Michael Jay Walsh, Ph.D.

Partner, Groundwork Data
Arlington, Massachusetts, USA
mjw@groundworkdata.org

PROFESSIONAL EXPERIENCE

Groundwork Data, Inc., *Founding Partner* *2021-Present*
Launched a mission-driven consultancy committed to accelerating a clean, equitable, and resilient energy transition. Developing decarbonization strategy and analysis for non-profit, university, private sector, and government clients focusing predominantly on gas transition, electrification, and alternative fuels technology and policy.

The Cadmus Group., *Senior Associate* *2019-2021*

Boston University, Institute for Sustainable Energy, *Senior Research Scientist* *2017-2019*

Future of Heat and Gas Transition

- Oversees research and analysis of state-focused "Future of Gas" studies.
- Provides expert support for interventions in "Future of Gas" proceedings
- Developed a framework and an analytical platform for the evaluation of alternatives to gas pipeline replacement. Applied evaluation framework to scenarios relevant to state policy and municipal utility operations.
- Evaluated long-term implications of evolving utility rates on energy bills in new construction.

Integrated Decarbonization Planning for States and Cities

- Project director for the Massachusetts 2050 Decarbonization Roadmap Study
- Technical Lead for the Carbon Free Boston (2019) report and co-lead of the Boston Climate Progress Report (2022)
- Analytical and policy support for various states and municipalities focused on technology pathways, policy development, energy efficiency program design, and implementation mechanisms.

Advanced Fuels, Bioenergy & Waste

- Facilitated diverse stakeholder input and elicitation for developing sustainability indicators and an evaluation framework for alternative waste management strategies.
- Provided expert witness testimony in an intervention to critique a utility proposal to develop a landfill renewable natural gas project.
- Led the writing and analysis in a study of bioenergy in New England.
- Conducted life cycle GHG assessments of waste streams for a city and a university.
- Evaluated pathways for emerging bioenergy technologies.

EDUCATION & ACADEMIC TRAINING:

- B.A. in Chemistry from Colby College (2005)
- Ph.D. in Environmental Engineering from Cornell University (2013)
- Fellow, Bentley University, Center for Integration of Science and Industry (2013-2017)

A list of academic publications is available on Google Scholar

Curriculum Vitae

Dorie Seavey

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Boston, MA 02108
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EDUCATION

1987	Ph.D. Economics, Yale University
1980	M.Sc. Economics, London School of Economics
1979	B.A. with Distinction (Phi Beta Kappa), Stanford University

PROFESSIONAL EXPERIENCE

Staff Positions & Independent Consultancy Practice

2023 to present

Groundwork Data, New York, NY

Senior Research Scientist

Lead the company's future-of-gas research, assisting cities, states, and utilities in crafting data-driven policy and regulatory tools.

2022 - 2023

HEET, Boston, MA

Principal Investigator

A research study investigating the financial cost of gas pipeline replacement activity by Philadelphia Gas Works.

A research study on the problem of methane emissions in the U.S. and local and state strategies for reducing and eliminating these emissions.

2022

RMI & Earthjustice, Baltimore, Maryland

Co-Principal Investigator

Provided research and analysis to a position brief making the case that Maryland should prioritize a comprehensive program to retrofit and transition housing for low-income households to electrification.

2020 - 2021

Gas Leaks Allies, Boston, MA

Principal Investigator

A 12-month research study evaluating the Massachusetts Gas System Enhancement Program (GSEP) and projecting its future cost.

2012 - 2018	**Seavey Vineyard, LP,** Saint Helena, CA *Managing Director* Responsible for leading Seavey, a small family-owned vineyard and winery. Oversaw day-to-day operations and company finances, and directed marketing and sales. Projects included: upgrading financial and accounting systems; developing 401K and other employee benefit programs; new website and branding materials; restructuring of wine club and hospitality programs; new capital projects (solar, vermiculture, HVAC).
2012 - 2015	**Paraprofessional Healthcare Institute (PHI),** New York *Consulting Senior Policy Advisor* Led PHI's advocacy for basic wage and hour protection for home care workers including authoring issue briefs and other strategic materials, collaborating with other non-profit advocacy organizations, submitting affidavits to court cases, and assisting with the drafting of a Supreme Court Amicus Brief in Harris v. Quinn.
2004 - 2012	**Paraprofessional Healthcare Institute (PHI),** New York *Director of Policy Research* Led PHI's research, analysis, and writing on economic, financial, and policy issues affecting the direct-care workforce and the long-term care industry. Managed PHI's analysis of national and state workforce data; led multi-year research contracts; and supported PHI's state policy directors with policy analysis and research.
2003 - 2005	**Center for Social Policy, McCormack Graduate School of Policy Studies, University of Massachusetts**, Boston *Co-Principal Investigator of Research Evaluation Project on the Impact of Enhanced Marketing & Sales Capacity on Alternative Staffing Organizations* An 18-month evaluation and research study assessing the impact of enhanced marketing and sales on the ability of organizations to create transitional employment opportunities for disadvantaged job seekers. (Funder: Mott Foundation).
2000 - 2004	**Paraprofessional Healthcare Institute**, New York *Consultant to Research Projects on Direct-Care Workforce Issues* Co-author of major research and policy report on paraprofessional work-force issues and the long-term care industry in New York State. Developed new methods for estimating the size of the long-term care population and the supply of traditional caregivers over time. Developed data series that

enable detailed regional analysis.

Also conducted research and analysis for: (i) *Health Care Workforce Issues in Massachusetts*, an Issues Brief of the Massachusetts Health Policy Forum, Schneider Institute for Health Policy, Heller Graduate School, Brandeis University, June 2000 and (ii) *Direct-Care Health Workers: The Unnecessary Crisis in Long-Term Care*, Aspen Institute/Domestic Strategy Group, February 2001.

2002-2005 **Public/Private Ventures,** New York

Special Report on Day Care Justice Co-op, Providence, Rhode Island

Co-author of policy report on the Day Care Justice Co-op, Inc., a membership association of low-income family childcare providers in Providence, RI whose mission is to improve conditions for family child care providers and the low-income children they serve.

2001 – 2003 **Radcliffe Institute for Advanced Studies**, Cambridge, MA

Senior Member of Research Team for National Study of Alternative Staffing Services

Co-author of report surveying alternative staffing organizations in the United States that place disadvantaged workers in temporary employment positions. Conducted in-depth interviews and site visits for a sample of 25 alternative staffing organizations. (Funder: Ford Foundation).

2001-2003 **AARP Foundation and Arizona Disability Law Institute,** Washington, DC and Tucson, AZ

Expert Witness for Ball v. Biedess

Contributed expert reporting and testimony regarding the status of the paraprofessional healthcare workforce in Arizona caring for low-income elderly and disabled persons who receive long-term home care though Arizona's Medicaid Managed Long-Term Care Program.

1999 - 2002 **Director, Food Security Institute, Center on Hunger and Poverty, Heller Graduate School, Brandeis University,** Waltham, MA

Established a new organization within the Center on Hunger and Poverty that: (i) works with policy makers, the public, and the media to promote greater understanding of hunger in America and its relationship to federal and state policies and programs; (ii) conducts analyses of food insecurity among at-risk populations; (iii) serves as a national clearinghouse for hunger and food insecurity studies; and (iv) provides technical assistance to state and local organizations conducting household food security surveys.

Received appointment as Senior Research Scientist to the Faculty of the Heller School of Social Policy and Management.

1998-2001 **Public Private Ventures,** Philadelphia and New York

Senior Member of Evaluation Team assigned to the Sectoral Employment Initiative of the Charles Stewart Mott Foundation.

Evaluated and provided technical assistance to three of ten Mott-supported sectoral employment initiative sites—a family childcare provider association in Providence, RI; a worker-owned paraprofessional health care staffing company in Manchester, NH; and a clerical temp agency and membership organization in Silicon Valley, CA. (Funder: Mott Foundation).

1998-1999 **Wellesley College Center for Research on Women**, Wellesley, MA

Principal Investigator, Project on Mental Health and Mental Retardation Service Delivery Systems in Massachusetts.

Conducted an independent study of service delivery systems in Massachusetts that meet the needs of persons with mental retardation and severe mental illness. Wrote report that highlights leading issues and trends. (Funder: Service Employees International Union Local 509).

1997-1998 **Collaborative Foundation-Sponsored Learning Exchange on Temporary Work and Disadvantaged Job Seekers**, Chicago, IL

Lead Consultant and Conference Organizer for Learning Exchange.

Planned, organized, and facilitated a conference in Chicago (March 1998) on the roles of non-profit and alternative proprietary staffing ventures in connecting disadvantaged job seekers with temporary employment. (Funders: ARCO Foundation, James Irvine Foundation, and Rocke-feller Foundation).

1996-1997 **Center for Community Change**, Washington, DC

Principal Investigator, Project on Nonprofit Temporary Employment Businesses.

Conducted case studies of six nonprofit organizations that help disadvan-taged workers gain access to employment through temporary work. Wrote report that presents the case studies and elucidates lessons learned. (Funders: US Department of Housing and Urban Development, Pew Charitable Trusts, and Center for Community Change).

1996-1997 **The Hillcrest Group**, Cambridge, MA

Research Director, Project on Issues Facing Disadvantaged Children and Youth in the US.

Principal author of major report (280 pages) presenting research findings on disadvantaged children and youth. Conducted research on: (i) six major program and policy areas affecting disadvantaged children and youth (family economic security, health, early childhood education and child care, education, youth development, and children in crisis), (ii) the status of needy children using the latest statistical data, and (iii) the structure and dynamics of efforts to address needy children. Developed a core list of thought and action leaders on disadvantaged children and conducted interviews.

1994-1996 **Wellesley College Center for Research on Women**, Wellesley, MA

Principal Investigator, Women and Poverty Research Project.

Completed major research report (160 pages) that reviews current social science literature on women's poverty and welfare reform in the United States, presents a statistical profile of women's poverty, analyzes the history of America's welfare system, and develops a conceptual framework for understanding women's poverty.

1993-1996 **Jobs for the Future**, Boston, MA

Principal Investigator, Employment Brokering Project.

Investigated innovative employment brokering ventures around the country for economically disadvantaged job seekers. Identified representatives from industry, community-based organizations, foundations, and local government to be brought together to discuss employment brokering for hard-to-place groups. Produced conference discussion paper and final report. (Funder: Annie E. Casey Foundation).

Principal Investigator, Temporary Help Services Project.

Prepared research study identifying and analyzing skills assessment, training, and job placement practices in the temporary help industry, including case study of Manpower, Inc., with implications for public-sector labor market functions and policies. (Funder: Aspen Institute).

1992-1993 **Dudley Street Neighborhood Initiative and Project Hope,** Roxbury and Dorchester, MA

Market Research Consultant

Conducted market study for proposed inner-city furniture factory and related employment training program. Estimated potential demand for proposed furniture products; analyzed competition; and developed preliminary marketing strategy recommendations. Data and information obtained by designing and fielding a survey questionnaire to a wide range of institutions and agencies active in the market sectors selected for analysis.

PUBLICATIONS, RESEARCH REPORTS, AND PAPERS

I. Future of Gas

Leaked and Combusted: Strategies for reducing the hidden costs of methane emissions and transitioning off gas, D. Seavey, Boston, MA: HEET, forthcoming February 2024.

Philadelphia's Gas Pipe Replacement Plan, D. Seavey, Boston, MA: HEET, March 2023.

Charting a Pathway to Maryland's Equitable Clean Energy Future: Electrification and Building Upgrades for Low-Income Residences, A. Gona, J. Barry, S. Miller, D. Seavey, C. Stix, Baltimore, Maryland: Earthjustice, Green & Healthy Homes Initiative, RMI, Sierra Club, January 2023.

"Spending billions fixing gas system makes no sense," D. Seavey, CommonWealth Magazine, April 26, 2022.

GSEP at the Six-Year Mark: A Review of the Massachusetts Gas System Enhancement Program, D. Seavey, Boston, MA: Gas Leaks Allies, October 2021.

II. Workforce Development for Workers in Health Care and Human Services

"Growing Home Care Industry Can Afford Basic Labor Protections for Workers," PHI FLSA Facts, No. 2, April 2015.

Declaration of Dr. Dorie Seavey in Home Care Association of America, et al v. David Weil, et al, No. 1:14-cv-00967, U.S. District Court of the District of Columbia, 5 January 2015.

Brief for the U.S. Court Supreme Court as Amicus Curiae The Paraprofessional Healthcare Institute (PHI) In Support of Respondents, Pamela Harris, et al., v. Pat Quinn, Governor of Illinois, et. al., No. 11-681, 30 December 2013 (provided research for the brief and detailed review and comments).

"*Now Is the Time to Boost Support for Paid Caregivers,*" D. Seavey: AARP Bulletin, December 2013.

Value the Care! No. 7 Minimum wage and overtime for home care workers, D. Seavey & Abby Marquand, NY: Paraprofessional Healthcare Institute, January 2013.

The PAS Workforce and Informal Caregivers, D. Seavey, Research Brief Prepared for the PAS Center for Personal Assistance Services, September 2012.

Private-Duty Industry Association Studies of DOL's Proposal to Revise the FLSA Companionship Exemption: What Do They Tell Us? D. Seavey, Bronx, NY: Paraprofessional Healthcare Institute, March 2012.

Can Home Care Companies Manage Overtime Hours? Three Successful Models, D. Seavey and Alexandra Olins, Bronx, NY: Paraprofessional Healthcare Institute, February 2012.

Caring in America, D. Seavey with A. Marquand, Bronx, NY: Paraprofessional Healthcare Institute, December 2011 (book-length manuscript).

Building Infrastructure To Support CLASS: The Potential of Matching Service Registries, CLASS Technical Assistance Brief Series, No. 16, D. Seavey and A. Marquand, The SCAN Foundation, Spring 2011.

Caregivers on the Frontline: Challenges and Opportunities for Building the Direct-Care Workforce, Generations – The Journal of the American Society on Aging, D. Seavey, Winter 2010-2011, Vol. 34, No. 4, pp. 27-35.

Expert Report for Ball v. Rodgers on Arizona's Policies to Address HCBS Service Gaps under the ALTCS Program (AZ Long Term Care Services), D. Seavey, September 2010.

The 2007 National Survey of State Initiatives on the Direct-Care Workforce: Key Findings, PHI and the Direct Care Workers Association of North Carolina, December 2009.

Suggested Revisions to 2007 North American Industrial Classification System (NAICS) Related to the Health Care and Social Assistance Sector, D. Seavey, Submitted to the Office of Management and Budget, OMB-2009-0001-0001, April 7, 2009.

The Need for Monitoring the Long-Term Care Direct Service Workforce & Recommendations for Data Collection, D. Seavey and S. Edelstein, National White Paper prepared for the National Direct Service Workforce Resource Center with funding from the Centers for Medicare and Medicaid Services, Washington, DC: DSW-RC, February 2009.

Suggested Revisions to 2000 Standard Occupational Classification (SOC) Related to Direct-Care Job Titles, Submitted to the Office of Management and Budget, OMB-2008-0010-0001, July 21, 2008.

"A Workforce Perspective on Caregiving," D. Seavey, in Family Caregiving: State of the Art, Future Trends, Report from a National Conference, San Francisco, CA: Family Caregiver Alliance, 2007, pp. 44-48.

Reimbursement Practices and Issues in Vermont's Long-Term Care Programs, D. Seavey and H. Turnham, Prepared for the Community of Vermont Elders, Bronx, NY: Paraprofessional Healthcare Institute, November 2006.

Paying for Quality Care: State and Local Strategies for Improving Wages and Benefits for Personal Care Assistants, D. Seavey and V. Salter, Washington, DC: AARP Public Policy Institute Policy Report #2006-18, October 2006.

Bridging the Gaps: State and Local Strategies for Ensuring Backup Personal Care Services, D. Seavey and V. Salter, Washington, DC: AARP Public Policy Institute Policy Report #2006-19, October 2006.

Addressing New York City's Care Gap: Aligning Workforce Policy to Support Home- and Community-Based Care, D. Seavey, S. Dawson and C. Rodat, Prepared for the New York City Workforce Investment Board, Bronx, NY: Paraprofessional Healthcare Institute, September 2006.

Engaging the Public Workforce Development System: Strategies for Investing in the Direct Care Workforce, D. Seavey, Washington, D.C.: IFAS/AAHSA, Better Jobs Better Care Issue Brief No. 6, January 2006.

Family Care and Paid Care: Separate Worlds or Common Ground? D. Seavey, Washington, DC: IFAS/AAHSA, Better Jobs Better Care Issue Brief No. 5, May 2005.

The Cost of Frontline Turnover in Long-Term Care, D. Seavey, Washington, DC: IFAS/AAHSA, Better Jobs Better Care Practice and Policy Report, October 2004.

Investing in Low-Wage Workers: Lessons From Family Child Care in Rhode Island, A. Roder and D. Seavey, New York, NY: Public Private Ventures, September 2006.

Direct-Care Health Workers: The Unnecessary Crisis in Long-Term Care, S.L. Dawson and R. Surpin (with D. Seavey, A. Van Kleunen, and M.A. Wilner), Aspen, CO: Domestic Strategy Group, The Aspen Institute, February 2001.

Health Care Workforce Issues in Massachusetts, B.W. Frank and S.L. Dawson (with D. Seavey, A. Van Kleunen, and M.A. Wilner) Issue Brief No. 9, Massachusetts Health Policy Forum, Waltham, MA: Schneider Institute for Health Policy, Heller Graduate School, Brandeis University, June 2000.

Industry Study of Services for People with Mental Retardation and Severe Mental Illness in Massachusetts: The Client/Consumers, the Workforce, the Providers, and the State, Special Report CRW 21, D. Seavey, Wellesley, MA: Center for Research on Women, Wellesley College, March 1999.

III. Employment Brokering for Low-Wage Workers

The Impact of Marketing and Sales on Alternative Staffing, Final Summary Report to the C.S. Mott Foundation, F. Carré and D. Seavey, Boston, MA: Center for Social Policy at University of Massachusetts – Boston, January 2006.

Employment Brokering for Disadvantaged Job Seekers: Improving the Temp and Temp-to-Perm Job Experience and Enhancing Job Opportunities, Report of the National Study of Alternative Staffing Services to the Ford Foundation, F. Carré, J. Herranz, Jr., D. Seavey, C. Vickers, A. Aull, and R. Keegan, Cambridge, MA: Radcliffe Institute for Advanced Study, Harvard University, June 2003.

Site Visit Reports for the National Study of Alternative Staffing Services, F. Carré, J. Herranz, Jr., D. Seavey, C. Vickers, A. Aull, and R. Keegan, Cambridge, MA: Radcliffe Institute for Advanced Study, Harvard University, June 2003.

"Chrysalis--A Case Study," included as one of four US case studies in *Improving Low-Income Job Seeker's Employment Prospects*, R. Kazis, Boston, MA: Jobs for the Future, July 1999. [Prepared for UK/US Seminar on Labor Market Intermediaries, July 15-16, 1999, Ashridge, England.]

New Avenues into Jobs: Early Lessons from Nonprofit Temp Agencies and Employment Brokers, Washington, DC: Center for Community Change, March 1998.

Improving Employment Brokering and Expanding Employment Options for Economically Disadvantaged Job Seekers, Boston, MA: Jobs for the Future, October 1996.

Training, Placement, and Employment Brokering Options: A Review of Seven Programs and an Analysis of the Issues, Boston, MA: Jobs for the Future, June 1995.

Skills Assessment, Job Placement, & Training: What Can Be Learned from the Temporary Help/Staffing Industry? An Overview of the Industry and a Case Study of Manpower, Inc., D. Seavey and R. Kazis, Boston, MA: Jobs for the Future, July 1994.

III. Domestic Food Insecurity and Hunger

The Consequences of Hunger and Food Insecurity for Children: Evidence from Recent Scientific Studies, Waltham, MA: Food Security Institute, Center on Hunger and Poverty, Heller Graduate School, Brandeis University, June 2002.

"*Families who've lost welfare need help*," J.L. Brown and D. Seavey, Boston Globe Op-Ed, 10 June 2001.

Food Insecurity and Hunger Among Households Leaving Welfare in Massachusetts: A Review of Recent Findings from the MA Department of Transitional Assistance, Waltham, MA: Food Security Institute, Center on Hunger and Poverty, Heller Graduate School, Brandeis University, February 2001.

Introduction to *Hunger in the United States: A Summary of Recent Studies on Hunger and Emergency Food Demand*, A.F. Sullivan, Waltham, MA: Food Security Institute, Center on Hunger and Poverty, Heller Graduate School, Brandeis University, August 2000.

Paradox of Our Times: Hunger in a Strong Economy, S. Venner, A.F. Sullivan and D. Seavey, Medford, MA: Center on Hunger and Poverty, Tufts University, January 2000.

Household Food Security Summaries (Second Issue), D. Seavey and A.F. Sullivan, Waltham, MA: Food Security Institute, Center on Hunger and Poverty, Heller Graduate School, Brandeis University, August 2001.

Household Food Security Summaries (First Issue), D. Seavey and A.F. Sullivan, Medford, MA: Food Security Institute, Center on Hunger and Poverty, Tufts University, April 1999.

IV. Poverty and Welfare Reform

Issues Facing America's Neediest Children: A Situation Analysis, The Hillcrest Group with D. Seavey, Principal Author, Cambridge, MA: The Hillcrest Group, 1997 (book-length manuscript).

"Women and Welfare: Popular Conceptions vs. Facts," Appendix B in R. Albelda and C. Tilly, *Glass Ceilings and Bottomless Pits: Women's Work, Women's Poverty*, Boston: South End Press, 1997, pp. 189-199.

"Getting to the Big Picture: Anti-Welfare Fertility Politics in Context," D. Seavey and B. Miller, *Society,* Vol. 33, No. 5, July/August 1996, pp. 33-36.

Back to Basics: Women's Poverty and Welfare Reform, Special Report CRW13, Wellesley, MA: Wellesley College Center for Research on Women, 1996 (book-length manuscript).

V. Community-Based Enterprise Development

Dudley Street Furniture Factory Market Study, Roxbury, MA: Dudley Street Neighborhood Initiative and Project Hope, November 1992.

Training Program Considerations for Proposed Dudley Street Furniture Factory, Technical Report, Roxbury, MA: Dudley Street Neighborhood Initiative and Project Hope, November 1992.

