems. Sustainable biorefinery outputs can support aquatic veterinary products, biobased recirculating aquaculture system filtration media, and alternative protein feed for aquaculture to create a symbiotic relationship between Maine's forest and marine economies not seen since Maine's world leading wood shipbuilding industry faded. Maine is geographically well-positioned to become a global leader in land-based aquaculture, and has the potential to attract nearly half a billion dollars in land-based aquaculture that utilizes recirculating aquaculture systems. Finally, some biochars produced by forest biorefineries can increase soil health, enhance soil carbon sequestration, and reduce nutrient runoff when used as soil amendments.

The University of Maine has been developing a pilot-scale forest biorefinery built around thermochemical pathways. UMaine's Forest Bioproducts Research Institute was established with funding from NSF and DOE EPSCoR programs, and has supported lab-scale demonstration and understanding of

fundamental chemistry underlying thermochemical pathways. Subsequent DOD grants have supported the transition of thermochemical technologies to the pilot scale with a feedstock processing capacity of one metric ton per day. Improving the carbon yields of current biofuels processes by creating markets for co-products and by effectively fractionating the feedstocks into components for alternative uses can enable forest biorefinery commercialization. Microbial conversion and hydrothermal liquefaction of underutilized biomass components have potential for improving net carbon yields for the resulting products. Novel biomass-derived filtration media for the land-based aquaculture wastewater treatment or novel biomass derived vaccine adjuvants for fish are a few examples of biorefinery synergies with other Maine industries.

Opportunities and Objectives

- Maine annually consumes about 190 billion BTU equivalent of petroleum derived fuels and replacing them with forest-derived biofuels can reduce the greenhouse gas emissions by at least 50%.
- The total agriculture land in Maine is about 1.3 million acres, and Maine's agricultural production and processing industries represented 4.6% of the state's GDP. Thus, improving soil health and mitigation of greenhouse gases and nutrient losses are necessary for sustainable agriculture growth.
- Maine's land-based aquaculture is expected to expand significantly in the next five to ten years.

Primary objectives are 1) develop forest biorefineries producing sustainable biofuels from forest residues and underutilized wood in Maine, and 2) synthesize biomaterials for use as soil amendments, vaccine adjuvants, and biofilters in aquaculture.

Notable Institutions and Organizations

- FOR/Maine
- MTI and FAME — for funding
- SEAMaine
- University of Maine Aquaculture Research Institute
- University of Maine Chemical and Biomedical Engineering
- University of Maine Forest Bioproducts Research Institute
- University of Maine Process Development Center
- University of Maine School of Food and Agriculture

Research Activities

Past

- Strategic assessment and planning for future forest economy by For/Maine
- DOE EPSCoR grant for fundamental understanding of thermal deoxygenation (TDO) pathway
- NSF EPSCoR and DLA funding to scale up integration of acid hydrolysis and dehydration and TDO technologies to pilot scale
- NSF funding for the sustainability assessment of thermochemical pathways and identifying potential coproducts of forest biorefinery for attaining commercial relevance

Current

- Catalytic ring opening of mono and bicyclic aromatic compounds of biooil to make advances fuels (diesel and jet fuels)
- Hydrothermal liquefaction of kraft lignin to biofuels
- Understanding the effects of preprocessing strategies on the conversion of forest residues to biofuels with the collaboration of Idaho National Laboratory technologies
- Studying the oleaginous yeasts and mixed cultures for the conversion of hemicelluloses to value-added products
- Field studies of the biochar produced in the acid hydrolysis and dehydration of forest residues as a potential soil amendment
- Synthesis of nanocellulose vaccine adjuvants for fish

Future

- Understanding the mechanism of biomass depolymerization using hydrothermal liquefaction with/without the presence of small, medium, and long chain fatty acids
- Study various oleaginous strains and mixed culture to produce small, medium, and long chain fatty acids from hemicelluloses
- Study various strains of protein rich microbes to convert hemicelluloses and organic acids to single cell protein suitable for blending into sustainable fish feeds.
- Develop novel separation processes for the extraction of aromatic compounds from hydrothermal liquefaction oil
- Upgrade hydrothermal liquefaction oil to advanced biofuels
- Synthesize and characterize novel biomass derived filters for the treatment of recirculating aquaculture wastewater and biomass based vaccine adjuvants for fish
- Life cycle assessment and techno-economic analysis of integrated forest biorefineries and land-based aquaculture
- Develop novel methods to modify biochar for maximizing the adsorption of nutrients
- Efficient preprocessing and fractionation of forest residues to produce advanced biofuels and biomaterials in a forest biorefinery

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BIOPLASTICS (BIOCHEMICALS CONTINUED)

Bio-derived polymers (i.e., plastics and rubbers derived from plant resources) are in increasing demand due to market and environmental forces aimed at reducing the carbon footprint and the disposal challenge of current materials. Consumers and government officials are driving the change through activities like plastic bag ban initiatives, pressure for more environmentally friendly packaging, and rules regarding plastic discharge into waterways. Companies and industry are attempting to respond to this pressure by utilizing biobased and biodegradable polymers. However, few biobased polymers currently exist. Both companies and the public are looking for alternatives. This need for new materials and Maine's forest resources creates a significant opportunity to develop new biobased polymers that can be sourced from raw materials in the state.

Biobased and sustainable polymer research has primarily been conducted at the University of Maine focusing on utilizing molecules derived from woody biomass residues, often as a potential side product in the lumber and pulp industries. One strategy is to use current bio-derived polymers from wood biomass, such as modified celluloses, and modify these materials further for high-value applications, such as biomedical uses. Another strategy is to use biocatalytic and catalytic methods to produce building block molecules that can be used to produce polymer monomers. These research efforts and molecules have the added benefit of being applicable to other specialty chemicals. These bio-derived molecules then can be further developed into replacement biobased polymer adhesives and new thermoplastics. One advantage of using bio-derived polymers is that biodegradability and recycling can be designed into the new materials, increasing the value proposition and positioning these materials to address the future material challenges driven by consumers and the government.

Opportunity & Objective

There are significant concerns about plastics, particularly when accidentally released in the environment. Bio-derived polymer usage is expected to increase significantly in the coming decades to address end-of-life and petroleum sourcing concerns. Monomer building blocks for polymers could become high-value side products for Maine's lumber and pulp industries.

The primary objectives are:

- Develop methods to convert wood derivatives into molecules that are the starting materials for current polymers
- Develop methods to convert wood derivatives directly into new biobased polymers
- Develop chemistry and catalysis to create new monomers for new biobased polymers
- Find new applications for currently available biobased polymers

Research Activities

Past

- Utilization of lignin pyrolysis products to create biobased phenolic resins (offshoot of DOE ESPCoR)
- Cellulose derivatives as coatings (part of NSF EPSCoR)
- Biobased thermoplastics from 5-hydroxymethylfurfural (HMF) and lignin (USDA NIFA coproducts from biomass feedstocks)

Current

- Biobased polymers from HMF and lignin for paper coatings

Future

- New biobased polymers for barrier coatings for paper
- Lignin derived polyesters for paper coatings
- New biobased resins for composites
- New catalysis and reaction methods to produce molecular building blocks for biobased polymers
- New applications for marine-derived polymers such as chitosan from lobster shells and hydrocolloids from seaweeds

NANOCELLULOSE (BIOCHEMICALS CONTINUED)

- There has been explosive growth in the development of new or improved products

based on nanocellulose, which is primarily obtained from wood. Companies are exploring and launching a wide variety of products using nanocellulose: to modify rheological properties (paints, coatings, drilling fluids), replace plastics (specialized papers, composites, absorbent materials, electronics), and replace synthetic formaldehyde-based adhesives or leverage the bio-compatibility of nanocellulose (biomedical, pharmaceutical, tissue engineering). Driven by the unique properties of these materials — strength and optical properties, their biocompatibility with the human body, the ability for sustainable sourcing, and their renewable nature — companies around the world are exploring how these materials can transform existing products and launch next-generation renewably based products.