SELECTED PROFESSIONAL ACTIVITIES INCLUDING TESTIMONY

Comments before the MA Department of Utilities, DPU Docket No. 20-80 Public Hearing on Future of Gas Investigation, May 5, 2022.

Testimony before MA Senate Committee on Global Warming and Climate Change, Hearing on the "The Future of Gas," April 4, 2022.

"Investing Billions in Leaky Gas Infrastructure is a REALLY Bad Idea," *The Energy Nerd Show*, January 2022.

Testimony before the MA Joint Committee on Telecommunication, Utilities, and Energy, Hearing on H.3298 / S.148: An Act relative to the future of heat in the Commonwealth," November 2, 2021.

Various presentations on the MA Gas System Enhancement Program (GSEP) to: Trustees of the Reservation, Multi-Town Gas Leaks Initiative, Mothers Out Front, King's Chapel Environmental Action Initiative, 2021 and 2022.

"The State Data Center: A Resource for Direct-Care Workforce Monitoring," Webinar for the Centers for Medicare and Medicaid Services, March 27, 2013.

"PCA Training Standards: Findings from a 50-State Study," National Webinar hosted by the National Center for Personal Assistance Services, January 22, 2013.

"PCA Training Standards: Findings from a 50-State Study," Presentation at a Capitol Hill Briefing sponsored by U.S. Senate Special Committee on Aging and U.S. Senate Committee on HELP, Washington, D.C., September 24, 2012.

U.S. Home Care Workforce: Basic Facts, Presentation to the Leadership Council of Aging Organizations, Washington, D.C., February 1, 2012.

"Training Developments for Personal Care Aides," Presentation at Symposium on Training & Services by Direct Care Workers, Gerontological Society of America, Annual Meeting, Boston, MA, November 19, 2011.

"America's Challenge: Building a Better Direct-Care Workforce," Presentation at a Capitol Hill Briefing sponsored by the Eldercare Workforce Alliance, May 25, 2011, Washington, DC.

"Direct-Care Workers and Transitional Care," Presentation to the American Health Care Journalism (AHCJ) Conference, April 16, 2011, Philadelphia, PA.

"The Massachusetts Direct-Care Workforce," Presentation at Legislative Briefing for the Joint Committee on Elder Affairs and the Joint Committee on Labor and Workforce Development, Massachusetts State House, May 5, 2010, Boston, MA.

Expert Report prepared at the request of plaintiffs' attorneys in Ball v. Rodgers (AZ Federal District Court), a class-action suit filed by the AZ Disability Law Institute and the AARP Foundation on behalf of AZ Medicaid recipients of home care services against the state Medicaid agency, September 2010.

"Improving the Direct-Care Workforce Through Better Wages & Benefits," IOM Symposium on Health Reform for an Aging America, March 12, 2009, Washington, DC.

"*The Direct Service Workforce in 2008,"* Keynote Address to the National DSW Symposium, May 8, 2008, Baltimore, Maryland.

"Expanding the "Registry" Concept: Creating Access to Care for Consumers and Employment for Care Workers," Webinar Presentation to U.S. Department of Labor Aging and Disability Resource Center (ADRDC) grantees, January 3, 2008.

Testimony before the Subcommittee on Workforce Protections, Committee on Education and Labor, U.S. House of Representatives, Hearing on "H.R. 3582: the Fair Home Health Care Act," October 25, 2007.

"A Workforce Perspective on Caregiving," Presentation at the Joint Conference of American Society on Aging and National Council on Aging, March 6, 2007, Chicago, IL.

"Strengthening New Hampshire's Direct-Care Workforce," Keynote Presentation for AARP New Hampshire and the New Hampshire Community Loan Fund, February 1, 2007.

"Engaging the Workforce System with Long-Term Care," Webinar Presentation to DOL's forum on "Building a 21st Century Long-Term Care Workforce," October 23, 2006.

"Paying for Quality Care," Presentation to the 22nd National Home & Community Based Services Conference, October 4, 2006, Minneapolis, MN.

"Homecare Provider Economics and the Impact of Workforce Instability," Presentation to the Homecare Association of New York State, May 23-24, 2005, Saratoga, NY.

"Massachusetts' Care Gap: The Growing Crisis in Recruiting and Retaining the Direct-Care Workforce" Keynote speaker at Human Services Roundtable, Massachusetts State House, October 2004.

Expert Witness in Ball v. Biedess (AZ Federal District Court), a class-action suit filed by the AZ Disability Law Institute and the AARP Foundation on behalf of AZ Medicaid recipients of home care services against the state Medicaid agency, October 2003.

"Hunger and Food Insecurity: Building the Public Health Case," Power Point Presentation to the Annual Convention of Arizona Food Banks, Phoenix, AZ, April 2002.

"Food Security among Households Leaving Welfare in Massachusetts," Paper presented to Academics Working Group on Poverty, Radcliffe Public Policy Institute, Cambridge, MA, February 2001.

US Department of Agriculture Food Security Measurement Expert Panel, Washington, DC, September 2000.

Working Group on Assessing Food Security in Vulnerable Populations at USDA Community Food Security Assessment Conference, Washington, DC, June 1999.

"The Status of Direct Care Workers in Massachusetts," Keynote Presentation at Legislative Briefing on Direct Care Workers, MA State House, Beacon Hill, April 1999.

"Reflections on Directions in Welfare and Poverty Research," Paper delivered to session of Eastern Economics Association, Boston, MA, March 1996.

COMMUNITY ACTIVITIES

Member, Vermont Community Geothermal Alliance and VT Energy Action Network (Networked Geothermal Action Team)

Treasurer, King's Chapel, Boston, MA (2021-2023)

Member, Finance Committee, Town of Provincetown, MA (2019-2021)

RI Investigation into the Future of the Regulated Gas Distribution Business

Technical Analysis Draft Results

February 13, 2024

DRAFT / PRELIMINARY

Energy+Environmental Economics

Content

Introduction to Technical Analysis

Energy+Environmental Economics

E3 modeled six scenarios for the Technical Analysis that **present distinct pathways to achieving RI's Act on Climate**

Variation in scenarios is primarily captured in the type of heating sector (residential, commercial & industrial) transformation achieved, keeping the level of action across other sectors similar across scenarios.

Scenario	Scenario focus	Research question
High Electrification	Emissions targets reached primarily through electrification.	What is the impact of pursuing a full-electrification decarbonization pathway that transitions Rhode Island away from gas infrastructure?
Hybrid Electrification + Delivered Fuels Backup	Emissions targets reached through combination of electrification and delivered fuels used as backup.	What is the impact of hybrid electrification (using backup heat in winter periods) on the energy system? What is the net benefit of avoiding gas infrastructure/decommissioning?
Hybrid Electrification + Gas Backup	Emissions targets reached through combination of electrification and gas used as backup.	What is the impact of hybrid electrification (using backup heat in winter periods) on the energy system? How can existing gas infrastructure be leveraged to reduce electric sector build outs?
Staged Electrification	Staged transition starting with a ramp up of hybrid heat pump conversion in the near-term (both gas and delivered fuels).	How can Rhode Island leverage existing infrastructure and mitigate customer impacts in the near-term, while allowing for a managed transition and achieving long-term electrification?
Alternative Heat Infrastructure	Decarbonization driven by a mix of networked geothermal where possible, all-electric heating, and hybrid heating.	How can highly-efficient heating systems (e.g., network geothermal) support decarbonization in Rhode Island? What is their net impact? Can they provide an alternative to gas investments?
Continued Use of Gas	Decarbonization achieved using a mix of electrification and supply of low-carbon gas.	How can existing gas infrastructure support decarbonization? What is the effect of and potential limit to low-carbon fuels such as biomethane and hydrogen?

The scenarios vary the level of electrification and low-carbon fuels while keeping other factors constant

Parameters refer to the 2050 "end-state" of Net-Zero.

	Efficiency & Weatherization	Building/ Industry Electrification	Zero Emissions Vehicles*	Clean Electricity	Low-Carbon Fuels**	Ag, Waste & Natural Sinks*	Negative Emissions Technologies*
High Electrification	Very High	Very High	Very High	Very High	Low	Medium	Low
Hybrid Electrification + Delivered Fuels Backup	Very High	High	Very High	Very High	Medium	Medium	Low
Hybrid Electrification + Gas Backup	Very High	High	Very High	Very High	Medium	Medium	Low
Staged Electrification	Very High	Very High	Very High	Very High	Low	Medium	Low
Alternative Heat Infrastructure	Very High	High	Very High	Very High	Medium	Medium	Low
Continued Use of Gas	Very High	Medium	Very High	Very High	High	Medium	Low

* The transition of the Transportation and Ag & Waste sectors will be applied similarly in all scenarios to allow better comparisons. In addition, the scenarios will apply similar levels of Negative Emissions Technologies.

** "High" levels of low-carbon fuels indicates high consumption of techno-economically available low carbon fuels. All scenarios will have a significant reduction in fossil fuel throughput resulting in a significantly reduced need for low-carbon fuels by 2050.

The Technical Analysis includes several sensitivities to reflect the uncertainty inherent to scenario modeling

Managed vs. unmanaged transition

- Explores the impact of targeted electrification and gas decommissioning on gas system investments, rates, and societal cost.
- Modeled as a sensitivity onto gas sector costs (avoidance of leak-prone pipe replacement).
- Results in insights regarding potential level of cost savings on the gas system that can be achieved per scenario if electrification takes place through a managed approach.
- Modeled for all scenarios.

Level of efficiency

- Explores the impact of higher levels of cold climate heat pumps performance, reflecting a worldview with accelerated technology improvements.
- Modeled as a sensitivity onto building sector energy demands and capacity needs.
- Results in insights regarding the potential electric sector impacts resulting from the adoption of higher efficiency technology.
- Modeled for the High Electrification scenario only.

Pace of ACCII/ACT

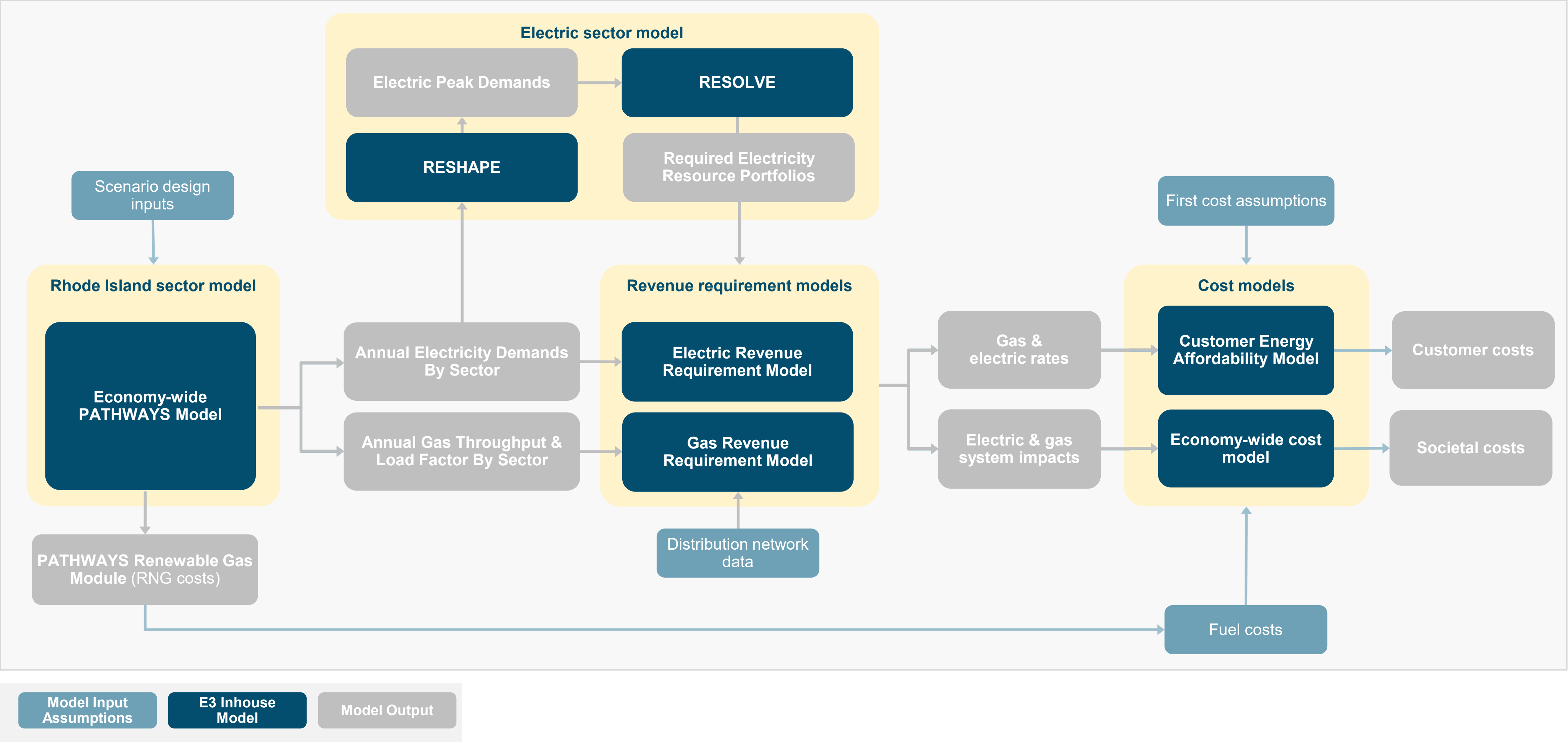
- Explores the impact of lower levels of transportation electrification, e.g., slower pace than Advanced Clean Cars II.
- Modeled as a sensitivity onto transportation sector technology adoption levels.
- Results in insights regarding the potential impacts to other sectors resulting from the slower adoption of electric vehicles.
- Modeled for the High Electrification scenario only.

Impact of GWP and biofuel emissions

- Explores the impact of different GHG accounting frameworks, including higher Global Warming Potentials, upstream fuel emissions and zero emissions benefit from biofuels.
- Modeled as a sensitivity onto fuel emissions factors.
- Results in insights regarding the potential risks associated with higher reliance on biofuels
- Modeled for all scenarios.

In addition, the Technical Analysis includes low/high sensitivities applied to the assessment of economy-wide costs for: heat pumps, networked geothermal systems, renewable gases, and the costs of RECs.

E3's modeling framework analyzes impact of scenarios on RI, RI's gas & electric system, and RI residents



The Technical Analysis addresses key questions raised in the Docket; some questions require follow up

Questions raised in the Docket	Addressed through Technical Analysis		Follow up
1. What infrastructure and non-infrastructure options exist for reducing emissions from the gas system?	✓	Decarbonization Pathways Technical Results - Technology adoption levels, impact on gas/electric system	
2. What scenarios for (all) sector-level emissions will allow the state to meet the emissions reduction mandates of the Act?	✓	Decarbonization Pathways Technical Results - Emissions	
3. What outputs of the Technical Analysis will inform the Policy Development phase?	✓	Decarbonization Pathways Assessment & Implications	
4. What assumptions and inputs are critical to the outputs of the Technical Analysis?	✓	Decarbonization Pathways Technical Results – Sensitivity analyses	
5. What statutory, regulatory, or stakeholder requirements and/or preferences exist that represent constraints on possible pathways for reducing gas system emissions consistent with the Act?			To be discussed in Policy Development phase
6. What final scenarios, including alternative testing and sensitivity ranges, should be included in RIE's scope for the Technical Analysis the company will perform?	✓	Decarbonization Pathways Scenario design	

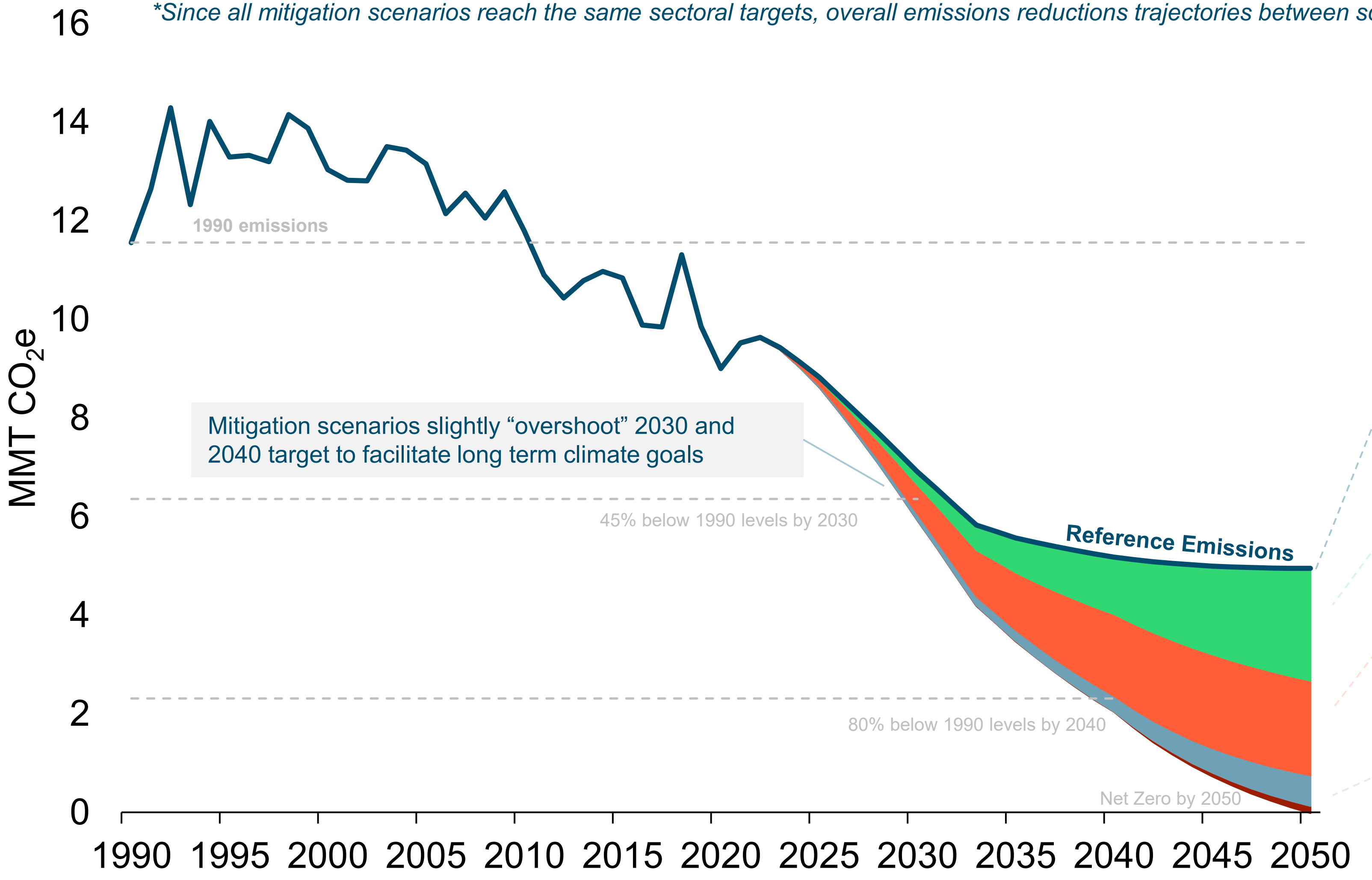
Summary and Key Findings

Energy+Environmental Economics

Emissions: All mitigation scenarios achieve the Act on Climate; large focus on buildings and transportation required

Rhode Island Statewide Emissions Reductions – Mitigation Scenarios*

*Since all mitigation scenarios reach the same sectoral targets, overall emissions reductions trajectories between scenarios are similar.



Reference scenario emissions:
57% emissions reduction by 2050.

The Reference scenario falls short of achieving the AoC Net Zero by 2050 target

Transportation sector:
- Growth in EV penetration for LDV and MHDV consistent with Advanced Clean Cars II and Advanced Clean Trucks

Building sector:
- All-electric and hybrid ASHP adoption; key variations by scenario
- Networked geothermal adoption in High Electrification and Alt. Heat Infrastructure
- Variations in renewable fuels blending

Industrial sector:
- The industrial sector decarbonizes through a range of electrification and fuel-switching measures, as feasible

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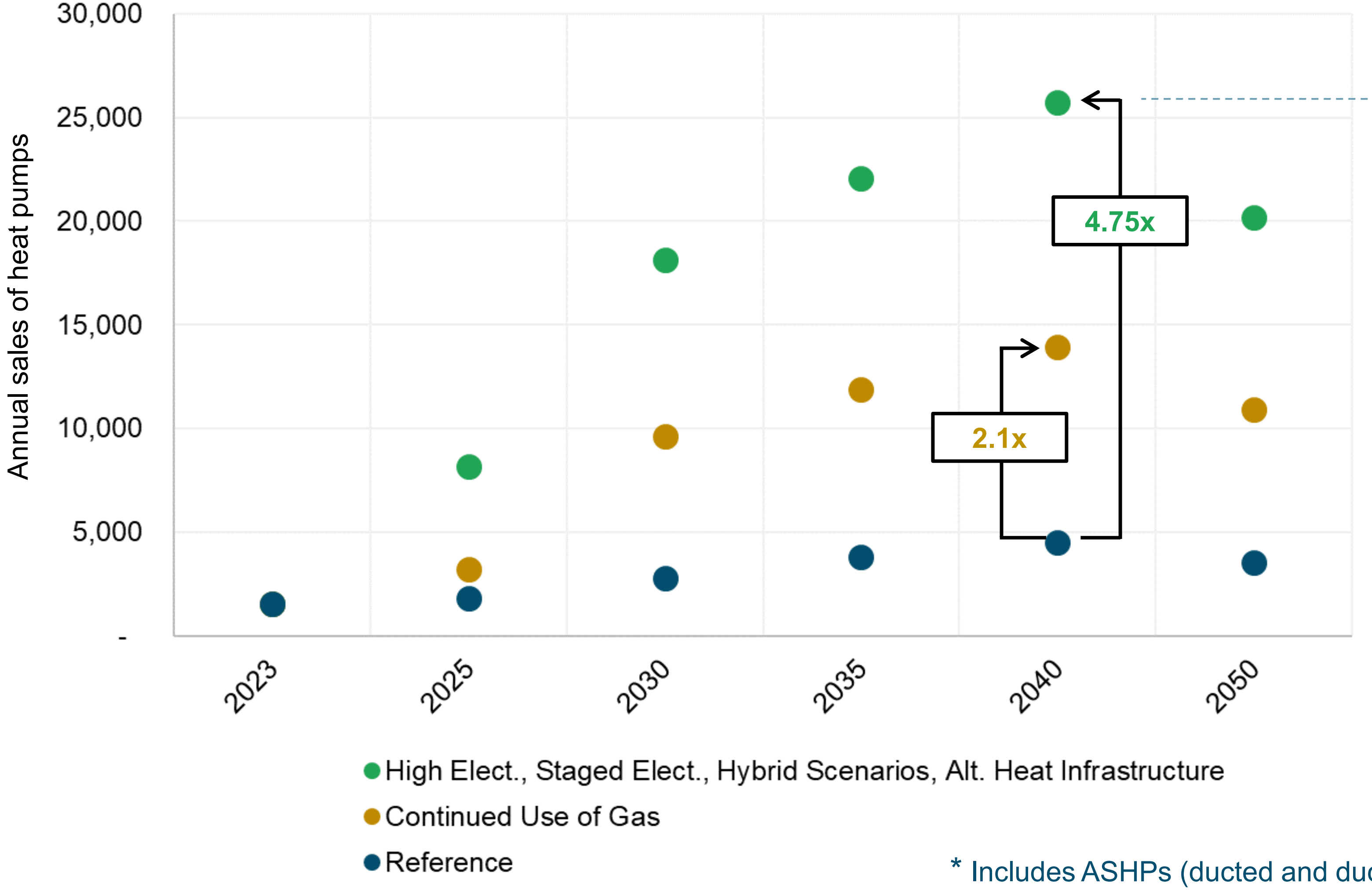
Emissions reductions from sector: Transportation | Buildings | Industry | Gas distribution | Sinks & NETs

Technology adoption: Annual adoption of decarbonization technologies needs to increase significantly to support AoC

Annual Sales of Heat Pumps* in the Residential Sector



Sales of heat pumps are expected to peak in 2040 in order to reach emissions reduction levels by 2050.

In scenarios focused on higher levels of electrification, annual heat pump sales exceed 25,000 devices in 2040, **nearly five times** higher compared to the reference scenario and approximately **10 times** higher than today's adoption levels.

The Continued Use of Gas scenario primarily relies on adoption of **hybrid heat pumps** and high-efficiency gas furnaces (the latter not included in the chart).

The Reference Scenario sees modest increase in heat pump adoption levels, **not reaching the AoC targets**.

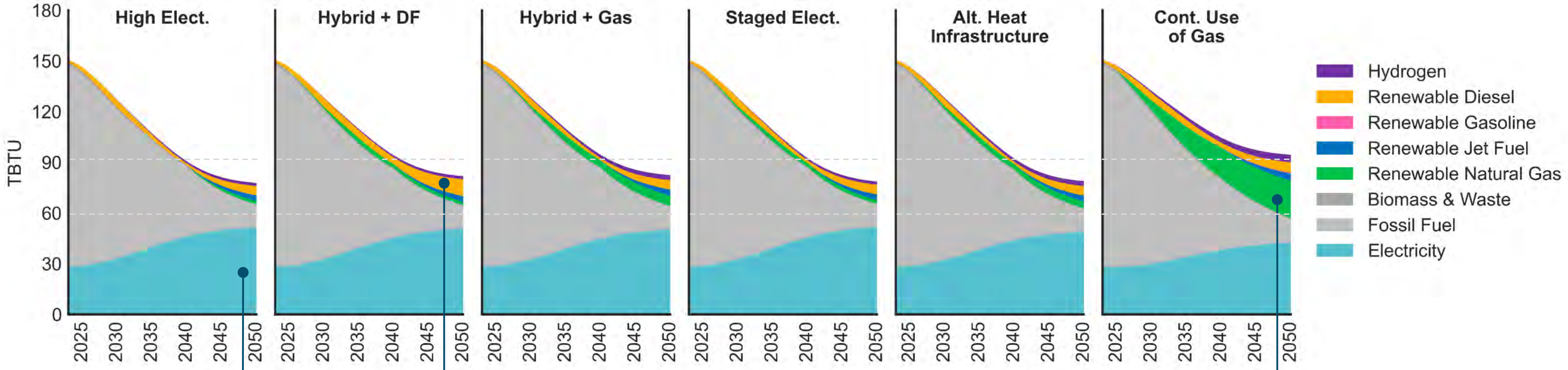
* Includes ASHPs (ducted and ductless), hybrid ASHPs, GSHPs, and networked geothermal

Fuels: By 2050, 40-60% of final energy demand is served by electricity while the need for renewable fuels increases

Across scenarios, **some level of renewable fuel blending** is needed to meet the 2050 emissions targets.

Scenarios with lower levels of electrification see higher renewable fuel blending to comply with AoC goals.

Change in economy-wide final energy demand across scenarios: 2023 - 2050



Lowest levels of renewable fuels

Highest levels of renewable diesel due to hybrid + DF HPs

Highest levels renewable natural gas and hydrogen

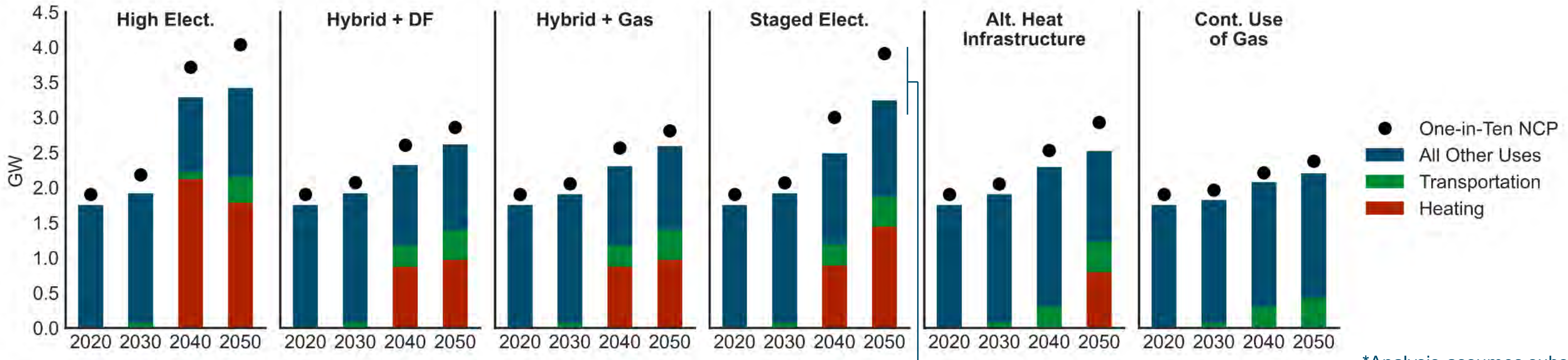
All scenarios comply with the Biodiesel Heating Oil Act of 2013, requiring 20% blend in 2025 and 50% blend in 2030

All scenarios rely on renewable fuels to meet emissions targets; lower electrification scenarios require higher levels.

Electric system: Most scenarios switch to a winter peaking system; scenarios with backup heat reduce electric impacts

Scenarios with high adoption of heat pumps switch to winter peaking in the 2030s. **Median peak demand doubles in the High Electrification scenario** – this effect is substantially mitigated in the hybrid scenarios that see a +/- 1 GW reduction in median peaks.

Post-Flexibility* Median Peak Loads by Contribution and 1-in-10 Total Noncoincident Peak (GW)



Scenarios with high reliance on either whole-home or hybrid HPs become winter peaking in the 2030s.

Peak loads in scenarios with high reliance on whole-home HPs are more sensitive to changes in weather. The High and Staged Electrification scenarios' 1-in-10 peaks grow more quickly than the Hybrid scenarios.

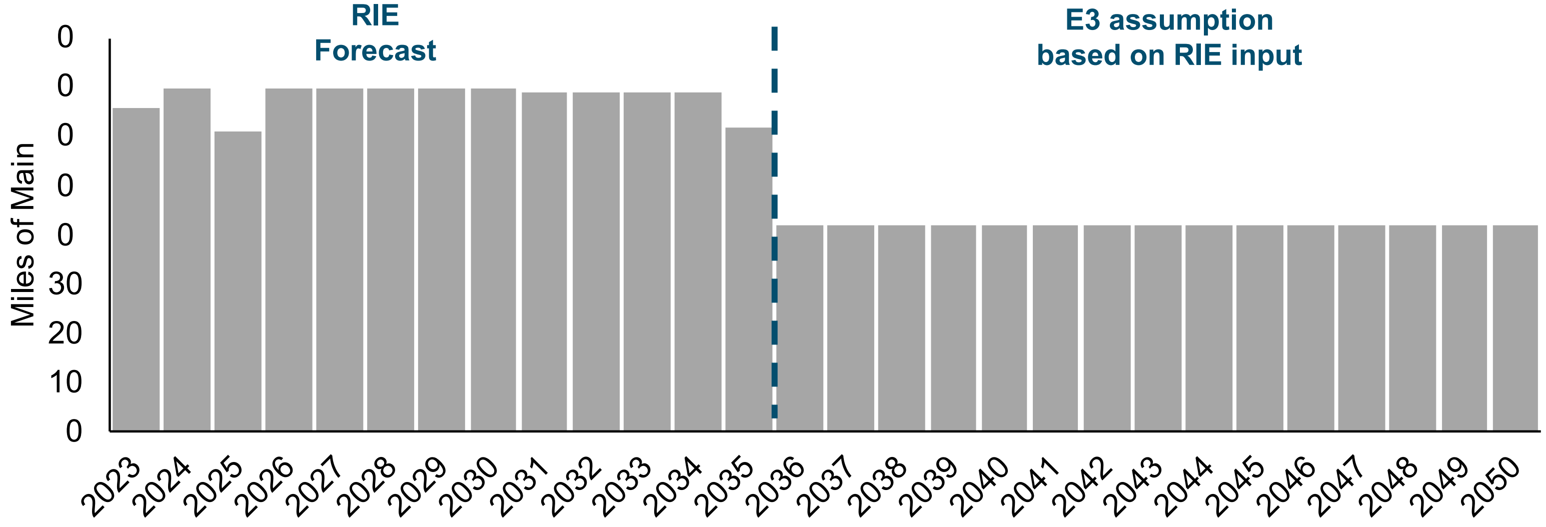
Scenarios with fewer ASHPs transition to winter peaking later or remain summer peaking.

*Analysis assumes substantial levels of load flexibility that allows peak contributions for several categories to shift load to different hours of the day. Assumptions include 50% LDV flexibility, 25% water heating flexibility, 5% space heating flexibility.

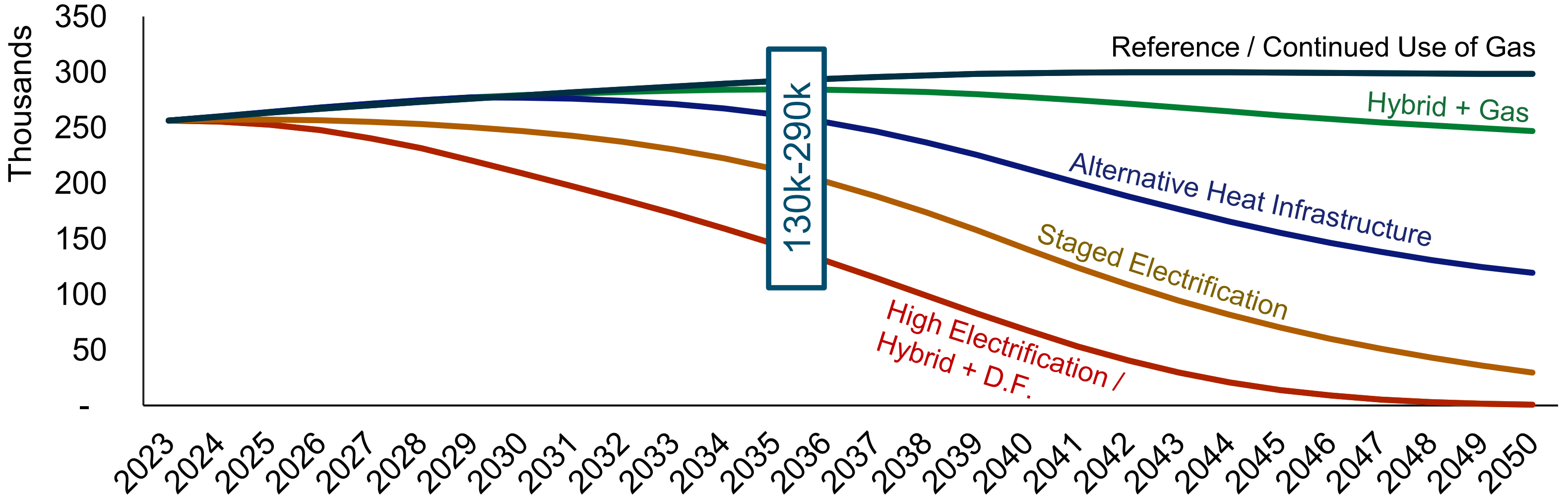
Gas system: In most scenarios, pipeline replacements driven by ISR will serve fewer customers over time

CLF-1-3

Replacement Miles (Mains)



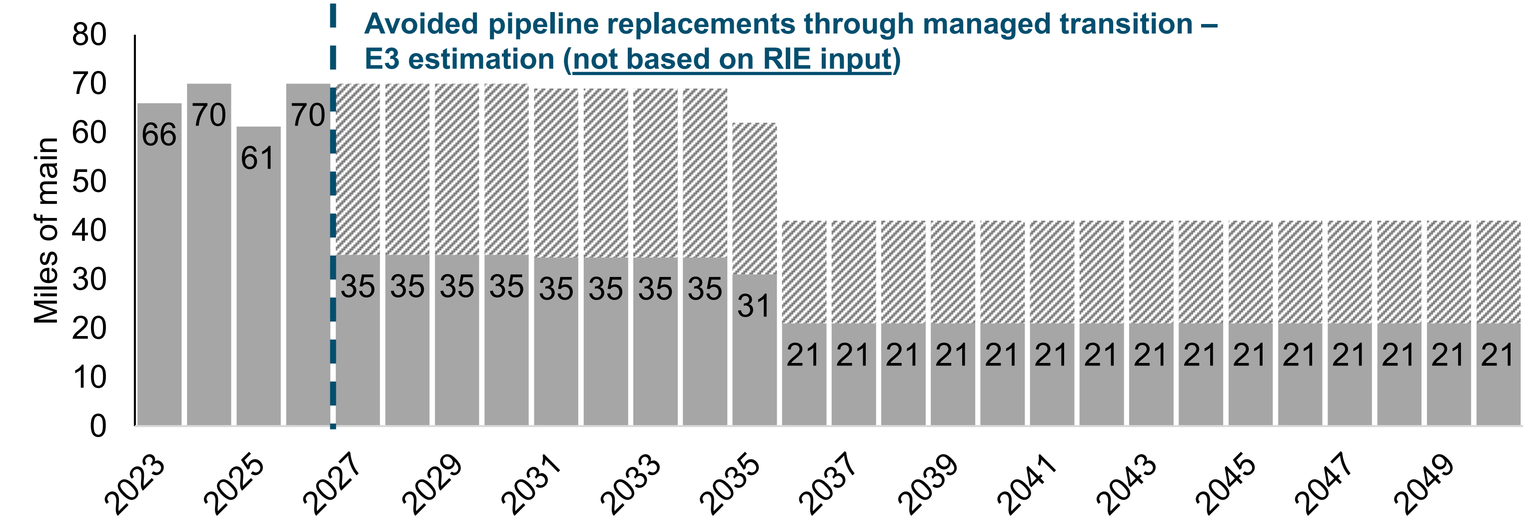
Customers with a gas connection



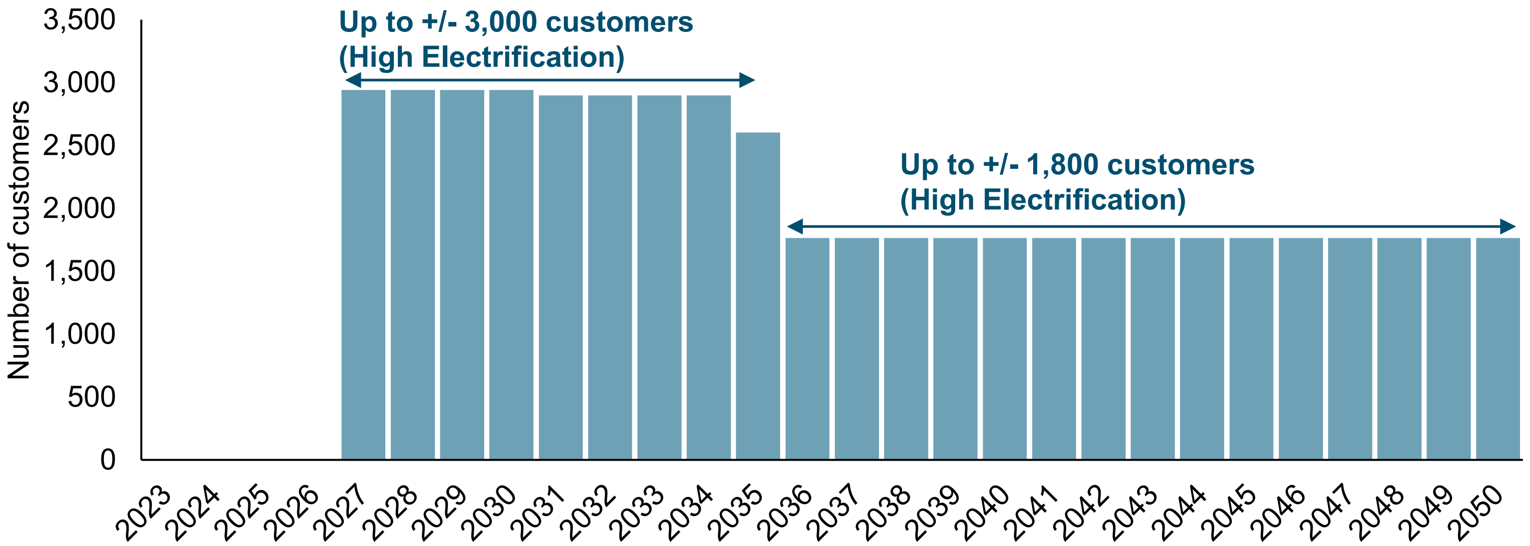
- The Infrastructure, Safety & Reliability (ISR) Plan ensures safe and reliable service of gas in the next decade, with a strong focus on **replacement of Leak Prone Pipe (LPP)** infrastructure.
- The ISR program is expected to replace up to 900 miles of pipe in the next decade, reaching **completion in 2035.** Post-2035, RIE expects to continue to replace (plastic) mains.
- In 4 out of 6 mitigation scenarios, electrification drives a reduction of gas customers. The High Electrification and Hybrid Delivered Fuels Backup scenarios have approximately 130,000 customers remaining by the end of the ISR program, **a reduction of +/-50% compared to today**.

Gas system: A managed transition may avoid replacements, but requires significant levels of targeted electrification

Replacement Miles (Mains)



Required targeted electrification customers

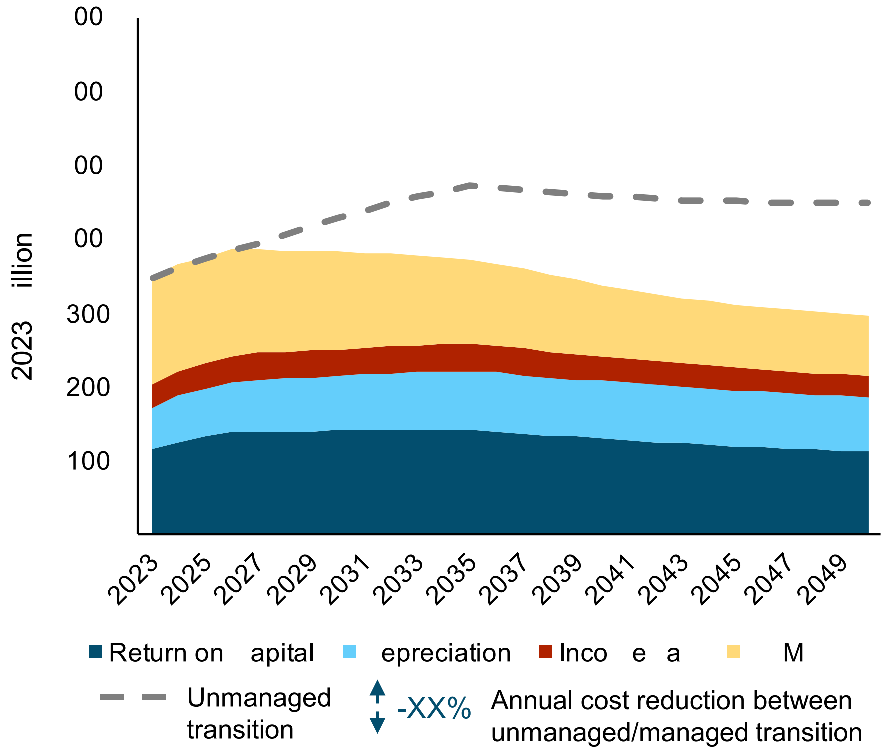


- In a managed transition, investments and incentives will be **geographically focused** to allow parts of the gas system to be decommissioned.
- To retire a gas pipeline, it must be considered ***hydraulically feasible,*** meaning the gas system maintains gas flow and the minimum allowable pressure.
- For the purpose of this study, E3 assumed that up to 50% of pipeline replacements may be avoidable in a managed transition***; this assumption is not based on input from RIE*** and needs significant additional study.
- If 50% of pipeline replacements are avoidable, up to 3,000 customers per year need to electrify their heating system in a targeted manner, with implications for customer choice.