- In July 2018, Indufor North America LLC, performed an extensive global market analysis, to evaluate potential forest-based markets that best match Maine's forest and other resources. This study was commissioned by FOR/Maine (formaine.org). The Northern Forest Region is home to assets that are nationally and globally unique for the production and use of nanocellulose. This study included a competitive benchmarking element to rate Maine's competitive advantage on a global scale. These reports identified nanocellulose as one of the top ten products for Maine to consider. In the final report, nanocellulose production in Maine was ranked second only to Finland when evaluated against key indicators, including raw material availability and cost, labor skill and cost, freight/infrastructure, regulations, taxes, energy, and an enabling environment. This report contrasted other U.S. regions, and Maine outranked the U.S. Southeast and Pacific Northwest, and confirmed the Northeast's potential to succeed in this market.
- The Northern Border Region is uniquely positioned to become "Nanocellulose Valley," akin to Silicon Valley in California. Maine can leverage the well-managed natural resources — trees — to extract and process both residuals and higher quality wood materials for cellulose nanofiber (CNF) production. The region can also capitalize on the largest concentrated knowledge base — the University of Maine — for developing and commercializing products using nanocellulose. These attributes, coupled with the lifestyles available within the states, can attract young professionals and entrepreneurs. The Northern Border Region also offers another unique advantage compared to other traditional forest-based economies — proximity to East Coast markets and ports. Not only does proximity to Boston, New York and Philadelphia provide excellent outlets for new products, but these cities offer technology and capital to invest in this new Nanocellulose Valley that is in their backyard. Many CNF-based applications are in the biomedical area, which would complement the region's healthcare industry and small businesses developing novel products.

Opportunity and Objective

- The growing global demand for climate-smart products, primarily as alternatives to plastics and synthetic resins, provides a unique opportunity for wood
- Leverage Maine's 16.3 million acres of privately owned working forests, utilizing a well-established infrastructure to sustainably produce 13 million tons of wood per year
- Deploy recent innovations using cellulose nanofiber in the construction, advanced manufacturing and biomedical fields
- Leverage our leadership in the development of cellulose nanofiber production and use from wood residuals
- The primary objectives are:
  - Develop scalable CNF production from forest residuals and other underutilized wood/non-wood sources
  - Develop CNF as a binder with other wood materials through foam forming and other forming technologies to produce structural and other construction materials
  - Develop and scale surface-modified CNF to further enhance properties
  - Develop biomedical applications of CNF in a variety of forms
  - Expand the use of CNF in additive manufacturing in particular large area additive manufacturing

Notable Institutions

- FiberLean (Hampden, Maine) — commercial supplier of CNF production technology
- FOR/Maine — an EDA-funded initiative to sustain and grow Maine's forest bioeconomy
- Forest Products Laboratory, USDA - the only federally funded wood utilization research laboratory in the U.S.
- GoLab (Belfast, Maine)
- Sappi NA (Westbrook, Maine) — commercial nanocellulose products
- University of Maine
- Valmet (Nashua, New Hampshire) — CNF production technology partner

Research Activities

Past

- Demonstration of pilot-scale production of cellulose nanofiber at one ton per day supported by $1.5 million investment: USDA. This enabled the first ever pilot-scale production line of CNF in the nation and accelerates research into traditional and novel applications
- USDA ARS funding — $300,000 every year from 2016-2020: USDA/ARS-funded research and development in binder applications of CNF led to several publications, technologies, and patents
- P3 Nano funding over $1.2 million from 2014-2021: Initiated the development of building products

using CNF

Current

- Developing pilot-scale continuous production of cellulose nanofiber — $2.1 million from Northern Border Regional Commission and ORNL Hub and Spoke Program
- $40 million over three years from the Hub and Spoke program with Oak Ridge National Labs (Phases 1-3, 2019-2025) focuses on optimizing low-energy production and use of cellulose nanofiber for large-area 3D printing applications
- Exploring use of cellulose nanofiber in fiber thermoforming as an additive, as well as a surface treatment after forming — $500,000 from Northern Border Regional Commission
- $400,000 from ARS in 2021: Enabled the first commercial trial to produce insulation-grade fiberboard in collaboration with Blue Ridge Fiberboard in Virginia.

Future

- Continue research and development in the production, drying, and surface modification of CNF for current and future applications Challenges are the energy consumption, expanding the raw material options, efficient drying while maintaining nanoscale dimensions, improve compatibility with other materials, and develop application-targeted CNF products
- Scaling the binder applications of CNF in construction and automotive industry through design and implementation of processing technology, improvement of formulations, as well as seeking novel future applications
- Biomedical applications
- Develop CNF and modified CNF as tailored feedstock components for large area additive manufacturing applications to improve processability and end-product performance

Biomanufacturing

Maine's forest can be a world-class source of nanocellulose — a plant substance with properties similar to plastic. This can fuel a vibrant manufacturing industry that combines advanced technologies with a renewable resource to create sustainable products.

- Goal 1 Research Objective
  Decrease the cost and energy-intensity of nanocellulose, and enhance it properties as a manufacturing material.

- Goal 2 Enterprise Objective
  Move rural manufacturing — and the jobs it provides — toward an economically, environmentally, and socially sustainable future by advancing the use of nanocellulose in a wide variety of products and industries.

- Goal 3 Workforce Objective
  Sustain world-class additive manufacturing research facilities and educational programs to train the next generation of professionals and technicians.

- Goal 4 Climate Change Objective
  Advance the use of high-performance, low-energy, climate sequestering products in a variety of industries.

ADDITIVE MANUFACTURING

Large-scale additive manufacturing (AM) is emerging as a promising and energy-efficient manufacturing technique for the future. Among the polymer 3D printing approaches, large-scale AM systems are 200 times faster than other conventional 3D printing equipment and can reach deposition rates comparable to those of today's high-volume production methods. Especially for custom and complex parts, feedstock materials with tailored properties are needed for improved processing capabilities, superior materials properties and characteristics, and lower cost. The most common feedstock materials for large-scale AM are relatively high cost and derived from high-embodied energy petroleum sources, thus motivating the development of alternative, renewable, and low-energy materials.

The Hub-and-Spoke collaborative research relationship between Oak Ridge National Laboratory (ORNL) and the University of Maine (UMaine) began when ORNL staff visited Maine as part of an Economic Development Assessment Team following the closure of five paper mills. During these visits, significant synergies were identified between UMaine and ORNL around large-scale additive manufacturing and forest-derived materials used for 3D printing, feedstock, and structural reinforcement (Lu et al. 2015). The research partners share a unified vision of leveraging their complementary expertise to move rural, U.S.-based manufacturing towards an economically,

environmentally, and socially sustainable future.

Notable Maine Institutions & Organizations

The Hub-and-Spoke model was established to strengthen regional manufacturing ecosystems by connecting university–industry clusters with U.S. Department of Energy (DOE) laboratories and ORNL's Manufacturing Demonstration Facility. The UMaine-ORNL partnership piloted this model and is now the first established Hub-and-Spoke. To date, the project has received $57 million in research grants focused on the development of biobased, cellulosic materials for use in large-area additive manufacturing. The UMaine team is led by the Advanced Structure and Composites Center and consists of more than 25 faculty and staff researchers from eight academic departments and research centers across UMaine, with an additional thirty student researchers (undergraduate, graduate and postdoctoral), half from underrepresented groups in STEM.