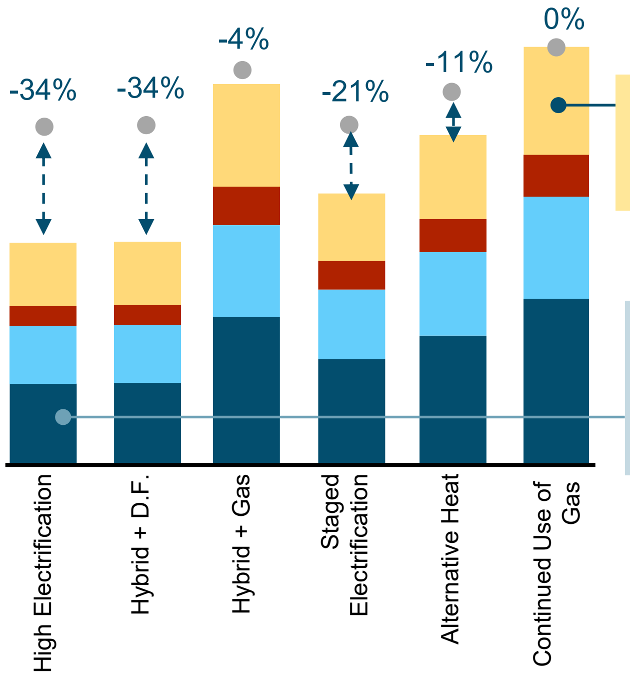
Gas system: If a managed transition is achieved, substantial gas system costs can be avoided in the long term

A managed transition could reduce the costs of the gas system by nearly 35%, or approximately $150 mln/year compared to an unmanaged transition by 2050, primarily in scenarios that transition away from the gas system in the near term (High Electrification, Hybrid + Delivered Fuels, Staged Electrification).

RIE Gas Revenue Requirement (RR) in the High Electrification scenario (managed)



2050 Mitigation Scenarios (unmanaged vs. managed)



Higher O&M costs in the Continued use of Gas and Hybrid+Gas scenarios that require full maintenance of the gas system in the long term.

Scenarios that allow for a managed transition see a +/-50% reduction in return on capital compared to scenarios that require full maintenance of the gas system in the long term.

Implications of scenarios can be viewed across multiple evaluation criteria to assess risks, benefits and challenges

Scenarios see different levels of benefits, risks and challenges across multiple evaluation criteria. The matrix below provides a first step in assessing the implications of scenarios across the evaluation criteria discussed with the Stakeholder Committee.

Evaluation Criteria	Key Metric		Detail on slide	High Electrification	Hybrid + Delivered Fuels Backup	Hybrid + Gas Backup	Staged Electrification	Alternative Heat Infrastructure	Continued Use of Gas
Economy-wide Costs	Cumulative NPV in $bln*		62-65	$16-20	$15-20	$14-19	$15-19	$17-23	$16-26
Customer choice	Number of targeted electrification customers in 2035	*Unmanaged*	46-48. 66	0	0	0	0	0	0
		Managed	46-48. 66	3,000	3,000	0	1,200	700	0
Long-term affordability	2050 monthly total cost of ownership for migrating customer		67-68	+/- $800	+/- $800	+/- $800	+/- $800	+/- $900	+/- $800
Cost shifting to non-migrating customers	2050 monthly total cost of ownership for non-migrating customer		67-68	> $3,000	> $3,000	+/- $1,500	> $3,000	> $3,000	+/- $800
Workforce Impacts	*Not yet assessed*								
Air Quality Impacts	Change in statewide fuel combustion between 2020-2050 (%)		69	-85%	-82%	-81%	-85%	-82%	-65%
Reliance on (out-of-state) fuels	Total annual volume of renewable fuel required by 2050 (Tbtu)		70-71	11	15	15	11	13	33
Technology Readiness	Likely range of Technology Readiness Levels required to achieve AoC**		72-73	8-10	7-10	7-10	8-10	6-10	6-11
Pace of Electric System Expansion	Total increase in distribution system capacity by 2035 (GW)		74	1.2	0.5	0.4	0.5	0.4	0.2

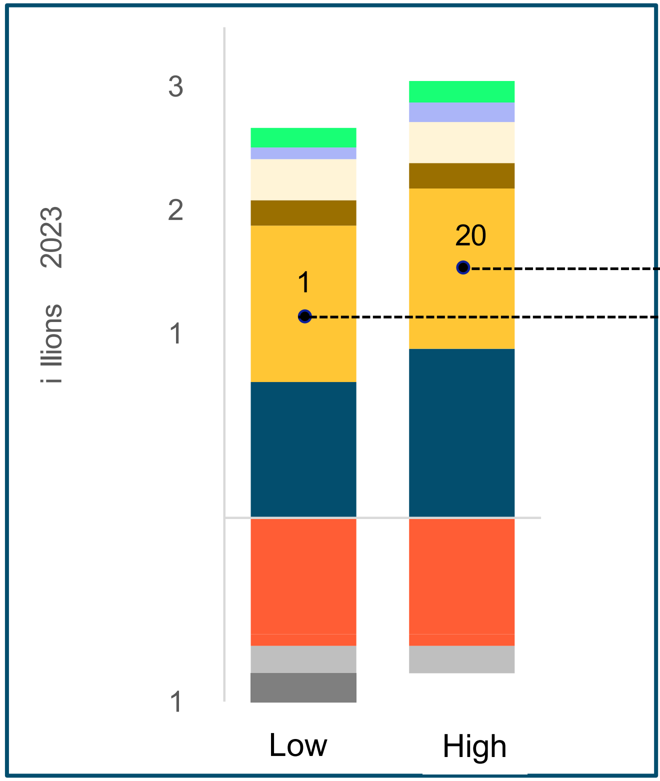
Initial considerations:

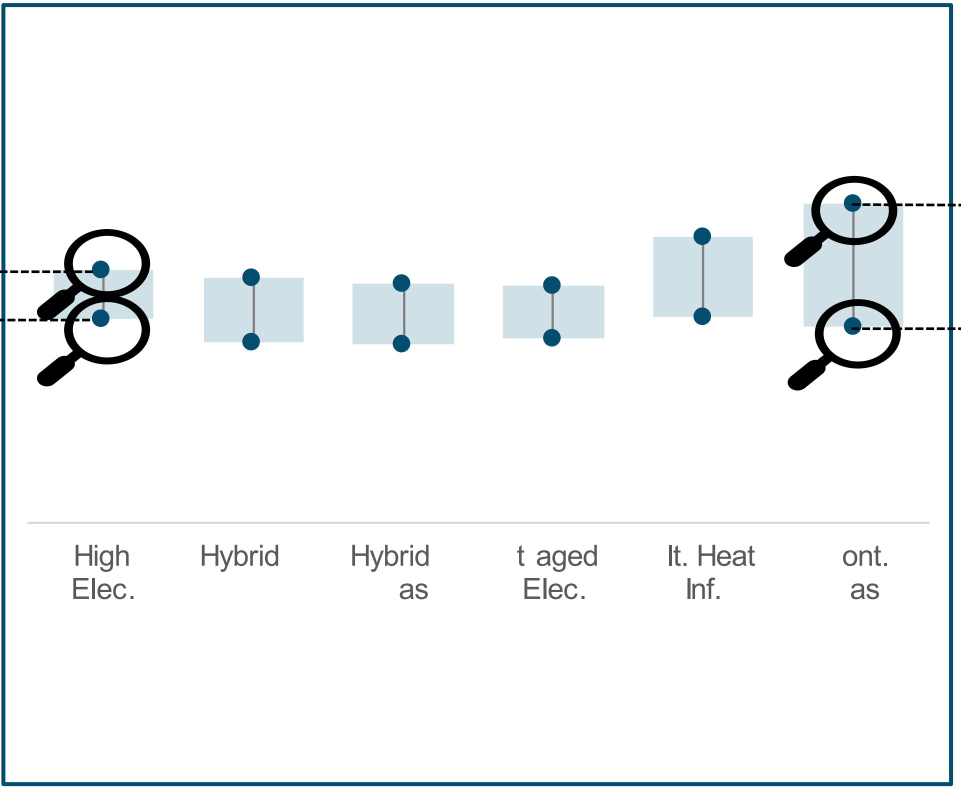
- Higher cost risk due to uncertainty in costs of large-scale renewable fuels
- High customer choice impacts if managed transition is achieved
- Relative affordability of heat pumps improves as delivery & supply costs of gas rise. Cost shift risk exist for scenarios with high levels of customer departure.
- Air quality benefits across scenarios, lower benefits for scenarios with more fuel combustion
- Higher risk of out-of-state fuel reliance for scenarios with higher levels of renewable fuels
- Reliance on networked geothermal or synthetic fuels to meet AoC targets
- Rapid electric capacity needs increase risk of system congestion

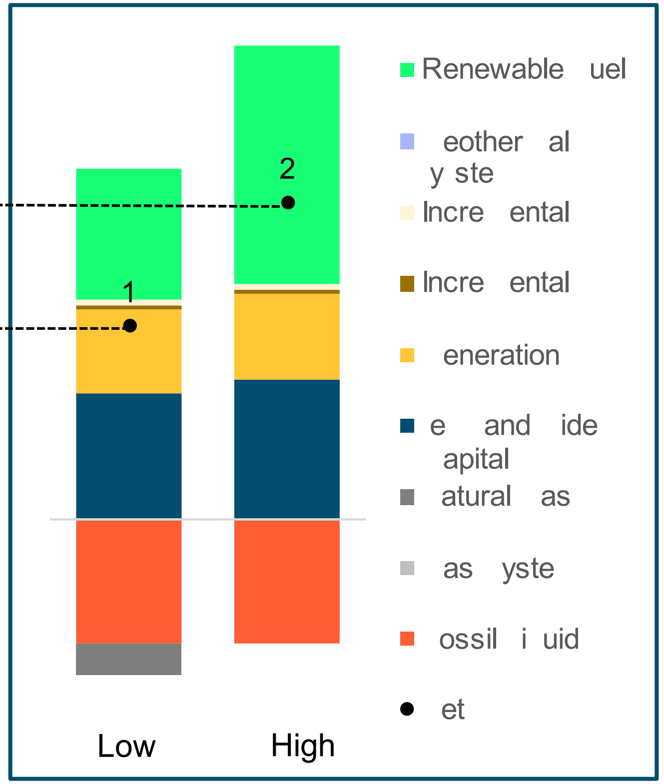
* Expressed as cumulative Net Present Value (NPV) between 2023-2050, incre ental to a reference scenario. osts shown for “un anaged” transition.
** Detail on Technology Readiness Level (TRL) ranges provided on slide 72.

Evaluation criteria example: Economy-wide costs show similar ranges with highest uncertainty in cost of renewable fuels

Detail by category: High Electrification	Range of cumulative net NPV* costs across scenarios	Detail by category: Continued Use of Gas







Device adoption and electric sector drive cost. Scenario shows the smallest range between optimistic and conservative cases due to limited role of fuels

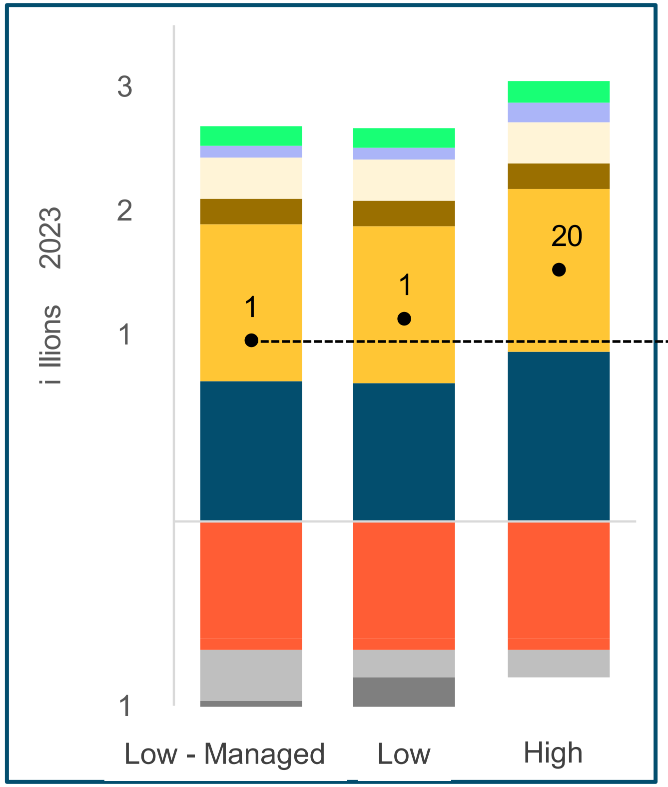
Scenarios with a role for hybrid heating are favorable under both conservative and optimistic parameters

Uncertainties in renewable fuel costs drive highest variability in Continued Use of Gas scenario.

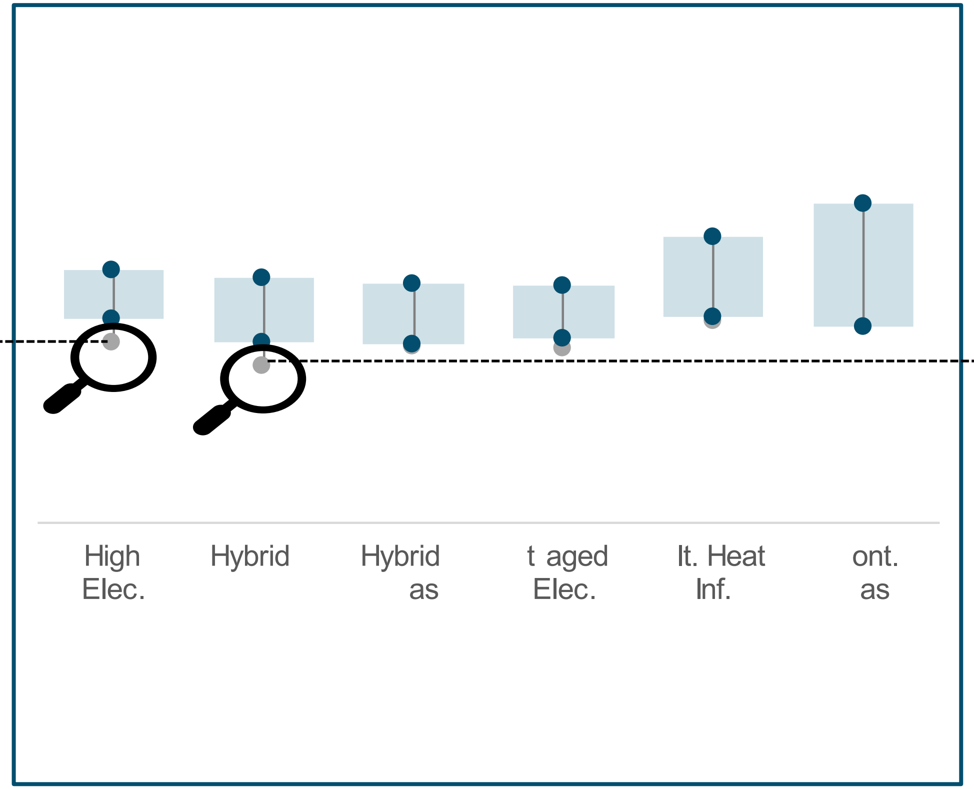
* Expressed as cumulative Net Present Value (NPV) between 2023-2050, incremental to a reference scenario. Discount Rate = 1%.

Evaluation criteria example: A managed transition can reduce costs if long-term gas infrastructure is avoided

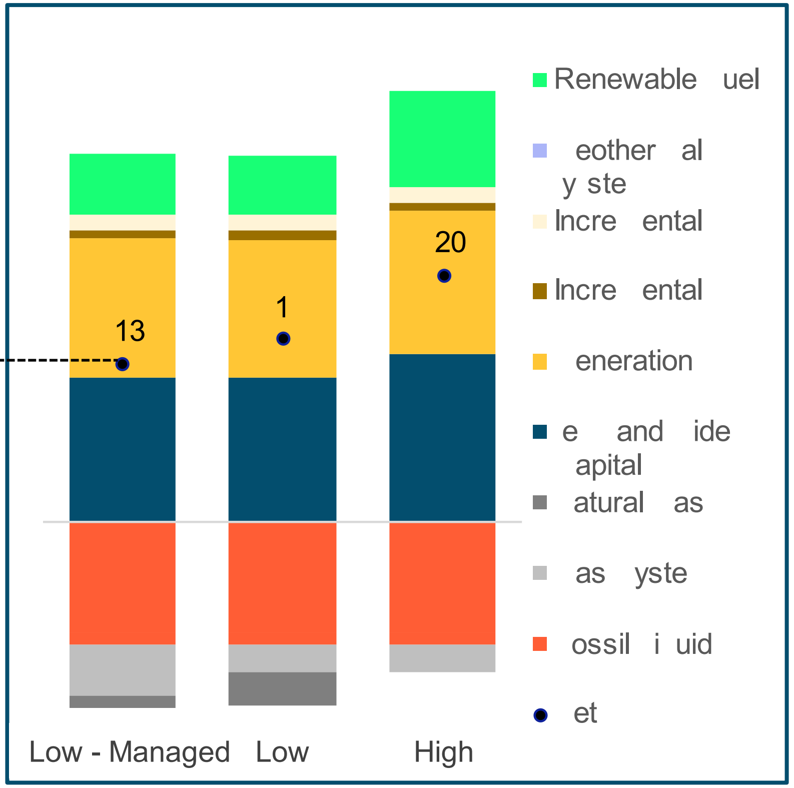
Detail by category: High Electrification



Range of cumulative net NPV* costs across scenarios



Detail by category: Hybrid + Delivered Fuels Backup



A managed transition reduces economy-wide costs, mostly in scenarios that are able to avoid long-term gas infrastructure.

Energy+Environmental Economics

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* Expressed as cumulative Net Present Value (NPV) between 2023-2050, incremental to a reference scenario. Discount Rate = 1%.

Outstanding Questions and Study Needs

The Technical Analysis raises key outstanding questions on the implementation and (technical) feasibility associated with decarbonizing the gas system, in particular related to a managed transition.

+ Technical feasibility and costs

- What parts of Rhode Island Energy RIE ’s syste can be classified as “hydraulically feasible”, i.e. can potentially be decommissioned while maintaining the gas flow and minimum allowable pressure required to ensure safe and reliable service of other parts of the gas system?
  - The Technical Analysis does not model the performance and operations of the gas system, nor does it provide a geographical representation of cost avoidance opportunities. Additional study by RIE is necessary to understand the magnitude of opportunity associated with targeted decommissioning.
- What parts of the gas system are cost-effective to electrify through targeted decommissioning?
  - Other studies* have identified the cost-effectiveness of targeted electrification through neighborhood-specific study of key parameters, such as system density, pipeline age, replacement costs, cost of electrification, etc. This type of study is necessary in Rhode Island to better understand the feasibility and opportunity associated with targeted electrification.
- What additional costs, if any, are associated with decommissioning of the gas system that are not yet captured in the current accounting of asset removal costs recovered by RIE in the annual revenue requirement?

+ Implementation and customer choice

- How can implementation of neighborhood-specific targeted electrification be planned for and achieved without jeopardizing key principles such as customer choice?
- How does a managed transition affect different types of customer classes? To what extent are C&I classes affected through targeted electrification?

Other key questions that arise through the Technical Analysis, such as those related to policy & regulatory options needed to mitigate affordability and equity issues associated with the transition will be addressed in the Policy Development phase of this Docket.

*See, for example: E3 - Benefit-Cost Analysis of Targeted Electrification and Gas Decommissioning in California;
Groundwork Data - Equitable Energy Transition Planning in Holyoke Massachusetts - A Technical Analysis for Strategic Gas Decommissioning and Grid Resiliency.

Decarbonization Pathways Technical Results

Preliminary overview of findings

Energy+Environmental Economics

Summary of preliminary findings in this section (1/2)

Emissions

+ Existing policies achieve significant emissions reductions relative to 1990 and today, achieving 40% reductions by 2030, largely driven by reductions in the electricity sector. Despite significant emissions reductions from existing policies and industry trends in a Reference Scenario, ***additional mitigation measures are required to achieve the Act on Climate***.
+ ***All mitigation scenarios achieve AoC goals under RI's current GHG accounting framework***. Scenarios with higher levels of renewable fuels may have higher emissions under alternative accounting frameworks.
+ ***Delayed achievement of ACCII/ACT requires deeper measures to achieve AoC***, primarily in the long term. The 2030 AoC target can be met with accelerated building sector measures that are already required to facilitate longer term climate goals.

Technology

+ Mitigation scenarios achieve AoC through a distinct mix of technology adoption in the residential and commercial sector; Scenarios focused on higher levels of electrification require heat pump adoption levels by 2030 and 2040 that are ***nearly 10 times higher than today's adoption levels.*** Scenarios with lower levels of electrification still require a 5x increase.
+ Industrial sector sees significant efficiency across scenarios and varying levels of industrial electrification; ***industries that are harder to decarbonize leave a role for pipeline gas and see increased adoption of dedicated hydrogen***.

Fuels

+ All scenarios see ***transformational changes*** in the way Rhode Island uses energy; across scenarios, final energy demand ***decreases between ~40-50%*** by 2050 as a result of efficiency & electrification.
+ RI will see increased use of biofuels through Biodiesel Heating Act. By 2050, ***~50-70% of the fuel mix across scenarios consists of renewable fuels***, with largest reliance in Continued Use of Gas scenario.
+ Gas throughput in Rhode Island ***declines by ~45-95% across scenarios***; supply costs of gas may increase by 4-5x post 2035.

Summary of preliminary findings in this section (2/2)

Gas system impacts

- Planned levels of capital expenditures through the Infrastructure, Safety and Reliability (ISR) program and additional customer connections in a Reference Scenario cause ***annual gas revenue requirement to nearly double towards 2050***, assuming an ***unmanaged transition.*** Scenarios that do not assume additional customer connections reduce annual costs by approximately 20% by 2050.
- A ***managed transition could reduce the costs of the gas system by up to 35%*** in scenarios that transition away from the gas system in the near term (High Electrification, Hybrid + Delivered Fuels, Staged Electrification).
- Except for the Continued Use of Gas scenario, ***all mitigation scenarios lead to untenable long-term gas delivery rates***; a managed transition can only partly mitigate this effect.
- Risk of stranded costs exists for scenarios with high levels of customer departures; potentially unrecovered rate base in 2050 ***between $2,6M (unmanaged) and $1,5M (managed).***

Electric system impacts

- By 2050, 40-60% of final energy demand is served by electricity. Scenarios with high levels of electrification see ***nearly doubling load by 2050*** co pared to today's levels.
- Scenarios with high adoption of heat pumps switch to winter peaking in the 2030s, ***median peak demand doubles*** in High Electrification scenario by 2050 and is ***mitigated by approximately 1 GW in hybrid scenarios***.
- Renewables become a major source of generation in the New England and Rhode Island electricity portfolio. ***Total cost of electric service increases*** across all scenarios driven by (1) higher electric demand and (2) higher cost of electric generation to meet the 100% Renewable Energy Standard.
- Cost of service increases are ***largely offset by increased loads***, especially for scenarios with high load factors. In a Reference Scenario, ***achieving the 100% Renewable Energy Standard increases rates by ¢1.3-2.3/kWh by 2035.***

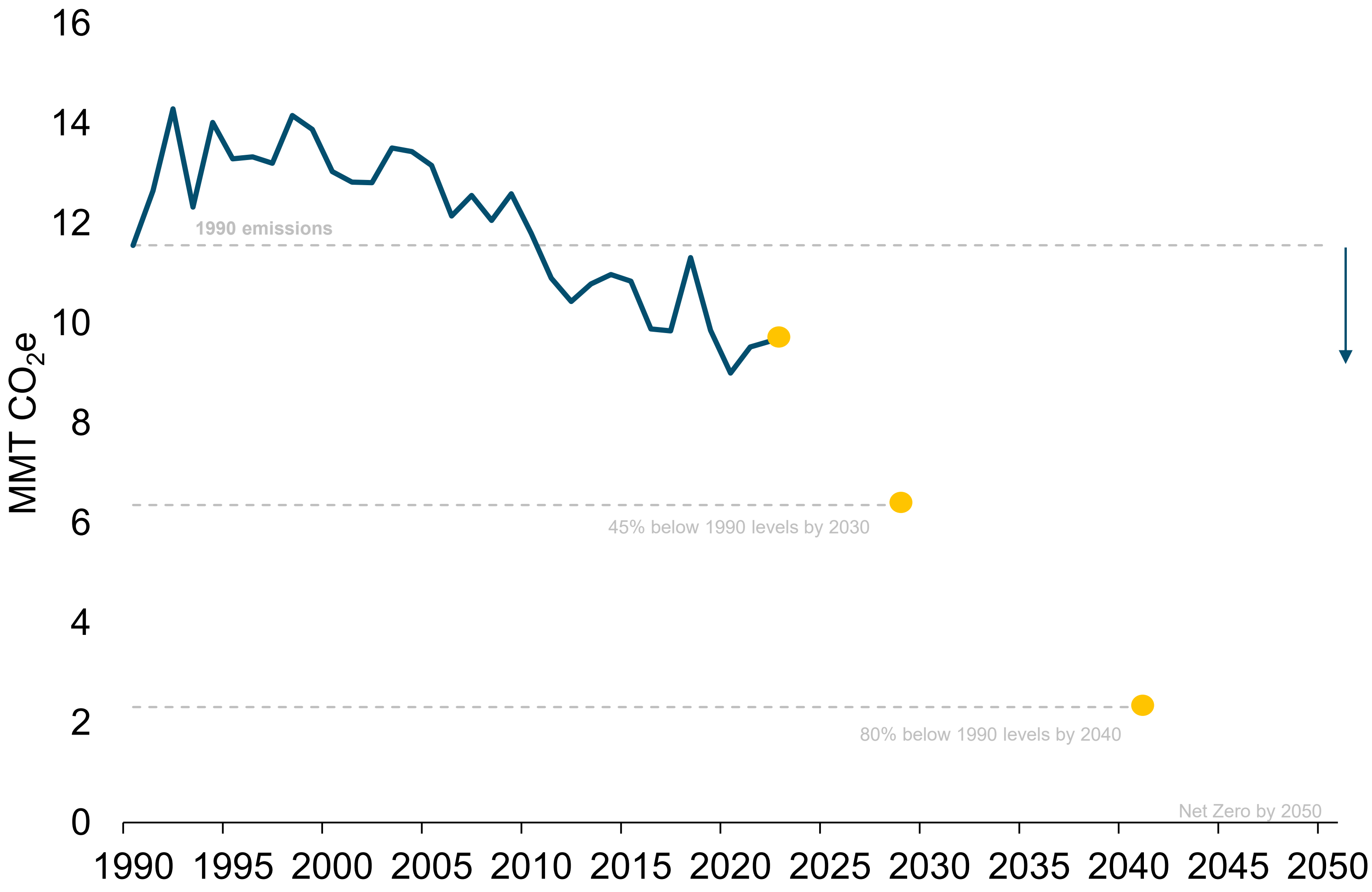
Decarbonization Pathways Technical Results

Impact on Emissions

Energy+Environmental Economics

Rhode Island's latest GHG Inventory shows a 20% reduction in emissions in 2020 compared to 1990 levels

Rhode Island Statewide Emissions Reductions – 1990-2020



2020 emissions: 22% below 1990 levels.

Key emissions reductions between 1990-2020 are attributed to:

- Electricity sector: - 27.7%
- Residential heating: -21.9%
- Transportation sector: -23.4%
- Fugitive methane emissions: -21.2%

Emissions from hard-to-decarbonize sectors, such as non-road sources and industrial process emissions, saw a slight increase.

Source: 2020 Rhode Island Greenhouse Gas Emissions Inventory: https://dem.ri.gov/environmental-protection-bureau/air-resources/greenhouse-gas-emissions-inventory

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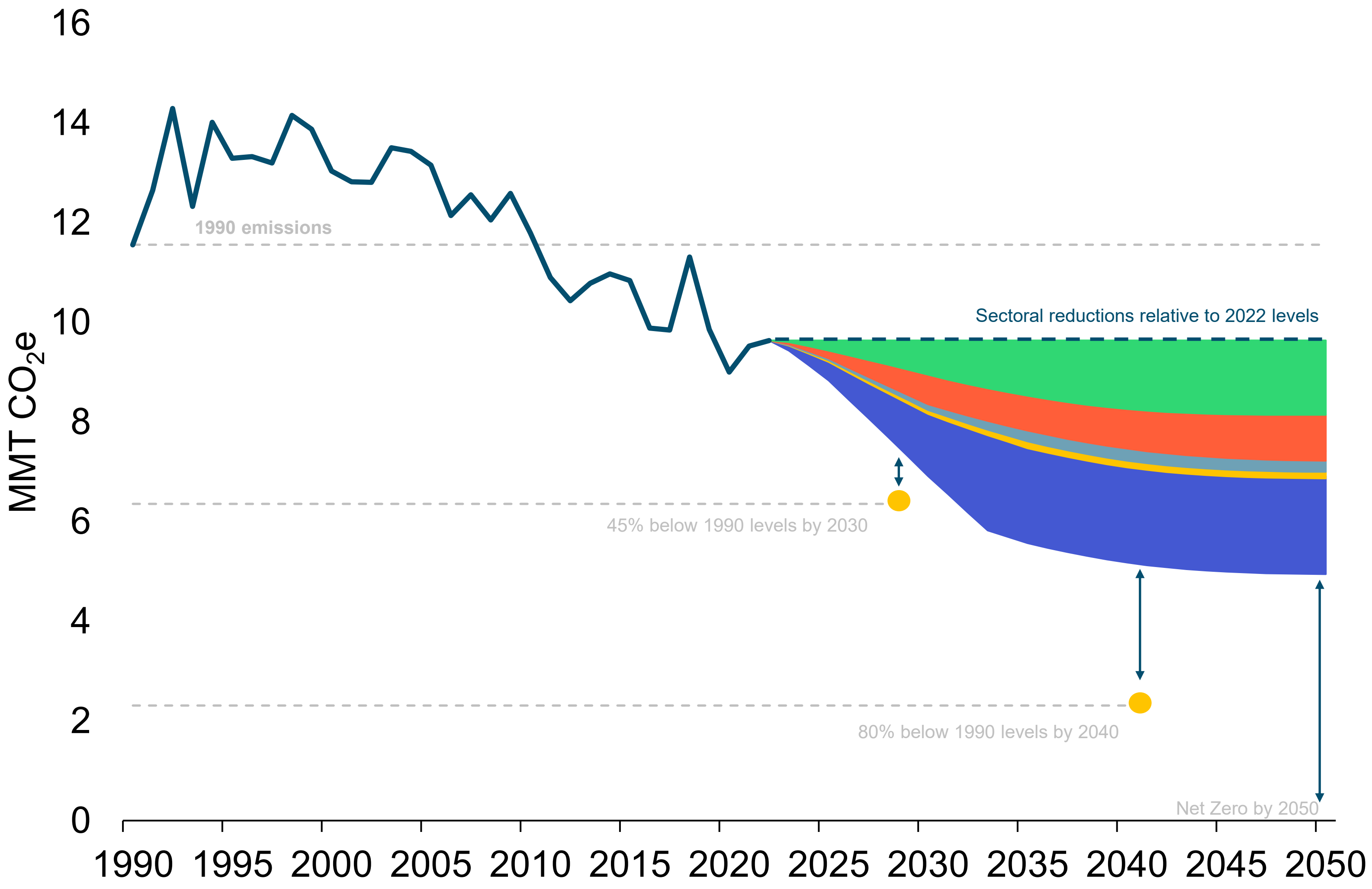
Existing policies and industry trends are expected to result in significant near-term emissions reductions

Rhode Island Statewide Emissions Reductions – Reference Scenario



Major emissions reduction contributions in reference scenario:

Transportation sector:
- Growth in EV penetration consistent with historical levels and EC4 target (10% of stocks by 2030)
- Modest levels of ZEV for MDV/HDV
- No adoption of ACCII/ACT

Building sector:
- Heat pump adoption & EE retrofits based on historical trends
- Biodiesel Heating Act: 50% biodiesel blending by 2030
- 100% sales shares of efficient gas furnaces by 2029
- Oil-to-gas conversions

Electricity sector:
- 100% Renewable Energy Standard by 2033

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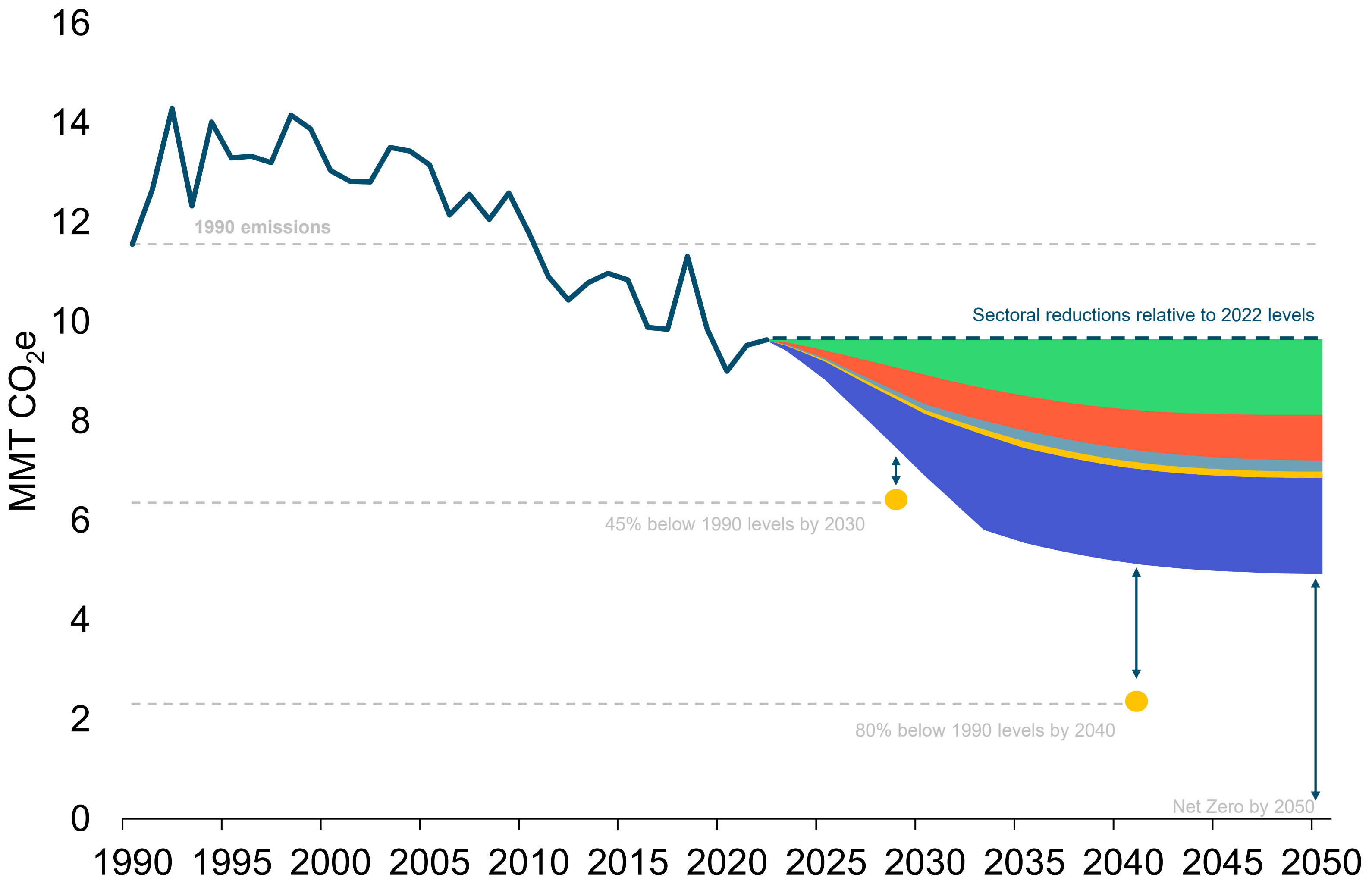
Emissions reductions from sector: Transportation | Buildings | Industry, Waste & Sinks | Gas distribution | Electricity

Despite significant emissions reductions, additional efforts are required to achieve the Act on Climate

Rhode Island Statewide Emissions Reductions – Reference Scenario



2022 emissions: 9.7 MMT CO_2e (-16%) Between 2020-2022, emissions are expected to increase as a result of post-COVID activity.

2030 emissions gap to achieve AoC: **0.7 MMT CO_2e**

2040 emissions gap to achieve AoC: **3.0 MMT CO_2e**

2050 emissions gap to achieve AoC: **5.1 MMT CO_2e**

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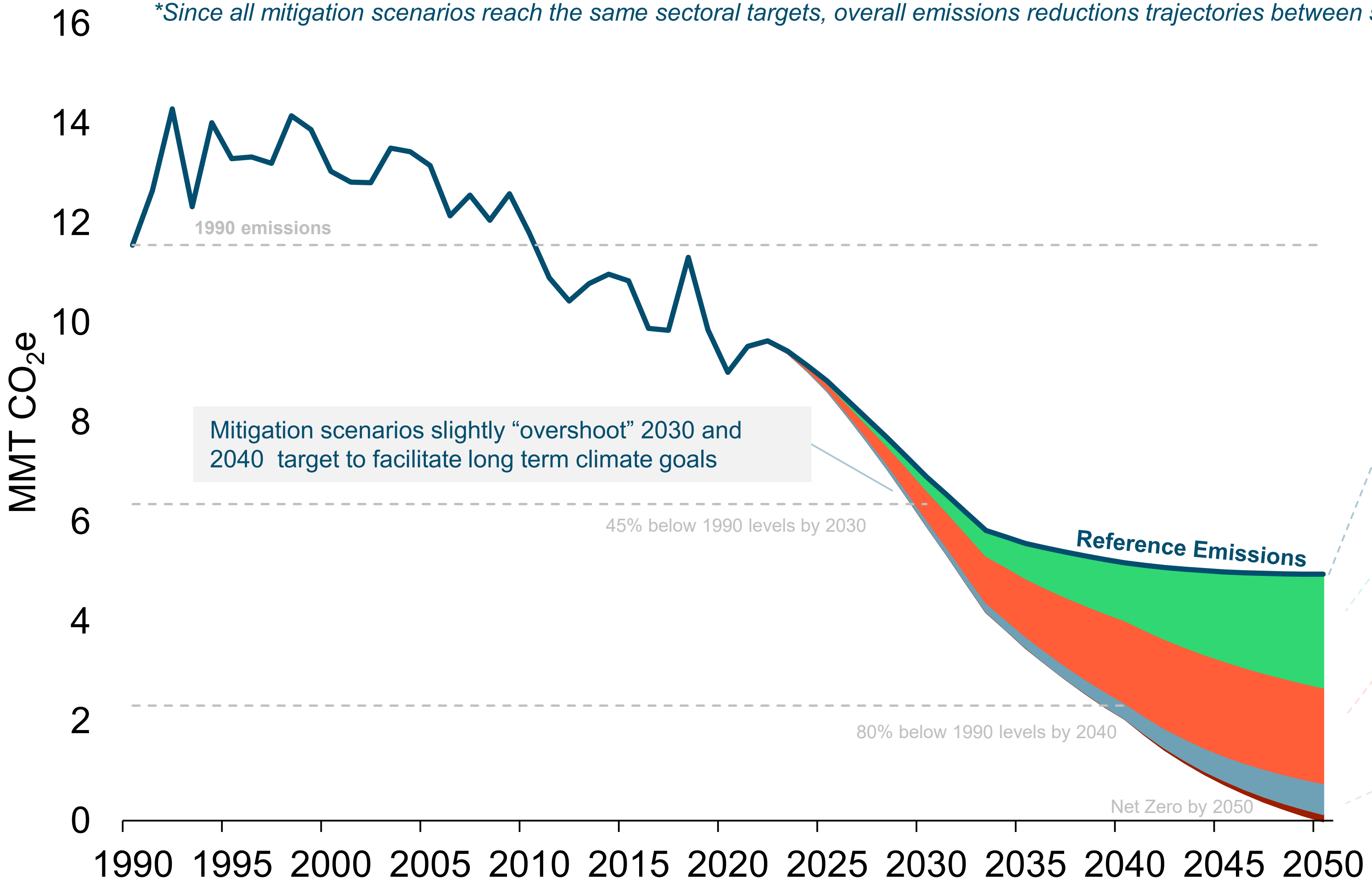
Emissions reductions from sector: Transportation | Buildings | Industry, Waste & Sinks | Gas distribution | Electricity

All mitigation scenarios achieve the Act on Climate, large focus on buildings and transportation required post 2030

Rhode Island Statewide Emissions Reductions – Mitigation Scenarios*

**Since all mitigation scenarios reach the same sectoral targets, overall emissions reductions trajectories between scenarios are similar.*



Reference scenario emissions:
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- Variations in renewable fuels blending

Industrial sector:
- The industrial sector decarbonizes through a range of electrification and fuel-switching measures, as feasible

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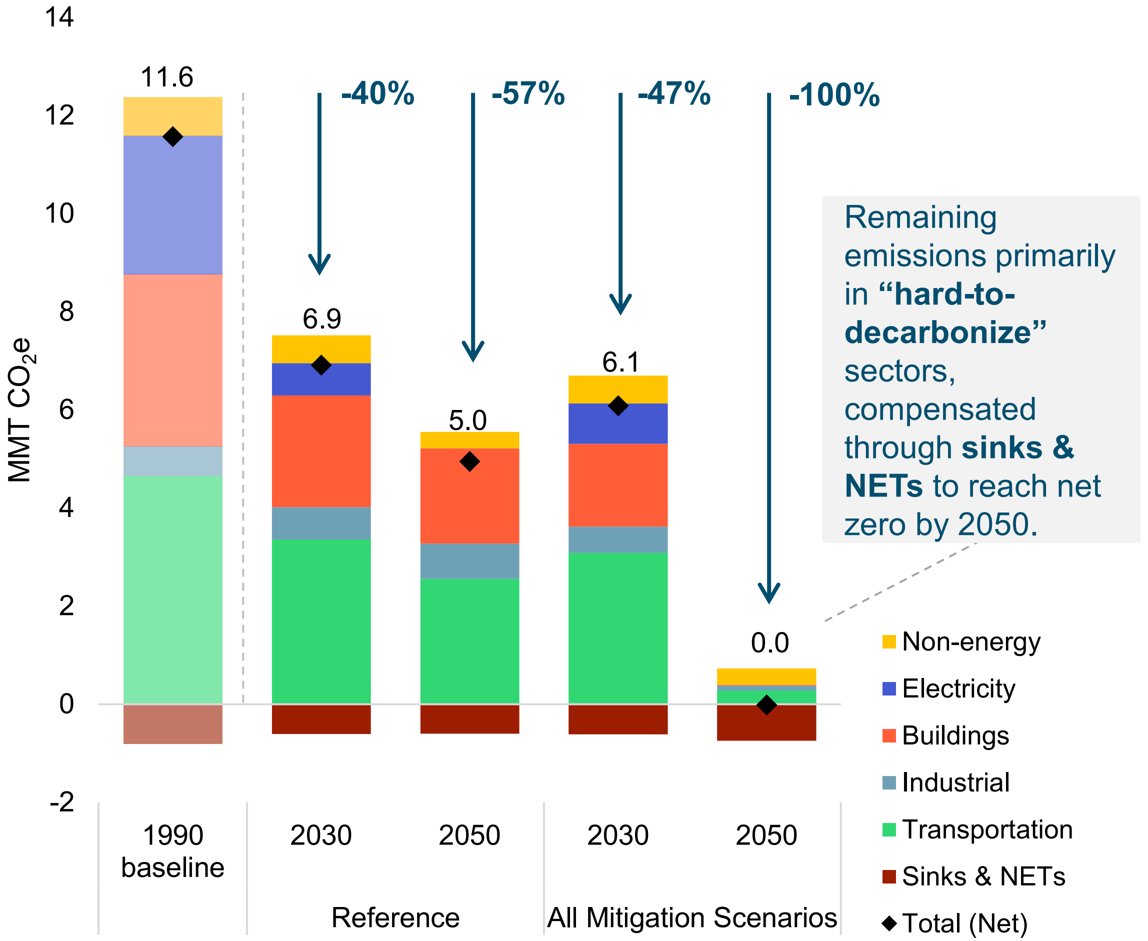
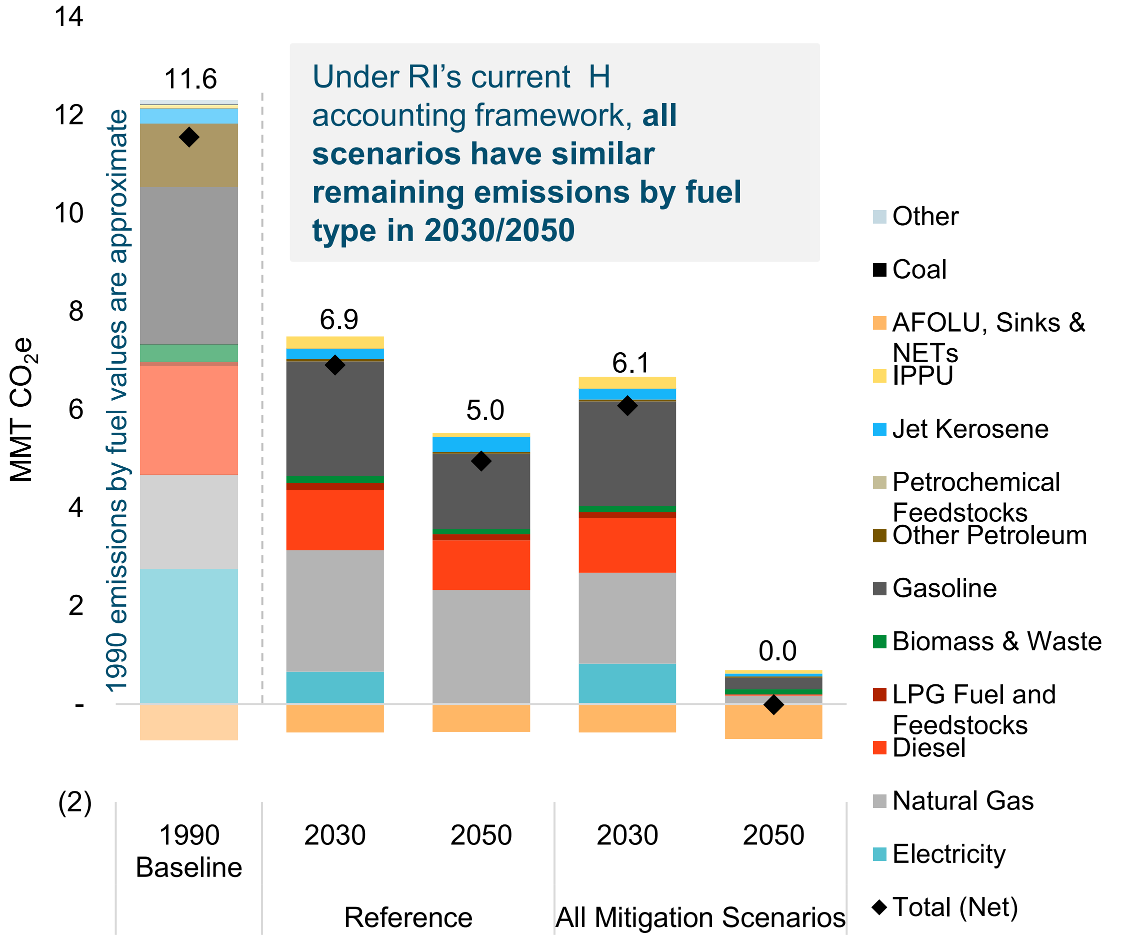
Emissions reductions from sector: Transportation | Buildings | Industry | Gas distribution | Sinks & NETs