Other Maine organizations performing relevant work:

- Compounding Solutions, LLC — Compounding wood fillers into AM feedstock
- Maine International Trade Association - Finland-Maine-Michigan Bioeconomy Collaboration-New Wood-Based Products Team https://www.mitc.com/wp-content/uploads/2022/02/FMM-Forest-Bioeconomy-Collaboration.pdf
- Maine Technology Institute — Technology cluster of Maine boatbuilders exploring large-area additive manufacturing (https://composites.umaine.edu/2018/10/17/advanced-structures-and-composites-center-receives-500000-to-help-boat-builders-incorporate-3d-printing-technology
- SAPPI — Evaluating wood fiber filled materials for AM feedstock

Research Activities

- MTI grant (UMaine/ORNL) — Hodgdon Yachts 3DP tooling using wood-filled biobased resin, proved the viability of the Hub-and-Spoke model
- MTI boat builder cluster award to facilitate collaboration and innovation from four of Maine's "Broad Targeted Technology Areas." Forest Product materials were used to develop new advanced composite materials for use in precision manufacturing of large-scale 3D-printed tooling for boatbuilding
- Phase I Hub-and-Spoke program (2019-2022): Decrease cost/energy of manufacturing nanocellulose, enhancing AM feedstock properties with nanocellulose, large-area AM biobased tooling for marine and wind industries
- Phase 2 Hub-and-Spoke program (2020-2023): Evaluate alternative renewable material sources for use in AM feedstocks, continuous processing of nanocellulose for scaled up production, artificial intelligence/machine learning used for improved large-area printing (improved part quality), increased throughput large-area AM (500+ lb/hr extrusion), business case for large AM for affordable housing/construction industry and marine industries
- DOE "Megaprint" — Sustainable AM tooling for wind blades
- Phase 3 Hub-and-Spoke program (2022-2025): Nanocellulose/mycellium insulating materials for AM printed buildings, advanced manufacturing collaborative robotics with AM for large structures, large-area AM applied to modular housing

Research Needs

The shortage of affordable housing is rapidly emerging as an emergency situation across the entire United States. There is not a single "state or county where a full-time worker making minimum wage (can) afford a two-bedroom rental home at fair market rent" (Parker, 2021). On average, 328,000 affordable units would need to be added each year until 2030 to meet the growing demand, yet the United States has only attained that target three times in the last thirty years (Ruiz-Goiriena, 2021). When potential housing solutions are discussed, myriad social, political, and financial barriers quickly rise to the forefront, including critical shortage of skilled labor, increased material costs, and supply chain issues. In the meantime, to achieve carbon-neutrality goals, steep reductions in emissions from existing buildings, and utilization of low embodied energy materials in new construction are necessary.

3D printing technology has been evolving at a rapid pace. Champions have been using it recently to print everything from wind turbine blade molds to custom shoes. Coupled with breakthrough technologies, 3D printing is one of, if not the, most promising technologies on the market with the potential to overcome both cost of construction and labor issues that limit the fabrication of affordable housing. However, innovation is needed in the materials used for 3D-printed housing, since the production of cement, currently the most widely used 3D-printed building material, generates more carbon pollution than almost every other industry and was responsible for 8% of global carbon dioxide emissions in 2015.

Two promising technology areas of materials and manufacturing development in affordable net zero buildings are:

- Automated offsite construction methods to accelerate house fabrication at lower cost. Optimization of additive manufacturing design and development of collaborative automation integrated with 3DP.

- Renewable, low-embodied energy construction materials for zero-carbon buildings.

The Hub-and-Spoke program is working with the forest products industry to produce new biobased material feedstocks that will be conducive to 3D printing large-scale products, such as building envelopes. UMaine is also working directly with

industrial partners to identify key modular fabrication methods that can benefit the most from 3D printing. The collaboration is positioning the industry to adopt materials and methods that will transition the construction industry to net zero and even net negative carbon buildings that combine affordability with design resilience at a reduced environmental footprint.

FOR/Maine (https://formaine.org) has created the Forest Opportunity Roadmap (https://formaine.org/wp-content/uploads/2020/09/FORMaine_Report_DL_041119.pdf) /Maine vision to diversify the Maine forest products industry and create forest-based material feedstocks for use in the emerging bioeconomy. This includes public/private partnerships that strengthen the supply chain of locally sourced materials, such as those being developed by ASCC and our Hub-and-Spoke partners.

Sustainability

Net-zero to net-negative materials for use in the construction industry are a key enabler of widespread adoption and increased market pull for biobased materials that can help accelerate the replacement of petrochemical derived products with renewables. UMaine has built a successful collaborative research relationship with ORNL in biobased, low-carbon materials. This research focus area leverages the infrastructure already in place to rapidly scale up and test innovative forest derived materials.

Economic impact

- Increased demand for low-value wood residuals
- Value-added products using wood fillers and nanocellulose, improving economic viability of a commercial scale nanocellulose production facility
- Increased demand for products of existing manufacturers (Compounding Solutions)
- Opportunity to establish an advanced manufacturing facility in Maine based on large-format AM
- Opportunity to increase inventory of affordable housing using this new technology

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SUSTAINABLE PACKAGING (BIO-MANUFACTURING CONTINUED)

Maine's forest-based economy and the rural communities it supports are under pressure because of global competition, aging infrastructure, labor supply, energy markets, and other issues. In the last decade, several paper mills have closed for various reasons. In addition, a majority of Maine's forests have seen decreased management due to this current lack of robust fiber markets (Woodall and Weiskittel 2021). At the same time, it has become clear that there is a need for sustainable solutions to our food packaging needs, especially with regards to plastics and pollution. The need to mitigate climate change through carbon sequestration is also a global need. Maine's forests have the potential to solve these issues and, at the same time, will increase the demand for fibers, increase revenue into the state, and generate new companies and jobs.

The ability to replace single-use plastics and plastic/metal/glass packaging with cellulose-based systems is within practical reach. Cellulose nanomaterials have shown in the laboratory to be excellent oxygen and oil/grease barrier layers that can be applied on paper or paperboard to generate a package for dry goods. With various drying techniques, these nanomaterials can generate porous foam-like structures that can replace expanded polystyrene. With the proper barrier layers, wood fiber-based packaging is possible for juices, milk ,and soups. Cellulose-based packaging should lead to packaging that is sustainable, can be recycled, decomposes to benign material in the environment, and sequesters carbon if placed in a landfill. There is a need to make these packaging systems economically competitive with the plastic option and to develop robust systems to recycle these materials.

Opportunity and Objective

Innovative sustainable packaging based on wood fiber should increase the economic activity in the paper industry, launch new companies, increase the demand for wood fiber, improve the job market in rural communities, and give consumers a sustainable packaging option.

Research Activities

Past

- EPSCoR 2008 started some work on materials production
- PDC generated refiner method to produce large quantities of materials and supplies to outside
- Cellulose nanofiber (CNF) in coating layers and as the coating layer (Bousfield/Tajvidi)
- Particle board work in Tajvidi lab as well as Cellubound patent
- Foamed structures (Mason/Tajvidi)
- CNF on paper to resist grease penetration and oxygen barrier properties of CNF layers (Tajvidi/Bousfield)

Current

- CNF as a release layer for barrier coatings
- CNF with wood waste to form structures such as plates
- CNF with wood particles to form porous structures
- CNF layer modified chemically
- Production of 3D objects from pulp suspensions.

Future

- Methods to characterize rheology of suspension and other properties to generate stable processing of suspensions
- Continuous processing methods to apply onto paper as a coating layer
- Equipment to support pilot scale production
- Methods to apply on 3D objects
- Methods to dry into foam structures
- Economic Impact
- New products produced from current infrastructure at paper mills will improve the long-term outlook for these mills, increase demand for labor, and bring revenue into the state
- Novel applications such as the production of single use plastic substitutes and other objects, should help startup companies locate in Maine near the raw material source
- Increase demand for wood fiber should support the supply chain from transportation, harvest and land management
- Cellulose-based packaging technology developed in Maine should lead to companies seeking out Maine solutions and innovations. Maine should cultivate conditions to become the "cellulose valley" of the U.S.
- Molded pulp technology .could produce items that are currently plastic such as salad containers, trays inside cookie packaging, plates or trays in frozen food items, and other such items. Modifications of cellulose could lead to antimicrobial properties that increase shelf life for many products.

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Biomedicine and Engineering Advances

Maine has nationally competitive expertise in basic biomedical research and a wide range of academic and healthcare institutions involved in basic and applied research. Their collective strengths and accomplishments create a unique set of opportunities. Maine's small population, served by a relatively small number of healthcare providers, suggests that collaboration and outreach will be necessary to engage patient populations in unique research initiatives.

- Goal 1 Research Objective
  Expand the application of precision medicine, biomedical data science, and genetic modeling of human disease.

- Goal 2 Enterprise Objective
  Continue generating the biomedical discoveries and expertise that have helped launch multiple spin-off companies in Maine. Make strategic investments to increase access to research infrastructure and incentivize the formation of strategic research clusters.

- Goal 3 Workforce Objective
  Continue generating Maine expertise in the fields of cancer, genomics, neurobiology, host-pathogen interactions, computational biology and bioinformatics, aging, addiction, metabolism, and renal disease through postbaccalaureate, graduate, and post-doctoral research training.

- Goal 4 Climate Change Objective
  Mitigate climate change enabled increased risk to infectious diseases (e.g, Lyme disease, West Nile virus)

Maine has a strong biomedical research community and strategic investments in R&D will accelerate basic knowledge of human disease needed to improve the health and well-being of the state and nation. There are several research institutions in the research community that continue to build the critical research infrastructure to attract and retain scientists. Each institution has numerous strengths and accomplishments that, together, present Maine with a unique set of opportunities. Maine is home to four Centers of Excellence in Biomedical Research (COBREs) funded by the National Institutes of Health (NIH). They focus on: 1) mesenchymal and neural regulation of metabolic networks (MaineHealth Institute for Research); 2) comparative biology, regeneration and aging (Mount Desert Island Biological Laboratory); 3) neurobiology of pain and sensory function (University of New England); and 4) acute care research and rural disparities (MaineHealth Institute for Research). COBRE are infrastructure building grants that focus on building a critical mass of workforce (faculty, student trainees), as well as research cores/instrumentation

to support the research themes. Maine's COBREs are highly collaborative and provide important biomedical research infrastructure to the state. The Northern New England Clinical and Translational Research Center is an NIH-funded center focused on building clinical research infrastructure in Maine and Vermont. The Jackson Laboratory, a National Cancer Institute-designated basic laboratory cancer center since 1983, is focused on deciphering the complex genetics of cancer and to design precision models of the disease.

Along with nationally competitive expertise in basic biomedical research, Maine has a wide-ranging inventory of academic and healthcare institutions involved in applied research aimed at vulnerable populations and rural health.

Precision Medicine

The National Institutes of Health launched the Precision Medicine Initiative (PMI) in 2016 that seeks to develop genetically targeted therapies. Concurrent with PMI is the rapid adoption of pharmacogenomics in countries such as the United Kingdom. Maine has opportunities to contribute to this research since it has a relatively small population, and few pathology providers and healthcare organizations. Collaborations between researchers and these providers may be easier to form.

Research on precision medicine seeks to develop diagnostics and treatments that are customized to individual patients through programs at specific healthcare organizations. For example, Maine Health Info Net collaborates with all major healthcare providers in Maine to provide centralized health records that could be used for research. Cancer, discussed below, is a specific disease that can be treated with precision medicine, but this approach can be applied to many others, including chronic renal disease, diabetes, and cardiovascular disease.

Cancer is the leading cause of death in Maine (Maine Center for Disease Control and Prevention, 2019) and basic oncology research would eventually lead to improved outcomes. While many factors contribute to the high cancer mortality rates, increasing screening for cancer has been a goal within the Maine Cancer Plan. For example, Maine has a lung cancer mortality rate of 60% that is higher than the national rate for white males. Increasingly inexpensive sequencing technologies could be used to screen large numbers of individuals. Low-cost diagnostics would address socioeconomic barriers to healthcare that exist in Maine. With appropriate funding, it may eventually be possible to screen every willing Maine resident and providing earlier opportunities to treat disease through:

- Low-cost sequencing techniques allowing for screening of disease-causing variants
- Tissue sampling that can occur at community hospitals or related sites
- Studies being done through the Jackson Laboratory (JAX) as part of the Maine Cancer Genomics Initative
- Genome Wide Association of chronic renal disease at Northern Light Clinical Research Center

Data Sciences

The promise of personalized medicine, in which diagnostics and treatments are tailored to an individual patient's genome, is helping drive an expansion in the sequencing, storage, and analysis of human genetic information. International genomics database consortia [1, 2], federally-directed research projects [3], independent efforts by biomedical institutions [4], and a growing market of consumer-based genomics test products [5] are driving an increase in the number, size, and utilization of human genomic data sets for biomedical investigation. With an explosion of independent international collections of genomic data, each with thousands of individual exomes or whole genomes, biomedical research requires data science methods to extrapolate meaning from the "big data" available today. Data science will apply computational methods, including artificial intelligence and machine learning to generate novel biological insights, validated by genetic models of human disease.

Genetic Models of Human Disease

Maine researchers have a long history of developing animal models of human disease and providing those resources to global research communities. Major model organisms include the mouse, zebrafish, and the roundworm (*C. elegans*). These animal models are genetically tractable in that several methods can be used to engineer mutations that mimic those found in humans. Many mouse models of human disease — over 13,000 strains that comprise the largest repository of mouse genetics in the world — have been designed and made available by JAX over several decades. More recently, methods to produce populations of outbred mice have been developed by JAX that are susceptible to different complex diseases similar to what occurs human populations. Mount Desert Island Biological Laboratory (MDIBL) is currently developing ways to use marine animal models for drug testing, providing a unique and valuable resource for Maine.

Research Infrastructure

Maine needs more research infrastructure to conduct basic biomedical research and clinical and translational research. Examples of the types of research infrastructure include the following:

- High-throughput DNA sequencing and analysis capacity
- High-resolution imaging capacity
- Robust infrastructure for stable storage, management, and controlled sharing of laboratory data
- BioBanks

Maine also needs to leverage existing resources where possible through effective collaborations in the following areas:

- Biomedical research expertise in computational biology and bioinformatics
- Northern Light Cancer Care BioBank
- MaineHealth Institute for Research BioBank – more than 50,000 samples from cancer and inflammatory disease surgeries.
- Clinical Trials Infrastructure — MaineHealth Institute for Research, NNE-CTR and others
- Maine Health Info Net — centralized electronic health records from the major healthcare providers in Maine.

Strengthen state-wide and regional research collaborative networks

- Statewide Networks
- Maine INBRE Network
- University of Maine Graduate School for Biomedical Science and Engineering
- Maine Cancer Genomics Initiative
- Maine's Impact Cancer Network — Maine's Comprehensive Cancer Control program

Regional Networks and Collaborations

Northern New England Clinical and Translational Research Network
Northern Light Health Cancer Center partnership with Dana-Farber Cancer Institute

- Acute Care Rural Health — MHIR, UNE
- Addiction — JAX, UMaine
- Aging — JAX, MDIBL, UMaine
- Biomedical Workforce and Leveraging Expertise in the Maine
- Cancer — JAX, MaineHealth, Northern Light
- Computational biology and bioinformatics — JAX, UMaine, MDIBL, Roux Institute
- Expertise in host-pathogen interactions — UMaine, MaineHealth Institute for Research
- Metabolism — MaineHealth Institute for Research (MHIR), UNE, JAX
- Neurobiology/ Neurodegeneration/Pain — JAX, UMaine, Northern Light, UNE
- Renal Disease — JAX, MDIBL, UMaine

Economic Impact

Biomedical research is a growing and resilient sector of the Maine economy. When the COVID-19 pandemic caused certain sectors of the economy to severely contract, the biomedical research and development services sector expanded. Maine biomedical research institutions attract significant economic resources to the state through federal research grants and revenue generated through unique biomedical research products and services. From 2017 to 2021, Maine institutions received over $515 million in competitive NIH awards. From 2001 to 2021, the top three patent holders in Maine are all biomedical institutions (IDEXX Laboratories, The Jackson Laboratory, MaineHealth Institute for Research). Likewise, nearly all of Maine's life science jobs are biomedical, in sectors including pharmaceutical and medical manufacturing, scientific research and development services, medical and diagnostics laboratories, and medical equipment and supplies manufacturing. These workers earn a median hourly wage of $31.05, 34% higher than the median hourly wage for all other occupations in Maine.