By 2050, remaining emissions from harder-to-decarbonize sectors are offset by sinks & NETs

2030/2050 remaining emissions by sector



2030/2050 remaining emissions by fuel



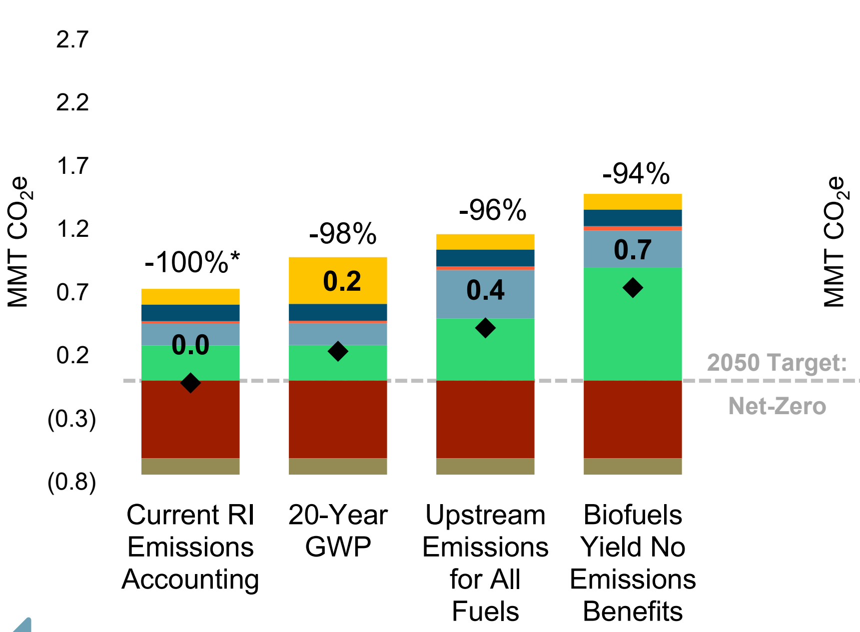
AFOLU = Agriculture, Forestry, and Other Land Use
IPPU = Industrial Processes and Product Use

Scenarios with higher levels of renewable fuels may have higher emissions under alternative accounting frameworks

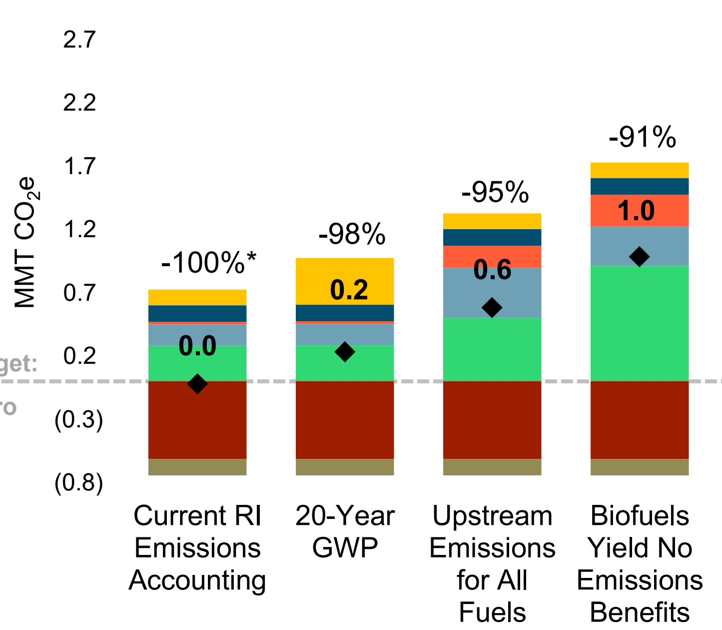
The Technical Analysis is based on emissions accounting **consistent with federal and RI's accounting standards**.

Through **sensitivity analysis**, E3 assessed scenario-specific differences under other types of emissions accounting methodologies. This analysis shows that scenarios that **rely more heavily on renewable fuels** are most sensitive to the use of alternative accounting frameworks.

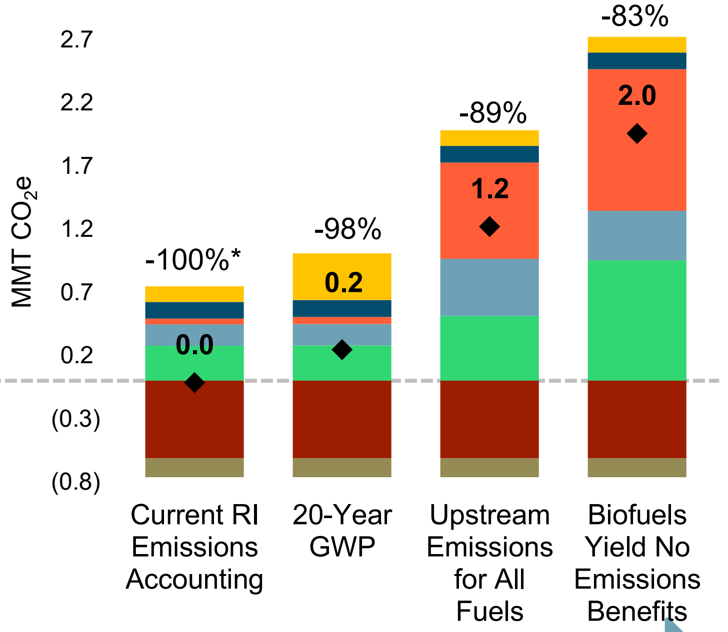
High Elect. 2050 Emissions



Hybrid + Gas 2050 Emissions



Cont. Use of Gas 2050 Emissions



Lower reliance on renewable fuels — Higher reliance on renewable fuels

NETs | Sequestration | Gas Distribution | Agriculture & Waste | Electricity | Buildings | Industry | Transportation | ◆ Net

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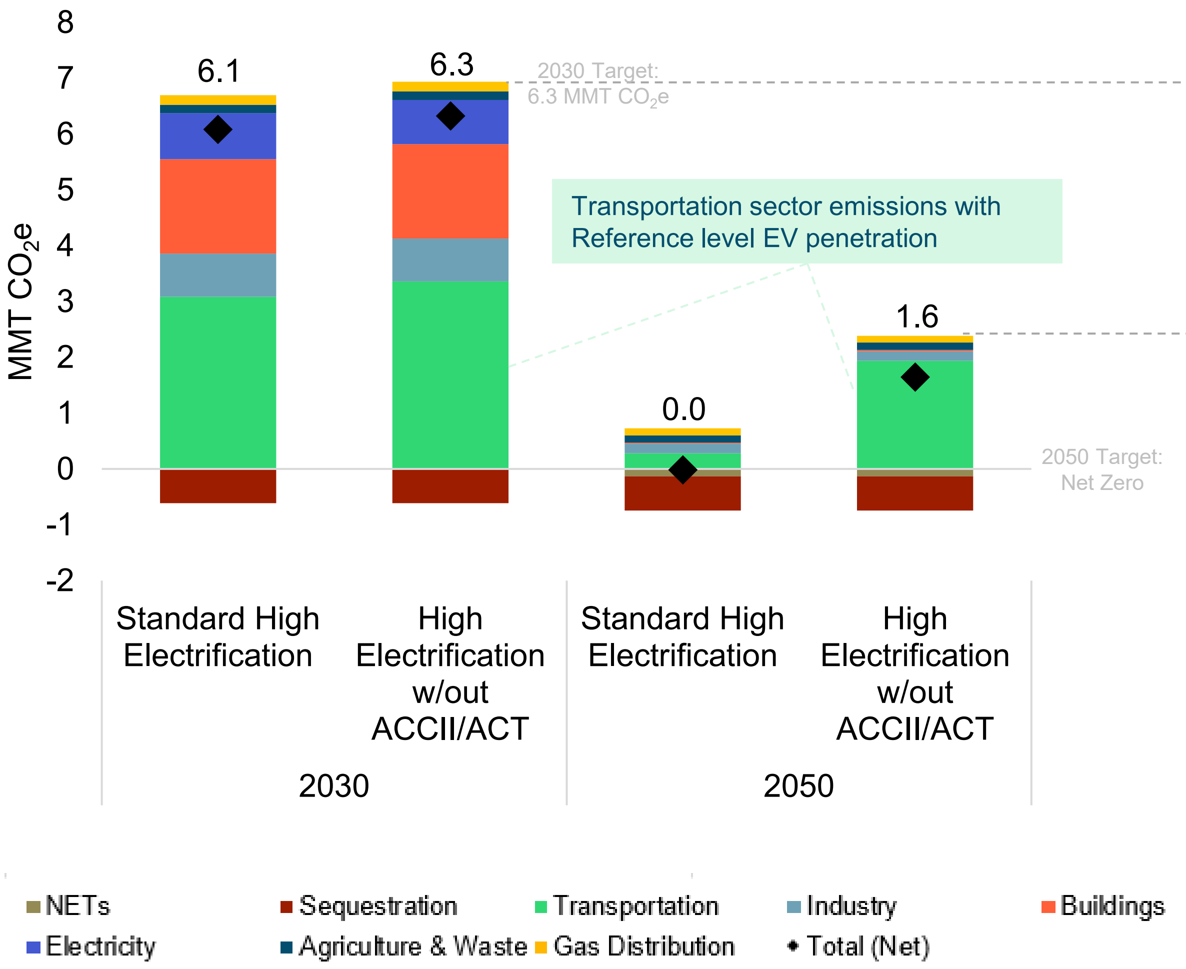
* Compared to 1990 emissions levels. The impact on other scenarios is provided in the appendix.

Delayed achievement of ACCII and ACT requires deeper measures to achieve AoC, primarily in the long term

Remaining Emissions w/ and w/out ACCII/ACT – High Electrification scenario



High Electrification **would meet the 2030** target even if ACCII/ACT follows a slower trajectory in the short term. This is due to accelerated action in the buildings sector that are required to reach longer term climate goals*

By 2050, High Electrification will have approx. 1.65 MMT CO_2e remaining in 2050 without achievement of ACCII/ACT, thus missing the target by about 14%

If EV penetration is consistent with historical levels and EC4 target (10% of stocks by 2050) instead of ACCII/ACT, RI will not meet the 2040/2050 AoC targets without higher renewable fuel blending or deeper measures in other sectors.

In High Electrification, the buildings sector is completely electrified. Thus, if the ACCII/ACT is not achieved, higher renewable fuel blending in the Transportation sector will be required.

In other mitigation scenarios, deeper building electrification measures can be adopted if the ACCII/ACT is not met.

*Note: The High Electrification scenario is designed to avoid blending of renewable fuels in the long term. As a result of slow stock rollover, accelerated adoption of building electrification in the near term is required to achieve this objective, resulting in deeper emissions reductions than required in the AoC.

Decarbonization Pathways Technical Results

Impact on Technology Adoption

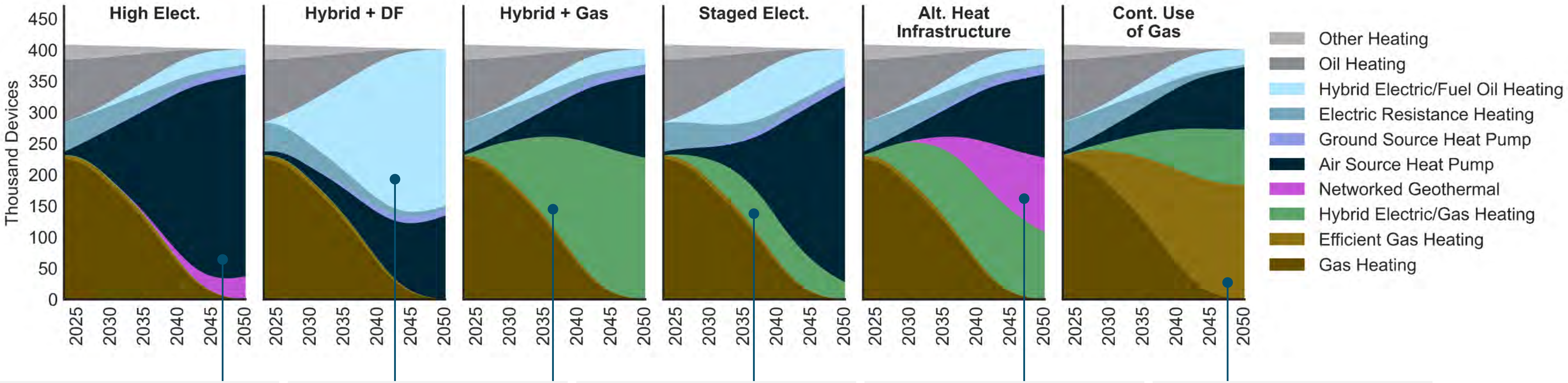
Energy+Environmental Economics

Mitigation scenarios achieve AoC through a distinct mix of technology adoption in the residential sector

Across scenarios, buildings reach similar **levels of emissions reductions** using a variety of decarbonization technologies.

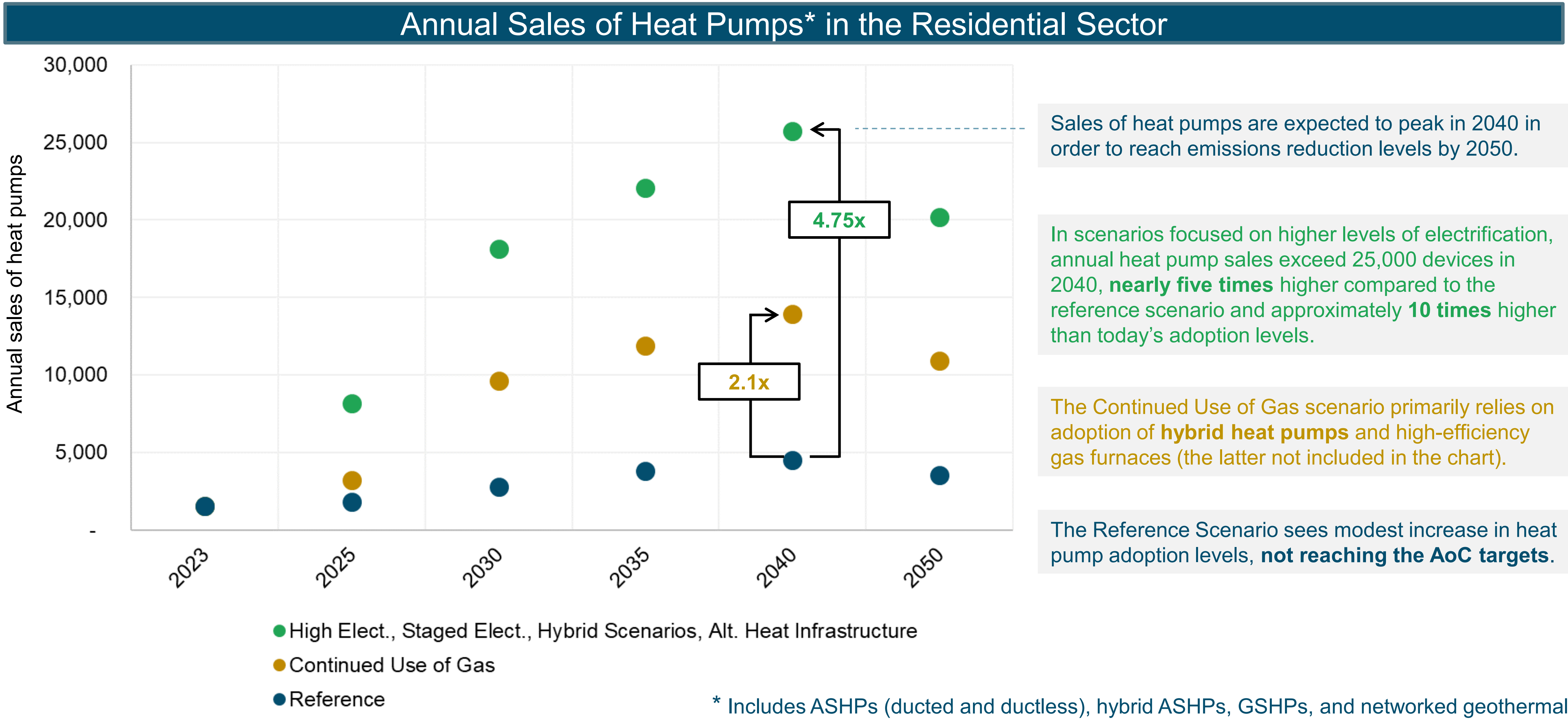
All mitigation scenarios **require rapid adoption** of space heating decarbonization technologies in the residential sector.

Residential Household Heating Equipment Adoption in Rhode Island



High Elect.	Hybrid + DF	Staged Elect.	Alt. Heat Infrastructure	Cont. Use of Gas
Focus on ASHP adoption, "niche" levels of networked geothermal	Same number of hybrid adoption, with different types of backup	Near-term adoption of hybrids, long-term conversion to ASHP	Combination of hybrids and networked geothermal systems	Continued adoption of high-efficiency gas, including hybrids
By 2050: 93% all-electric 6% hybrid	**By 2050: 36% all-electric 62% hybrid**	**By 2050: 81% all-electric 17% hybrid**	**By 2050: 66% all-electric 33% hybrid**	**By 2050: 25% all-electric 28% hybrid**

Annual adoption of decarbonization technologies needs to increase significantly to support AoC



Sales of heat pumps are expected to peak in 2040 in order to reach emissions reduction levels by 2050.

In scenarios focused on higher levels of electrification, annual heat pump sales exceed 25,000 devices in 2040, **nearly five times** higher compared to the reference scenario and approximately **10 times** higher than today's adoption levels.

The Continued Use of Gas scenario primarily relies on adoption of **hybrid heat pumps** and high-efficiency gas furnaces (the latter not included in the chart).

The Reference Scenario sees modest increase in heat pump adoption levels, **not reaching the AoC targets**.

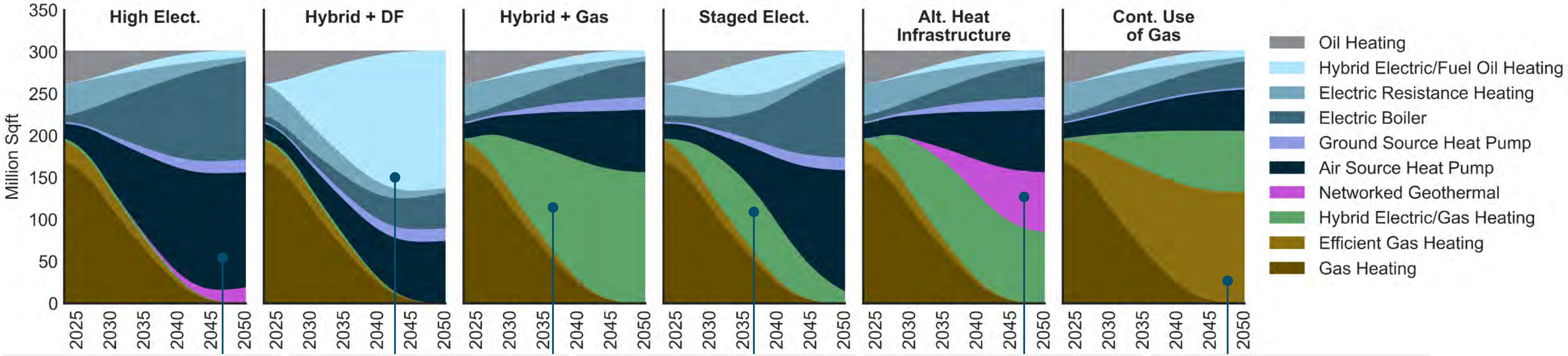
* Includes ASHPs (ducted and ductless), hybrid ASHPs, GSHPs, and networked geothermal

Commercial sector sees similar levels of technology adoption to residential; larger focus on boilers

Across scenarios, buildings reach similar **levels of emissions reductions** using a variety of decarbonization technologies.