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Maine Department of Labor, Center for Workforce Research and Information

2022 State of the Industry, Biosciences Association of Maine

Healthy Aging

Maine is home to the oldest population in the U.S. In the coming decades, understanding how factors outside the healthcare setting influence the mental and physical health of older adults will be one of the state's major public health challenges.

- Goal 1 Research Objective
  Prioritize funding of research centers and individual projects focused on improving the mental and physical well-being of older adults and their caregivers.

- Goal 2 Enterprise Objective
  Encourage the creation of elder-appropriate technology solutions for older consumers, especially in the areas of AI, virtual and augmented reality, household technologies, and cybersecurity.

- Goal 3 Workforce Objective
  Prepare an age-capable workforce that can adequately identify and respond to the mental and physical health needs of older adults, especially in rural areas.

- Goal 4 Climate Change Objective
  Assess and mitigate the impact of climate change driven diseases of highest risk to the elderly.

In the long-term care sector (i.e., nursing homes and assisted living communities) person-centered care represents a parallel effort to maximize the quality of healthcare received by older adults in these settings through organizational culture change, empowering a care team, keeping the older adult and family at the center of decision making. All older adults, and certainly those in the oldest state in the nation, should have access to the health resources and support needed to feel safe, and achieve maximum health, longevity, and well-being. Age-friendly health systems aim to: follow an essential set of evidence-based practices; cause no harm; and provide structures that create a positive daily routine and lead to better health outcomes.

The health of older adults is not only influenced by access to quality care, but also by factors operating outside of the healthcare setting (Rural Health Gateway, 2019). These "social determinants of health," including educational and employment opportunities, socioeconomic status, housing, transportation, food, social support, physical environment, and community infrastructure, are the most powerful predictors of older adult health outcomes and, ultimately, longevity perhaps especially because of the cumulative effects over the life span (Henning-Smith, 2021). Understanding the differential impacts of these social determinants of health, and enacting policies and programs that will most effectively and efficiently reduce these barriers to the ability of all older adults to thrive, especially in rural communities, is the challenge that lies ahead for the state.

Notable Maine Institutions & Organizations

- Area Agencies on Aging — Southern Maine, Spectrum Generations, Aroostook, Eastern, and Seniors Plus
- Center for Community Inclusion and Disability Studies, University of Maine
- Center for Excellence in Aging and Health, University of New England
- Center of Excellence in Collaborative Education, University of New England
- Center on Aging, University of Maine
- Dirigo-Maine Geriatrics Society
- Harvard Pilgrim
- LeadingAge Maine & New Hampshire
- Maine Council on Aging
- Maine Gerontological Society
- MaineHealth
- Margaret Chase Smith Policy Center, University of Maine
- Muskie School — Cutler Institute, University of Southern Maine
- Northern Light
- Office on Aging and Disability Services, State of Maine
- State of Maine Office of Aging and Disability Services

Current Activities

There are several concurrent initiatives across the state that seek to increase Maine's efforts to ensure the provision of age-friendly and person-centered long-term care, and reduce the negative cumulative negative impacts on older adults of a range of social determinants of health factors.

These programs include:

- AgingME, the HRSA-funded Geriatrics Workforce Enhancement Program (GWEP). A partnership of the University of Maine, the University of New England, and a large array of community health and human service partners, GWEP aims to create a more age-friendly health system by better preparing an age-capable workforce, transforming primary care practices, and engaging and empowering older adults.
- The Age-Friendly movement in Maine remains ahead of the national curve in terms of activity across the state. During the past year the University of Maine Center on Aging provided technical assistance and coordination of age-friendly and lifelong communities in partnership with AARP national and the state chapter, and Americorps. The Maine Council on Aging is performing complementary efforts with additional lifelong communities across the state.

Suggested Future Research

The transportation needs and challenges that older adults and people with disabilities face in rural communities continue to be significant as they try

to access healthcare, meet their daily needs, and avoid social isolation. The pandemic has increased the urgency of innovation in the offering of rural transportation services. Viable solutions must address not only enabling accessing specialized healthcare services that address urgent chronic care needs, but satisfy daily living, quality of life, and socialization needs as well. Furthermore, such efforts need to be equitable ensuring responsiveness to the needs of diverse older adults, people with disabilities and their caregivers, including those residing in marginalized communities. Existing resources to turn to include the National Aging and Disability Transportation Center, National Rural Transit Assistance Program, National Center for Mobility Management, National Center for Applied Transit Technology, Shared Use Mobility Center, USDA Transport Services Division, ITNAmerica, and The Federal Transit Administration.

- Expanding the number of age-friendly communities, in a state that has already qualified as just one of ten in the U.S. that is age-friendly, is essential to continue to make them livable for older adults and others across the life span. This includes providing increased numbers of small cities and towns with the technical assistance and financial resources to address their built environments, including those facets of such settings that are more likely to be underdeveloped and of lesser quality than urban settings, including water quality, space for recreation and exercise, access to nutritious food, and availability of broadband internet and cellular connectivity, among other community infrastructure and physical environment features. Research is needed to tease out the preferred strategies and evidence-based best practices for advancing livability across the recognized domains of an age friendly community.
- The scarcity of adequately trained health and mental health personnel is a long-standing problem and may be growing more serious given the fact that this workforce is aging more rapidly than most other employment sectors with large numbers expected to exit the workforce over the next ten years. The lack of direct care workers who provide daily direct support to older and disabled adults in their homes and long-term care settings is particularly acute in rural communities due to low compensation, inadequate training, limited career advancement, high turnover, and the unique barriers created by rural conditions. More emphasis on rural economic development, widespread broadband, employment programs for an aging rural workforce, and navigation assistance and workforce skills development programs are badly needed (Dorrer, 2021). Increased availability of respite and relief programs for elder caregivers is also warranted. Research continues to be needed to fully understand healthcare workforce needs in rural communities to be able to strategically target resources and identify the most efficacious workforce intervention strategies.
- Older adults remain less likely to be digitally literate than other segments of the rural population. While not the sole solution to ensuring they have access to the information and products needed to live safer, healthier, and more engaged lives, technology can be an important supplement to more traditional modes of human exchange. Resources are needed to provide more training and create more user-friendly designed devices and apps. For individuals, especially older adults and others still adjusting to a high-tech, digital world, more readily available, elder-appropriate technology solutions for older consumers are needed, especially in the areas of artificial intelligence, virtual and augmented reality, the Internet of Things (IoT), and cybersecurity.
- Social connectivity is more important than ever, given the significant increase in the number and proportion of older adults experiencing the harmful effects of social isolation and loneliness, both prior to and subsequent from the COVID-19 pandemic. Research-driven, evidence-based programs that both prevent and can reverse instances of social isolation and loneliness are badly needed, including those that provide opportunities for socialization, recreation, leisure, and the receipt of needed health and human services. In addition, research is still needed for identifying the risk and occurrence of social isolation and loneliness in communities.

Offshore Wind Energy

Floating offshore wind is a strategic opportunity for Maine to meet its renewable energy targets and create a resilient Maine-made clean energy industry. In 2009, Maine's Legislature embraced this opportunity by passing the Maine Wind Energy Act, which set the goal of offshore wind generating 5,000 megawatts by 2030.[36] With one of the nation's most robust offshore wind resources, and nearly a decade and a half of floating offshore wind innovation, Maine is poised to be a global leader in this burgeoning industry.

- Goal 1 Research Objective
  Prioritize offshore wind research in three areas: 1) the technical aspects of engineering, manufacturing, installing, and operating floating wind turbines and farms in the Gulf of Maine, 2) their environmental and ecological impacts, and 3) the human dimensions and socioeconomic impact of offshore wind development.

- Goal 2 Enterprise Objective
  Catalyze the development of a floating offshore wind farm in the Gulf of Maine, and support the development of a local supply chain that creates export opportunities for services, processes, and technology developed and patented in Maine.

- Goal 3 Workforce Objective
  Sustain world-class floating offshore wind research facilities and educational programs to train the next generation of offshore wind professionals and technicians.

- Goal 4 Climate Change Objective
  Expand Maine's clean energy portfolio by sourcing energy from Maine's abundant floating offshore wind resource and catalyze the creation of a commercial floating offshore wind industry in the Gulf of Maine.

Opportunity

The U.S. Department of Energy estimates the U.S. offshore wind resource potential is more than 2,000 GW of capacity, almost double the nation's electricity use.[37] Much of this capacity, nearly 60%, is over water depths greater than 60 meters, a depth too deep for fixed bottom technologies.

The Gulf of Maine (GOM) has 156 GW of offshore wind capacity within 50 miles offshore and is one of the best offshore wind resources in the world. Winds in the GOM are at their strongest and most consistent in the winter, when Maine's energy use is at its peak. Harnessing just 3% of the GOM's offshore wind resource will allow Maine to electrify heating and transportation, attract $20 billion of renewable energy investment, create over 10,000 jobs, and allow the state to achieve carbon neutrality by 2045.

Maine's Resources

Over the past 14 years, the University of Maine Advanced Structures and Composites Center (ASCC) has been a leader in developing an economical way to harness clean, renewable offshore wind energy from our deep ocean waters. Since its founding, with support of the National Science Foundation, ASCC has created 14 spinoff companies, received 120 patents, financially sponsored more than 2,600 students, and been honored with more than 40 national and international awards for research excellence. ASCC has collaborated with dozens of private and public entities in Maine and beyond. The center is dedicated to driving research innovation in green energy and materials to create a greener, more sustainable world while bolstering economic development in Maine and beyond. Unique research facilities have been built at UMaine, including the Alfond W^2 Wind-Wave basin, the only such facility in the U.S. that can apply accurate wind and wave environments on offshore wind turbines (see figure). This is a 1:50-scale offshore model testing facility that accurately simulates towing tests, variable water depths, and scaled wind and wave conditions that represent some of the worst storms possible anywhere on Earth.

The university has also developed and operated two unique FOWT test sites — one off Castine for intermediate scale prototype testing, and the other off Monhegan Island for full-scale FOWT testing.

The University of Maine's School of Marine Science has substantial research infrastructure that has been applied to understanding offshore wind development-environmental interactions. Specifically, the University of Maine partners with the Northeast Regional Association of Ocean Observing Systems to deploy and maintain buoys in the Gulf of Maine to observe wind, waves, current speed and direction, and other oceanographic conditions known to influence the composition and abundance of marine organisms. Facilities at the Ira C. Darling Marine Center include a new flowing seawater lab and research vessels for deployment of oceanographic and ecological monitoring equipment. Expertise in fisheries science, benthic ecology, marine mammals, and oceanography have regularly contributed to offshore wind projects in Castine, Monhegan Island, and the new proposed Research Array. The New Jersey Audubon Society conducted radar studies to track birds and bats for one year to assess movement patterns of aerial vertebrates near the test site location near Monhegan Island, and the Lubird Kennedy Environmental Services conducted 41 surveys to determine the bird species presences and relative abundance at the UMaine Deepwater Offshore Wind Test Site.

36 Maine Revised Statutes, Title 35-A, §3404.

37 U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, "Computing America's Offshore Wind Energy Potential," September 9, 2016.

The Biodiversity Research Institute (BRI) was founded by David Evers, who has made great strides in bringing critical ecological issues to the forefront of our nation's and the world's consciousness. Their mission is to assess emerging threats to wildlife and ecosystems through collaborative research, and to use scientific findings to advance environmental awareness and inform decision makers.

Maine Sea Grant supports marine science for Maine people through sharing information and solving problems as one of 34 NOAA programs throughout the coastal and Great Lakes states. Working in partnership with University of Maine Cooperative Extension, members of this team work on issues of concern to Maine's coastal communities. This 25-person committee helps identify stakeholder needs and ensures that our work is relevant to the people of Maine.

Maine Maritime Academy is building capacity for conducting research on training/O&M operations.

The Nature Conservancy tackles the dual threats of accelerated climate change and unprecedented biodiversity loss, using science to determine where to focus and how to achieve long-lasting results. In order to maximize the ability to impact change, this team brings together real-world solutions, policy expertise, and collaborative partnerships.

The Gulf of Maine Research Institute is dedicated to the resilience of the Gulf of Maine ecosystem and the surrounding communities who depend on it. GMRI develops and supports solutions that will benefit the bioregion for years, and takes an integrated, interdisciplinary approach to understanding how natural, social, and economic systems interact.

Maine is heavily engaged in offshore wind through the Governor's Energy Office (GEO), which is leading a road mapping effort for offshore wind, bringing the Departments of Transportation, Economic and Community Development, Marine Resources, and Inland Fisheries and Wildlife.

Past Research Activities

In 2008, Governor John Baldacci established the Maine Ocean Energy Task Force to recommend a strategy to develop the renewable ocean energy resources in the Gulf of Maine. The Ocean Energy Task Force Final Report, published in December 2009, set Maine's renewable ocean energy goals, including the installation of 5 GW (5,000 megawatts) of offshore wind energy by 2030. Beginning in 2010, UMaine, in collaboration with regional partners, conducted comprehensive environmental studies with five plus years of baseline ecological data, including a radar study, boat survey, acoustic bat survey, passive acoustic avian monitoring, and avian and bat monitoring at the 1:8 scale turbine in Castine. In 2013, UMaine and its partners successfully deployed the Volturnus 1:8, a 1/8th scale, 65-foot-tall prototype that was the first grid-connected floating wind turbine in the Americas. Data collected during this deployment is being used to inform design and construction of an 11MW full-scale floating offshore wind turbine utilizing the Volturnus platform technology.

Current Research Activities

A timeline of past and future planned floating offshore wind deployments off the Maine coast takes a deliberate approach ("crawl before you walk and walk before your run") to address engineering, environmental, and social issues of offshore wind deployment in the Gulf of Maine. Following the successful 2013 deployment of Volturnus. 1:8, the University of Maine is working with the U.S. Department of Energy and commercial partners RWE and Diamond Offshore Wind (a Mitsubishi corporation), to design an 11 MW demonstration floater, expected to be installed in 2024 off Monhegan Island. The State of Maine submitted a BOEM proposal to develop up to ten to twelve turbines floating research array, 150MW project called the Maine Research Array (MeRA) in 2026-2027.