All mitigation scenarios **require rapid adoption** of space heating decarbonization technologies in the commercial sector.

Commercial Heating Equipment Adoption in Rhode Island



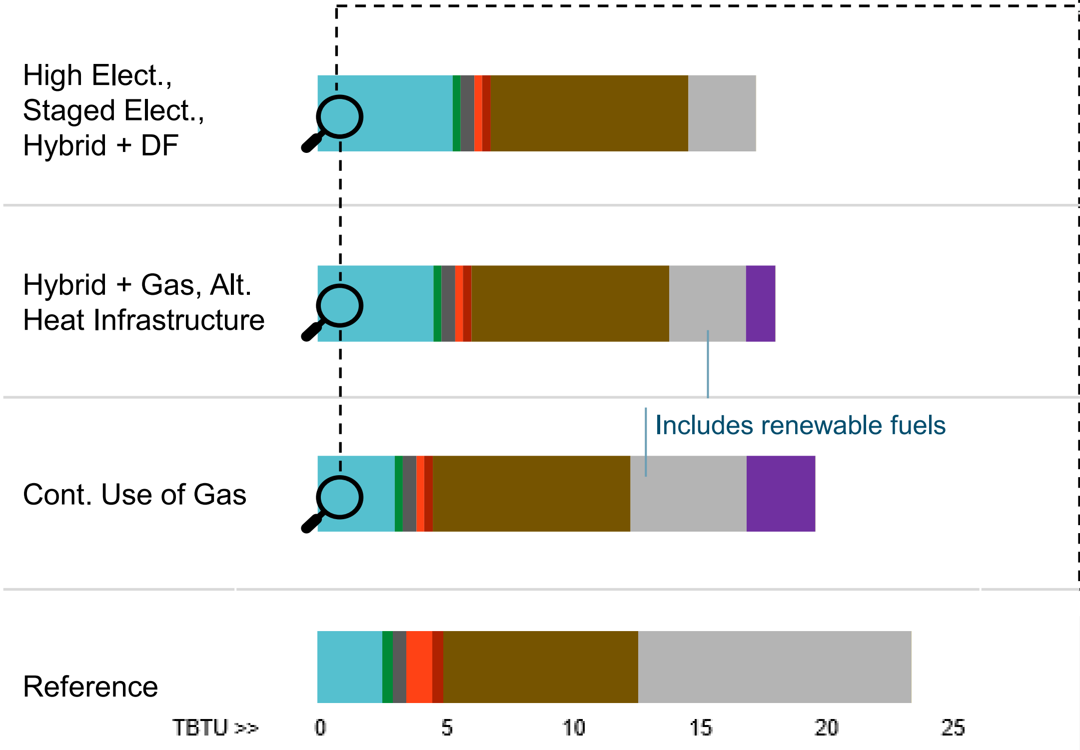
High Elect.	Hybrid + DF	Staged Elect.	Alt. Heat Infrastructure	Cont. Use of Gas
Focus on ASHP and electric boiler adoption with some networked geothermal	Same number of hybrid technology adoption (HPs and boilers), with different types of backup	Near-term adoption of hybrid HPs and boilers, long term conversion to all-electric	Combination of hybrid HPs, hybrid boilers, and networked geothermal systems	Continued adoption of high-efficiency gas, including hybrid HPs and hybrid boilers
By 2050: 96% all-electric 2% hybrid	**By 2050: 44% all-electric 54% hybrid**	**By 2050: 89% all-electric 9% hybrid**	**By 2050: 67% all-electric 31% hybrid**	**By 2050: 28% all-electric 27% hybrid**

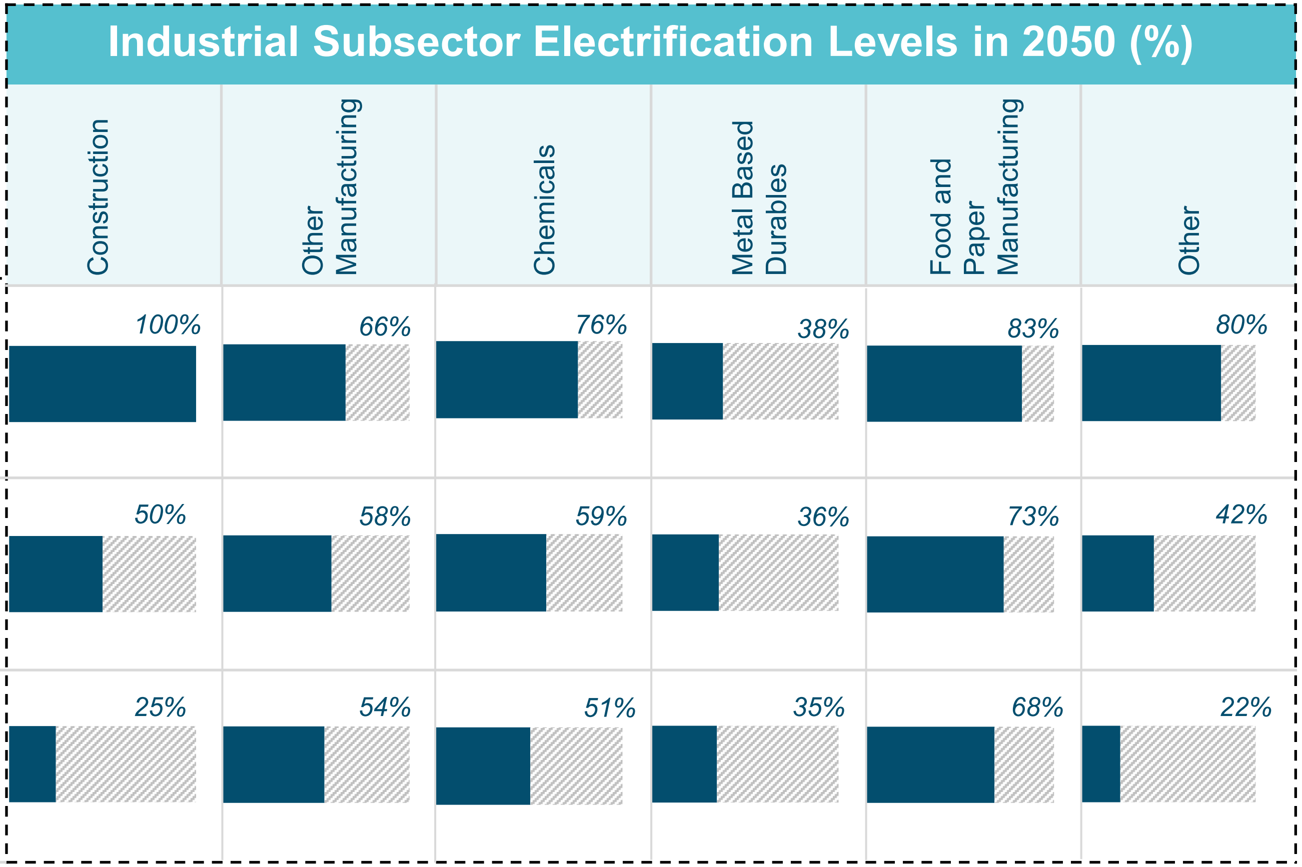
Industrial sector sees significant efficiency across scenarios; reliance on electrification vs. fuel-switching varies

CLF-1-3

Energy Demand in 2050 (TBTU)

Energy demand shrinks in all scenarios compared to the Reference trajectory due to efficiency and electrification, though levels of electrification vs. fuel switching varies





Subsectors with **high electrification potential are primarily electrified** across scenarios, with more aggressive adoption levels in the high electrification scenario. Subsectors that are harder to decarbonize **leave a role for pipeline gas** and see **increased adoption of dedicated hydrogen**.

DRAFT / PRELIMINARY

Electricity | Biomass & Waste | Gasoline | Jet Kerosene | Diesel | LPG Fuel and Feedstocks | Other Petroleum | Pipeline Gas | Hydrogen | Petrochemical Feedstocks

Electrified | Not Electrified

Decarbonization Pathways Technical Results

Impact on Fuel Usage

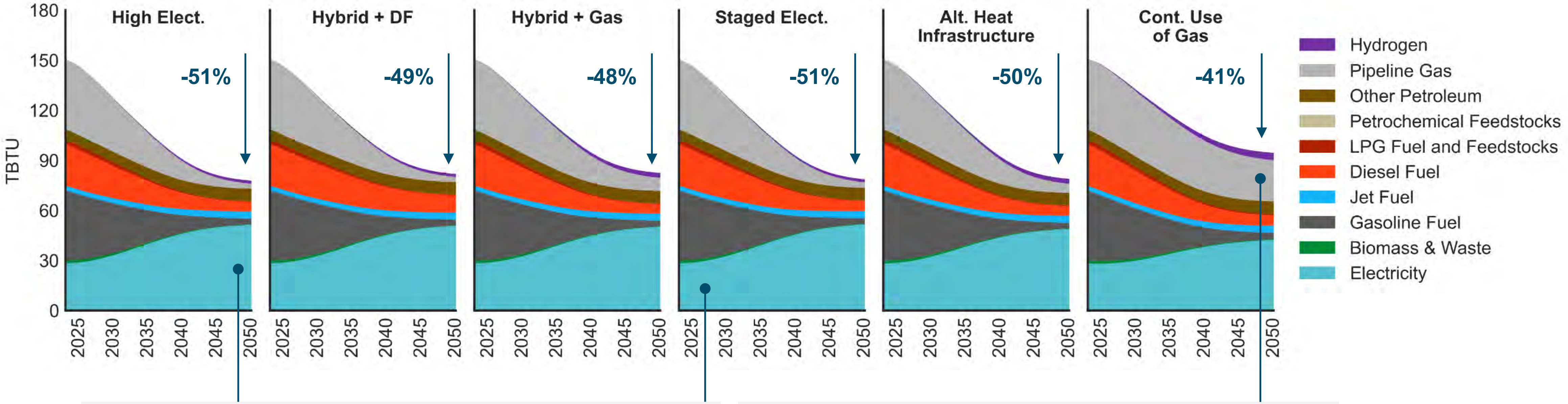
Energy+Environmental Economics

Final energy demand declines across scenarios as a result of efficiency and fuel switching

Across scenarios, **final energy demand decreases between ~40-50% by 2050** as a result of efficiency & electrification.

All scenarios see **transformational changes** in the way Rhode Island uses energy.

Change in economy-wide final energy demand across scenarios: 2023 - 2050



Highest levels of EE due to electrification

Highest levels of remaining pipeline gas* & hydrogen

None of the scenarios fully eliminate gas. Scenarios with high levels of electrification leave gas usage in the industrial sector

All scenarios see **increased levels of electricity load** and a significant **reduction in gasoline and diesel fuel**

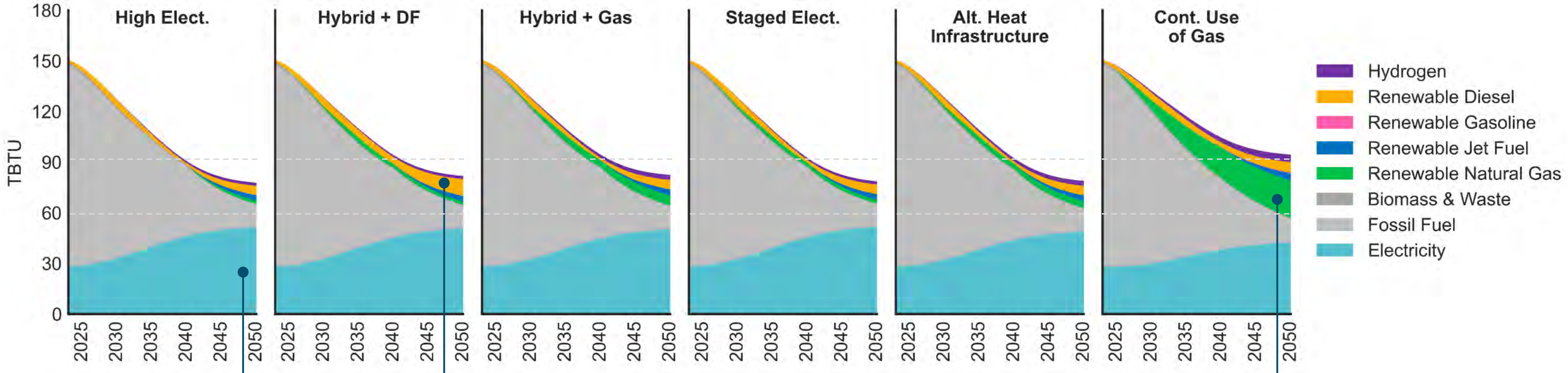
*Includes renewable fuels, visualized on the following slide.

By 2050, 40-60% of final energy demand is served by electricity while the need for renewable fuels increases

Across scenarios, **some level of renewable fuel blending** is needed to meet 2050 emissions targets.

Scenarios with lower levels of electrification see higher renewable fuel blending to comply with AoC goals.

Change in economy-wide final energy demand across scenarios: 2023 - 2050



Lowest levels of renewable fuels

Highest levels of renewable diesel due to hybrid + DF HPs

Highest levels renewable natural gas and hydrogen

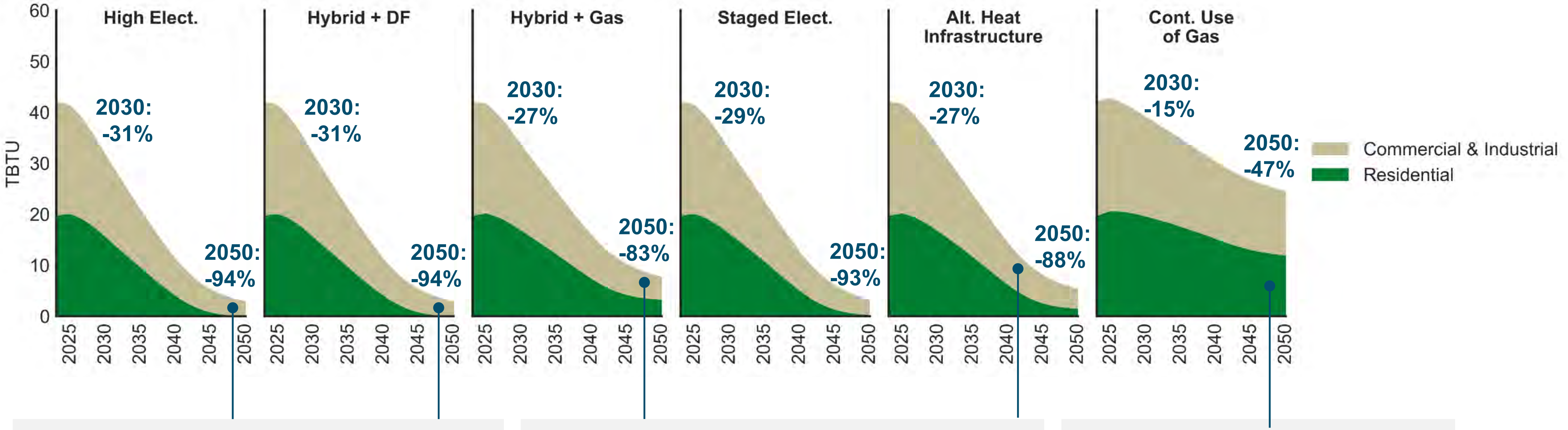
All scenarios comply with the Biodiesel Heating Oil Act of 2013, requiring 20% blend in 2025 and 50% blend in 2030

All scenarios rely on renewable fuels to meet emissions targets, lower electrification scenarios require higher levels.

Gas throughput in Rhode Island declines across all scenarios

Across scenarios, **final gas throughput decreases between ~45-95% by 2050** as a result of efficiency & electrification.
Some levels of gas throughput remain in the Commercial & Industrial sector.
All scenarios see some level of **RNG blending** by 2050, with higher levels in scenarios that rely more heavily on gas.

Change in levels of gas throughput: 2023 - 2050



Gas use remains in small portions of the system to serve hard-to-decarbonize C&I loads

Residential & commercial gas use primarily for winter backup heating

35% of industrial use switches to hydrogen

By 2050: 70% RNG blend

By 2050: 72% RNG blend

By 2050: 82% RNG blend

By 2050: 70% RNG blend

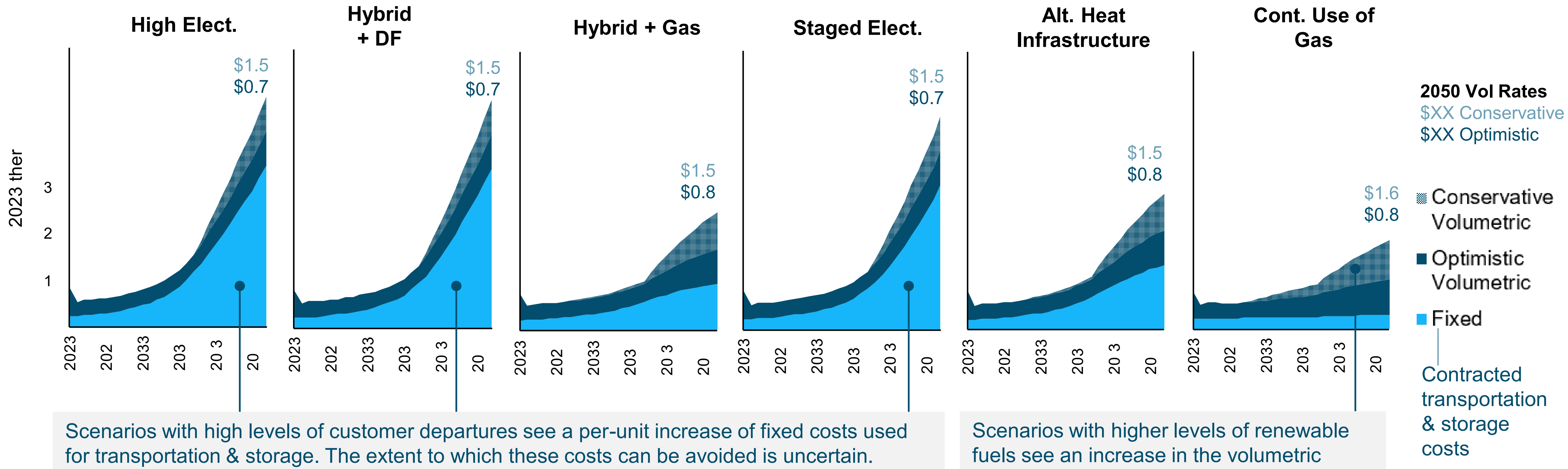
By 2050: 78% RNG blend

By 2050: 92% RNG blend

Costs of gas are expected to rise for gas customers as a result of increased RNG blending

As a result of increased blending of renewable fuels and a decline of system throughput, **the cost of gas is expected to rise**. In scenarios with high levels of electrification, fixed costs (transportation & storage) rise as the costs are spread among fewer customers. After 2040, C&I customers are expected to rely on higher levels of RNG increasing volumetric costs. Residential costs of gas are provided in the Appendix.

Costs of C&I gas supply across scenarios, distinguishing fixed & volumetric components*: 2023-2050



Scenarios with high levels of customer departures see a per-unit increase of fixed costs used for transportation & storage. The extent to which these costs can be avoided is uncertain.

Scenarios with higher levels of renewable fuels see an increase in the volumetric (commodity) component of the costs of gas.