Maine Offshore Wind Roadmap
The State of Maine Governor's Energy Office (GEO) has been leading the development of the Maine Offshore Wind Initiative. As stated on the GEO's website this road map will create an economic development plan for the offshore wind industry in Maine by building on the state's record of planning, research and development, and innovation that stretches back over a decade:
This work is supported by a $2.166 million grant from the U.S. Economic Development Administration (EDA) to the Governor's Energy Office (GEO) to develop the road map as an initiative for growing Maine's overall economy and improving Maine's economic resilience through targeted development of this global industry. The Offshore Wind Roadmap will be developed by an expert advisory committee and several working groups with broad public input, focusing on energy markets, ports and infrastructure, socioeconomic impacts, equity, manufacturing and supply chains, workforce development, and ocean and environmental compatibility. This effort will identify how to support the growing offshore wind sector in a way that embraces the opportunity, while ensuring compatibility with our Maine coastal heritage and minimizing the impacts on fisheries and the environment. Maine's 10-year economic strategy identifies offshore wind as a critical opportunity to grow the state's economy, and encourages the state to set forth a balanced agenda that maximizes economic benefits for Maine people while creating a culture of innovation that creates a foundation for future leadership in this growing industry.

New England Aqua Ventus I, 11 MW Floating Offshore Wind Demonstration Project
Funded through DOE and private industry, ASCC is poised to deploy the first U.S. commercial-scale

11 MW FOWT in 2024. This demonstration project is unique in that it will mount an 11 MW wind turbine to a floating semisubmersible concrete hull designed by the ASCC. The innovative concrete hull technology allows for the hull to be fabricated locally. Hull fabrication, construction, and deployment provide a major economic opportunity for Maine. A typical offshore wind project may have approximately 25% of its capex in the hull, therefore a gigawatt-scale project would require nearly $1 billion in hull procurement. The patented Volturnus hull technology has been demonstrated in independent reports to reduce the cost of offshore wind to <6 cents kWh at commercial scale. The turbine is held in position by mooring lines securely anchored to the seabed, and connected by subsea cable to the Maine power grid. The project goals are to demonstrate the innovative design of the Volturnus with a full-size offshore wind turbine, develop the state supply chain by working with local contractors and manufacturers to generate local economic benefit, create and keep Maine jobs in Maine, and provide renewable energy now and in the future.

Maine Research Array (MeRA) Maine Floating Offshore Wind Research Site
In October 2021, the Governor's Energy Office (GEO) submitted an application to the Bureau of Ocean Energy Management (BOEM) to lease a 15.2-square-mile area nearly thirty miles offshore in the Gulf of Maine for the nation's first floating offshore wind research site in federal waters. The state hopes to deploy a small-scale research array of twelve or fewer wind turbines on innovative floating hulls designed at the University of Maine. This project will advance UMaine's patented technology and will foster leading research into how floating offshore wind interacts with Maine's marine environment, fishing industry, shipping and navigation routes, and more.

Research Priorities

Research is needed in three areas: 1) the technical aspects of engineering, manufacturing, installing, and operating floating wind turbines, 2) their environmental and ecological impacts, and 3) the human dimensions of offshore wind development. Research should also explore ways that offshore wind can coexist with, and enhance, other marine industries.

- Technology/Engineering
  - FOWT modeling and design for next-generation large turbines (>15-30MW turbines)
  - Next-generation floating offshore wind hull technologies suitable for large turbines (15-30 MW)
  - Active and passive controls for large floating wind turbine systems
  - Innovations in design, manufacturing and towers and blades, including the use of advanced materials and manufacturing processes, such as thermoset and thermoplastics composites
  - Anchors and mooring systems innovations for water depths and geophysical conditions unique to the GOM
- Manufacturing scale-up methods for locally produced concrete hulls
  - Green materials for local fabrication of hull components, including green concrete technologies, and ultra-high-performance concrete (UHPC)
  - Tow-out and installation methods
  - Grid integration, including inter-array, dynamic and export cables, and floating substations
  - Operations and maintenance (O&M), including use of digital twins, Artificial Intelligence (AI), sensors, data processing, and remote and drone monitoring to reduce costs and injuries
  - Port facilities development specifically to FOWT
  - Development of locally-produced vessels to support O&M operations, including composite materials CTVs, and 3D-printed tooling and vessels

- Environmental and Ecological Sciences
  - Marine ecosystems, including fish and wildlife, response to floating offshore wind turbines

- Social Sciences
  - Human dimensions of floating offshore wind development
  - Transdisciplinary sustainability science research and workforce-relevant skills and training programs in the state
  - Applications of human dimensions and social-environmental systems knowledge to decision making and business development, and acceleration through collaborative research in partnership with the fishing and shipping industries, other seafood-related sectors, and port and municipal authorities

- Convergence of engineering, environment, and social sciences:
  - Co-location of aquaculture and floating offshore wind
  - Opportunities for the fishing industry to participate in floating offshore wind
  - Designs of FOWT systems to enhance ocean ecological habitat

Potential Economic Impact

In June 2019, Governor Janet Mills signed into law LD994, announcing the establishment of the Maine Offshore Wind Initiative to capture a portion of an offshore wind market estimated to be valued at $1 trillion by 2040. Maine's 10-year Economic Development Strategy identifies offshore wind as a key component to its goal of adding 75,000 jobs to the state's economy by 2030. According

to the Workforce Development Institute, these are well-paying jobs requiring technical skills and spanning 74 occupations, including direct jobs in engineering, manufacturing and construction and indirect impacts in downstream and supply chain professions. The University of Maine conducted an analysis of the statewide economic impact of a commercial-scale (500MW) floating offshore wind farm in the Gulf of Maine. Such a farm would consist of nearly a $2 billion investment, would generate 3,077 full- and part-time jobs (in hull fabrication alone) during construction, and 1,602 operation and maintenance jobs.

Tidal Energy

The Gulf of Maine, particularly the Western Passage between Maine and Canada, is one of the best tidal energy resources in the nation. With a successful ten-year history of R&D and commercialization that has advanced expertise in the field, Maine is strongly positioned to be a leader in tidal energy technology.

- Goal 1 Research Objective
  Prioritize tidal energy activities in four areas: 1) an inventory of potential tidal energy sites, 2) research on environmental impacts, 3) research on the human dimensions of tidal energy development, and 4) creation of a scaled tidal energy test site.

- Goal 2 Enterprise Objective
  Form a tidal energy cluster that encompasses research and design, manufacturing, installation, operation and maintenance, regulation, and site development.

- Goal 3 Workforce Objective
  Support the creation of a well-trained, well-paid tidal energy workforce, with opportunities for a diverse range of professionals, from engineers and managers to technicians and tradespeople.

- Goal 4 Climate Change Objective
  Expand Maine's clean energy portfolio by catalyzing the creation of a commercial-scale tidal energy operation in Maine.

Marine hydrokinetic devices, or tidal stream turbines, capture the water's kinetic energy when in a free-flowing tidal stream. Tidal stream generators use the same principle as that of the wind turbine, but the condition under which they operate is different. It uses the kinetic energy of the flowing water to produce power, and since water is approximately 830 times denser than air, even at slow current speeds tidal turbines can produce more power than wind turbines. Tides, and therefore tidal energy, are also more predictable and reliable than other renewable energy sources. Tidal power development occurs in estuaries and coastal areas where tidal influence is amplified due to shallowing waters and converging coastline shapes; the same technology is now being used for river sites — in all cases, without dams or impoundments. In addition, power generation from the tides is restricted to areas of the globe that have tidal currents fast enough to generate power. The newer tidal stream technologies are feasible in areas with maximum currents of 1.5 m/s (Khojasteh et al., 2022). The areas in the United States with the best tidal energy resources are the Gulf of Maine, Puget Sound, Washington and Cook Inlet, Alaska. Further, the U.S. Department of Energy (DOE) considered these locations for tidal energy development and pointed to Western Passage, a waterway on the border of Maine and New Brunswick, Canada, as a prime site (Kilcher et al., 2016). With a successful ten-year

history of supporting research and development and industry activities that have advanced tidal energy expertise, Maine is strongly positioned to continue leadership and support for tidal energy technology.

Western Passage is a region that has been proposed as a tidal energy site since the 1940s, (when technologies were limited to dam development) and the Electric Power Research Institute has identified this area as the best free-flowing stream tidal energy development opportunity on the East Coast. Estimates identify the overall energy potential within the state of Maine as over 250 MW (Ferland, 2020). Ocean Renewable Power Company (ORPC) was the first company to advance tidal stream technology in Maine. In 2012, ORPC built and operated a TidGen® Power System in Cobscook Bay in Eastport and Lubec. It was the first revenue-generating, grid-connected tidal energy project in North America, and the first ocean energy project to deliver power to a utility grid anywhere in the Americas. However, challenges still exist in bringing the technology to full commercialization in the U.S., including difficulties with environmental characterizations in turbulent ocean conditions and developing equipment and bottom infrastructure that can withstand the harsh marine waters.

Opportunity

- With a decade of experience with research and development and commercialization activities, Maine is uniquely situated to be a leader in tidal energy development as it is located next to one of the most promising tidal power sites in the United States.
- ORPC is currently located in the U.S., Canada, Ireland, and Chile, making Maine and the University of Maine situated to become a leading source of public information about new tidal technology development, environmental assessments, and the industry's role in the larger energy strategy for the state, the nation, and the world.
- Maine's Blue Economy promotes the sustainable use of ocean and coastal resources for economic growth, improved livelihoods, and jobs while preserving the health of ocean and coastal ecosystems.
- Opportunity to catch up with European countries that added 2.2 MW of tidal stream installations in 2021 generating 68 GWh to electricity generation, with 1.4 MW of tidal energy slated for Europe in 2022 and 1 MW anticipated in the rest of the world with Canada leading these efforts (Ocean Energy Europe, 2022; Figure 2).
- Demand for sustainable energy globally to reduce the effects of climate change.
- Microgrid Technology
  - Opportunity to advance in microgrid and power storage technology powered by local renewable energy in coastal communities. Microgrid technology is necessary for rural and "off-grid" facilities.
  - Opportunities for on and off-grid applications in tidal areas, rivers, and colocations with bridges, piers, and breakwaters.
  - ORPC is working to replace diesel-fueled microgrids with renewable energy in Alaska to reduce electricity costs. This adaptation is a potential research area for Maine (DOE, 2022).

Notable Maine Institutions & Organizations

- Advanced Structures and Composites Center
- Civil and Environmental Engineering
- Cobscook Bay Resource Center
- Maine Maritime Academy (MMA) provided engineering evaluation analysis for tidal energy technology. Held a federal preliminary permit with the goal of developing the Tidal Energy Device Evaluation Center (TEDEC), a tidal technology testing site, although the status of the site is unknown
- Maine Sea Grant
- Maine Technology Institute (MTI)
- Maine Tidal Power Initiative (MTPI)
- Ocean Renewable Power Company (ORPC)
- School of Marine Sciences
- Senator George J. Michell Center for Sustainability Solutions
- Substantial industry supply chain providing manufacturing, assembly, installation and environmental services
- University of Maine and University of Maine at Machias
  - Advanced Structures and Composites Center
  - Civil and Environmental Engineering
  - Maine Tidal Power Initiative (MTPI)
  - School of Marine Sciences
  - Senator George J. Michell Center for Sustainability Solutions

Past Research Activities

- The Maine Tidal Power Initiative (MTPI) is a transdisciplinary team of marine scientists, social scientists, engineers, and oceanographers that used a sustainability science approach to collect data (biophysical, engineering and social) for understanding human and natural system interactions in the context of tidal energy development in Maine (Jansujwicz and Johnson 2014). MTPI's social science research identified key stakeholders and their preferred engagement strategies (Johnson et al. 2015), documented the regulatory and permitting process (Jansujwicz and Johnson 2015), and gathered data on perceptions related to tidal power development in Downeast Maine (Cobscook Bay and Western Passage). The study site was located in Washington County, which according to the U.S. census has one of the highest rates of unemployment and poverty in Maine and the U.S. From this study, it was found that the communities adjacent to the tidal power development site were most interested in the jobs that would become available due to the

installation of tidal power technologies (Johnson et al. 2013).
- Series of environmental impact assessment studies conducted alongside local communities to best establish environmental conditions prior to and during TidGen® Power device deployment in Cobscook Bay (Shen et al., 2016; Viehman and Zydlewski, 2017; Staines et al., 2020; Grippo et al., 2020).
- The Western Passage Student Research Collaborative (WPSRC) was established in spring 2019 to engage undergraduate students in a one-year training program focused on research relevant to the development of tidal energy development in coastal areas and the need for environmental impact monitoring. A publication resulting from this study (Cammen et al., 2021) produced an interdisciplinary training, research, and communication framework, and recommendations to facilitate the adaptation and implementation of this framework were provided.
- Kreshing et al. (2019) studied the impacts of tidal energy in the Gulf of Maine and how sea level rise will alter theoretical tidal power estimates. They found that 1 m of sea level rise will significantly increase tidal energy resources in some areas, but extracted energy depends on the technology being used.
- Industry and university collaborations: ORPC has worked with UMaine researchers from the School of Marine Sciences and the Advanced Structures and Composites Center over the past several years, which led to research funding, scientific publications, and student experiences in the tidal energy discipline for academic research and job opportunities.

Current Research Activities

Understanding the human dimension of tidal power development by professors Teresa Johnson and Dr. Jessica Jansujwicz at the University of Maine. Environmental assessment for monitoring fish and marine mammal interactions to establish thresholds for regulatory decision-making is currently on hold.

Future Research

- Characterize marine environments to increase understanding regarding the relationship between ocean energy extraction and marine ecosystems.
- Mapping of coastal and estuary tidal energy power potential to understand suitable tidal energy development. This would include both 'large' sites like Passamaquoddy Bay and Western Passage and 'small' sites that could be in estuarine areas along the Maine coast (Maine Governor's Energy Office, 2015).
- Create a public repository of marine environmental information. This will reduce the cost of the permitting process for energy developers by having credible scientific information about the marine resource readily available.
- Create a pathway to commercialization developed collaboratively by industry, government, scientists, and stakeholders.
- Develop a scaled tidal energy test site in Maine for developers to test technologies. This can be coupled as an offshore wind and wave energy scaled test site as well. Current locations, such as Dyce Head off Castine could be a potential testing site as this has housed the UMaine Volturnus offshore wind scaled test, the UMaine ERDC floating breakwater tests, and is a future test site for wave energy conversion (WEC) devices. Cobscook Bay could also be used for this purpose. Having a test bed site could simplify submerged land leasing requirements for tidal energy testing projects.
- Couple development of offshore wind turbines with tidal energy turbines as the technologies are similar, but at varying spatial scales.
- Add engagement of local and traditional knowledge into the regulatory decision-making process.
- Longitudinal research on evolving public perceptions and other social data needed to inform social impact assessments, permitting, and engagement needs for developers.

Economic Impact

Tidal energy development would create jobs and higher income opportunities for rural Down East coastal counties with high rates of unemployment and people living in poverty. (ORPC has spent nearly $50 million in Maine and almost $7 million in Washington County alone). Jobs would be created in management, engineering and technology positions, and would include the trades and marine operations positions that have commonly anchored the workforce of coastal communities: metal and fiberglass fabricators, electricians, carpenters, boat operators, and boat crew. (Ferland, 2008). Tidal devices are designed and manufactured using composite materials. This equipment could become a standard product offering from Maine's composite companies and may lead to further market penetration into other marine energy technologies, such as wave energy.

All of this activity would help Maine become a world leader in tidal energy expertise through the formation of a Maine tidal energy cluster (Ferland, 2008). The activities associated with tidal energy technology development encompass marine composites manufacturing, marine installation, operations and management services, marine technology research and development, environmental research, industry standards development, and the refinement of collaborative processes that allow developers, communities, regulators, and other stakeholders to sensibly plan for the industry's evolution and promise.

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