DRAFT / PRELIMINARY

*Fixed component includes the costs of storage & transportation contracts. ***Delivery costs of gas are not included on this slide.***

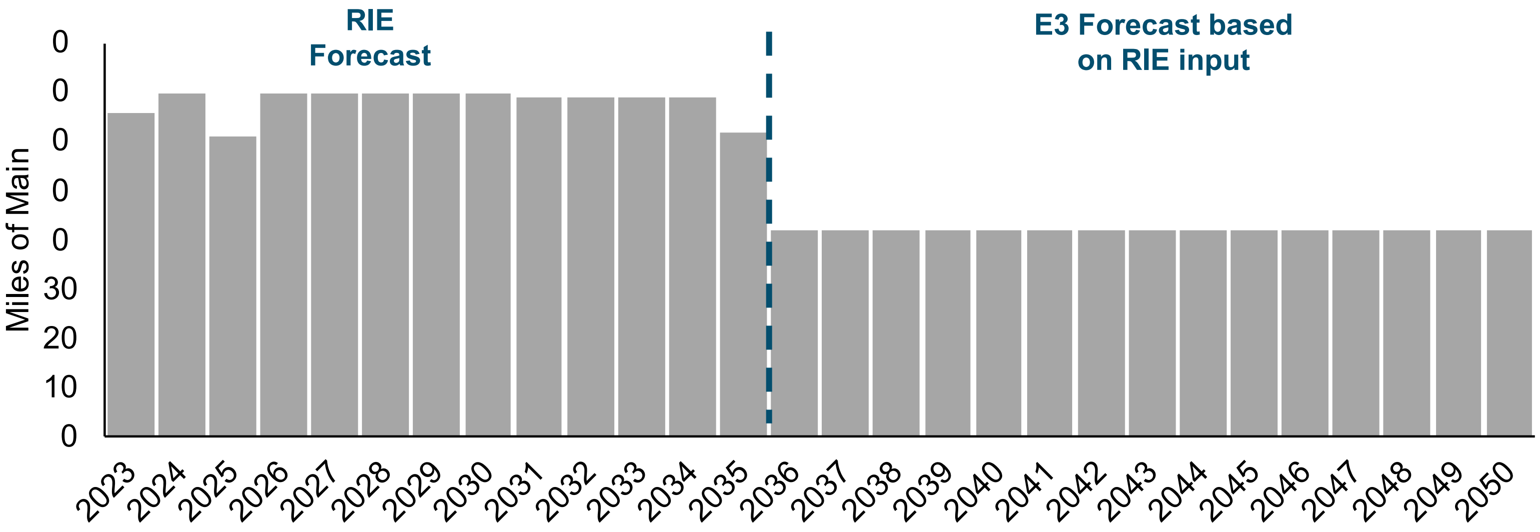
Decarbonization Pathways Technical Results

Impact on Gas System

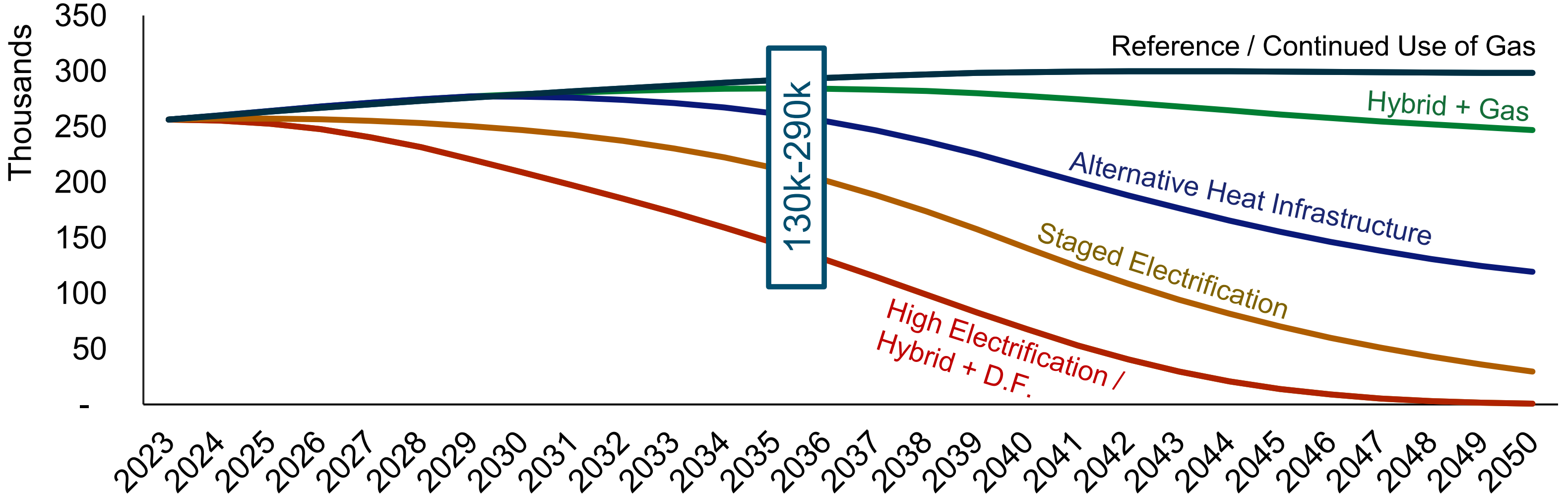
Energy+Environmental Economics

In most scenarios, pipeline replacements driven by ISR[CLF-1-3] will serve fewer customers over time

Replacement Miles (Mains)



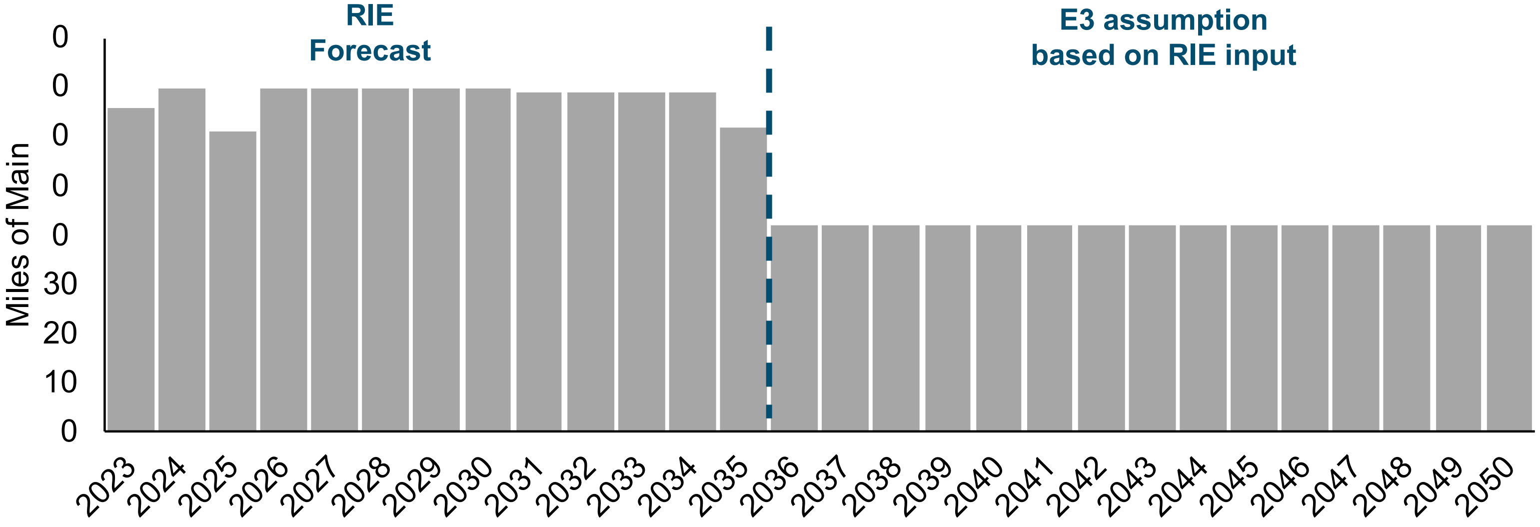
Customers with a gas connection



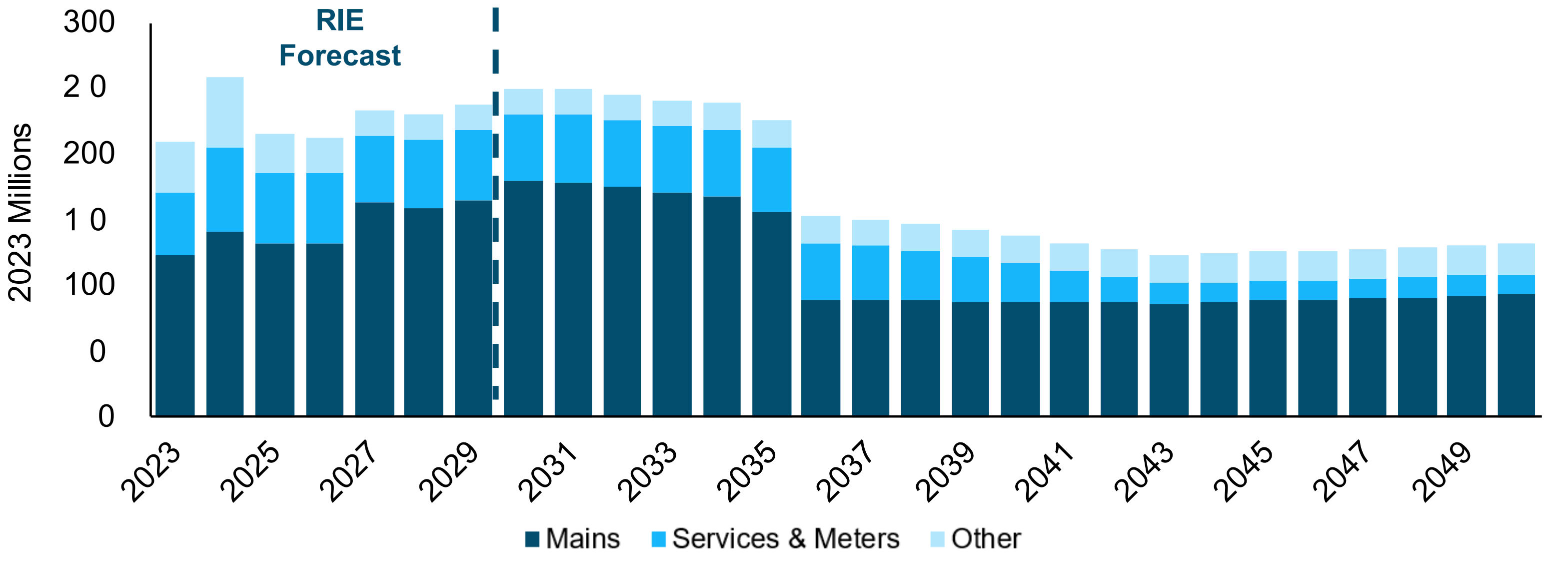
- The Infrastructure, Safety & Reliability (ISR) Plan ensures safe and reliable service of gas in the next decade, with a strong focus on **replacement of Leak Prone Pipe (LPP)** infrastructure.
- The ISR program is expected to replace up to 900 miles of pipe in the next decade, reaching **completion in 2035.** Post-2035, RIE expects to continue to replace (plastic) mains at end-of-life
- In 4 out of 6 mitigation scenarios, electrification drives a reduction of gas customers. The High Electrification and Hybrid Delivered Fuels Backup scenarios have approximately 130,000 customers remaining by the end of the ISR program, **a reduction of +/-50% compared to today**.

High level of capital expenditures are expected in the next decade through the Infrastructure, Safety & Reliability Plan

Replacement Miles (Mains)



Capital Expenditures

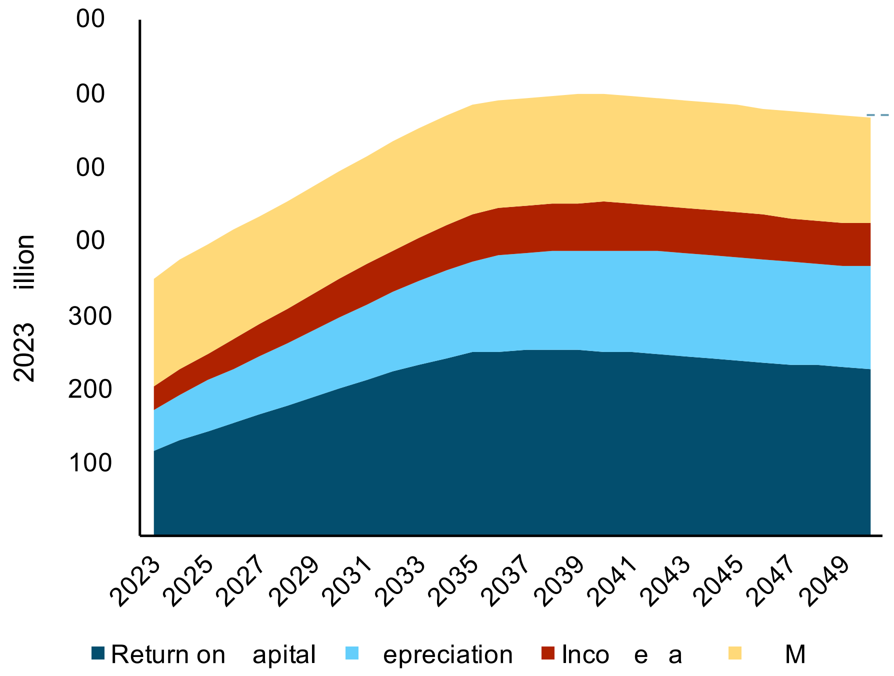


- Elevated capex through 2035 reflects the high **rate of mains and service replacements** for newer, plastic pipes. Beyond 2035, RIE expects a continuous replacement program for mains & services that are reflected in the CAPEX forecast, assuming CAPEX cost escalation.
- CAPEX related to new gas ***customer connections***, representing oil-to-gas conversions are also represented on the (bottom) chart. On this chart, total CAPEX including new customer connections are shown for a Reference Scenario. In an unmanaged transition, the CAPEX trajectory will show slight variations across scenarios due to differences in customer connections.

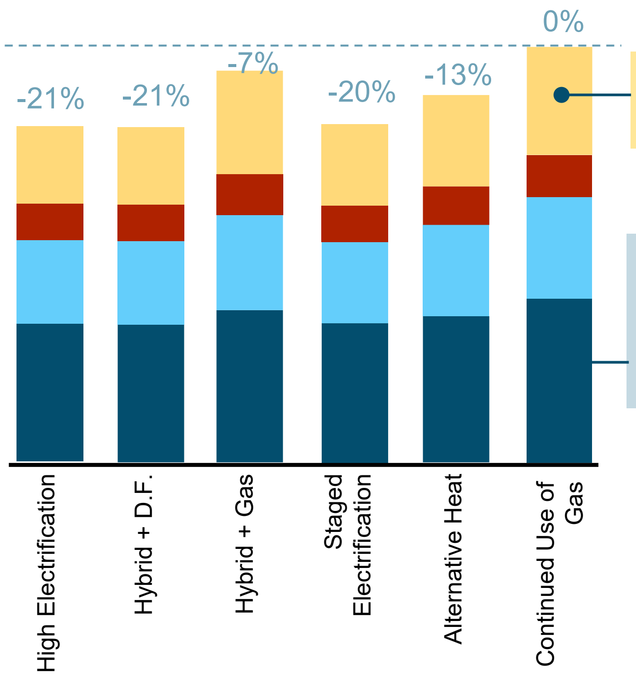
In an unmanaged transition, costs of the gas system will continue to rise

Planned levels of capital expenditures through ISR program and additional customer connections in a Reference Scenario cause **annual costs of the gas system to nearly double towards 2050**, assuming an *unmanaged transition.* Scenarios that do not assume additional customer connections reduce annual costs by approximately 20% by 2050.

RIE Gas Revenue Requirement (RR) in Reference Scenario



2050 Mitigation Scenarios (unmanaged)



Variations in O&M are a result of differences in customer departures and customer additions.

Return on capital costs increases across all scenarios as a result of capital expenditures. Scenario variations are the result of lower new customer connections compared to the Reference.

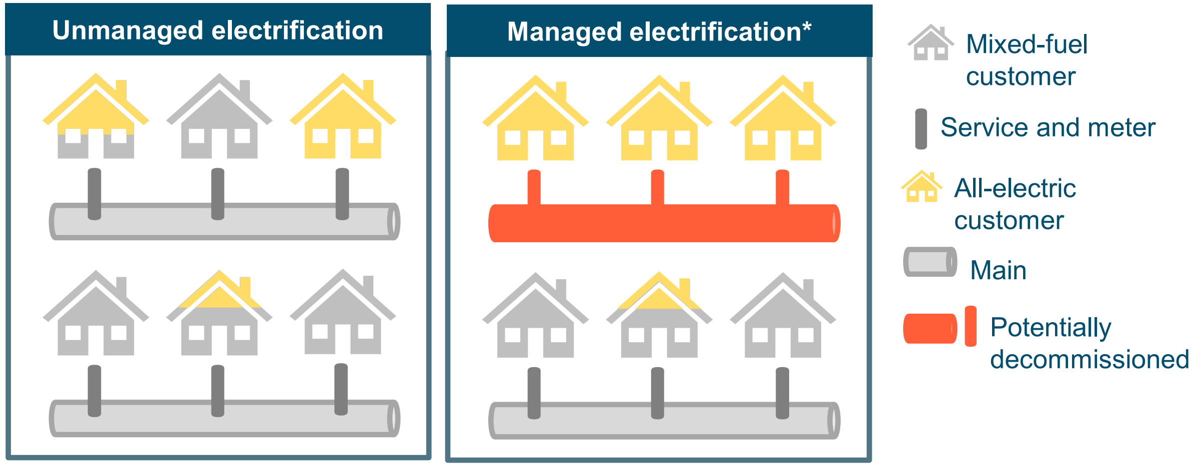
A managed transition assumes a portion of planned capital replacement costs can be avoided

All RIE Gas Distribution Mains **~3,200** miles

Scheduled Replacements **~1500** miles by 2050*

Hydraulically feasible **~750 miles** (50% of scheduled replacements **-** E3 illustrative assumption; requires RIE-specific study)

? ⟷ **Cost Effective** *For further investigation (out of scope for this study)*



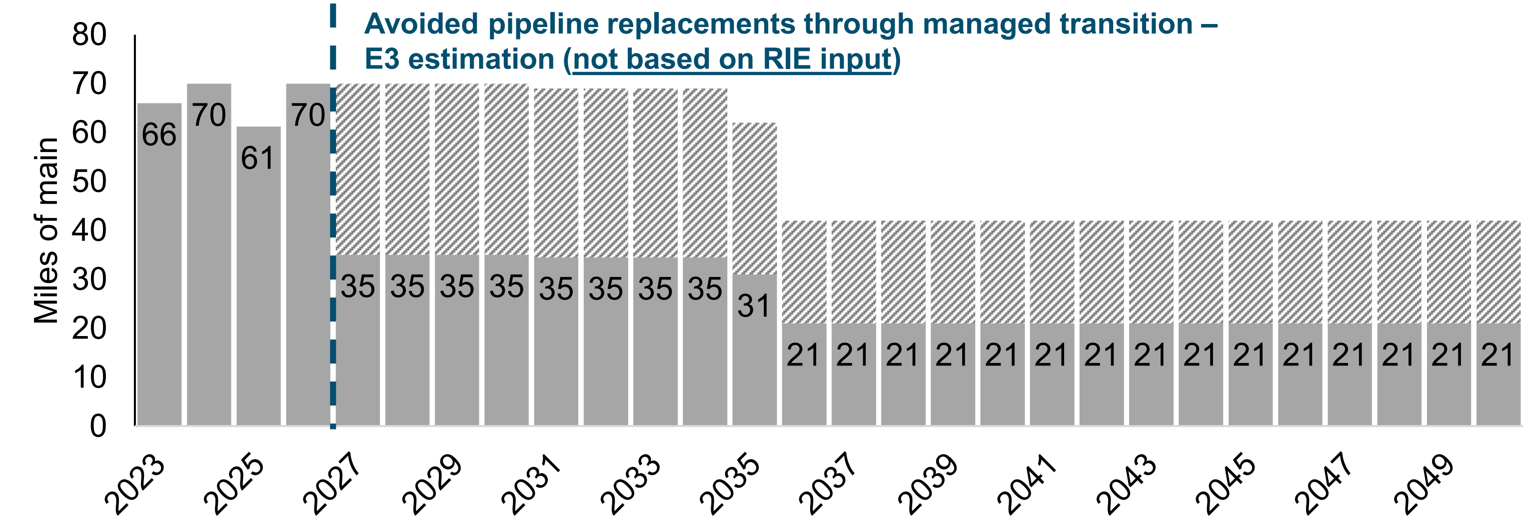
* Is o referred to as “**targeted/zonal electrification and gas decommissioning**”

- In a managed transition, investments and incentives will be **geographically focused** to allow parts of the gas system to be decommissioned
- Between now and 2050, **only a portion of RIE’s gas mains are up for replacement** and can result in avoided capex if retired. Capex is not avoided when retiring undepreciated gas mains.
- To retire a gas pipeline, it must be considered ***hydraulically feasible,*** meaning the gas system maintains gas flow and the minimum allowable pressure

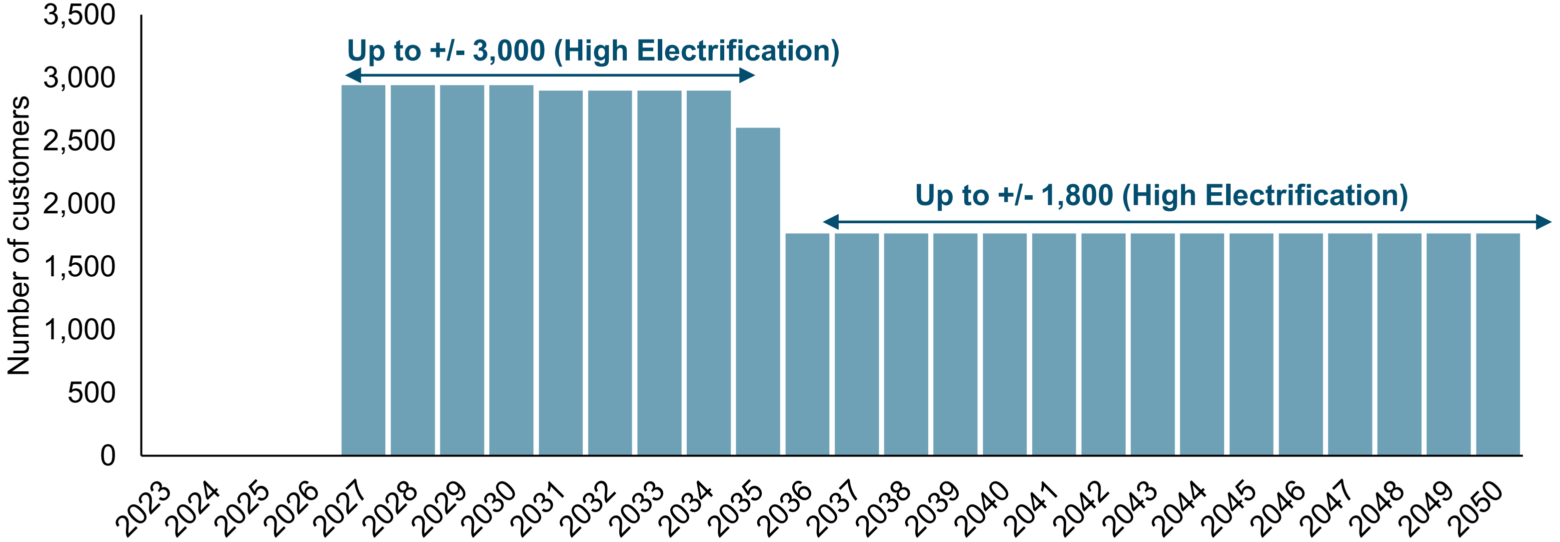
* ased on RIE’s esti ation of replace ent iles between 2023-2050 (see slide 43). Represents all cast iron + unprotected steel, plus additional post-2035 plastic mains that are expected to reach end of life.

A managed transition may avoid replacements, but requires significant levels of targeted electrification

Replacement Miles (Mains)



Required targeted electrification customers

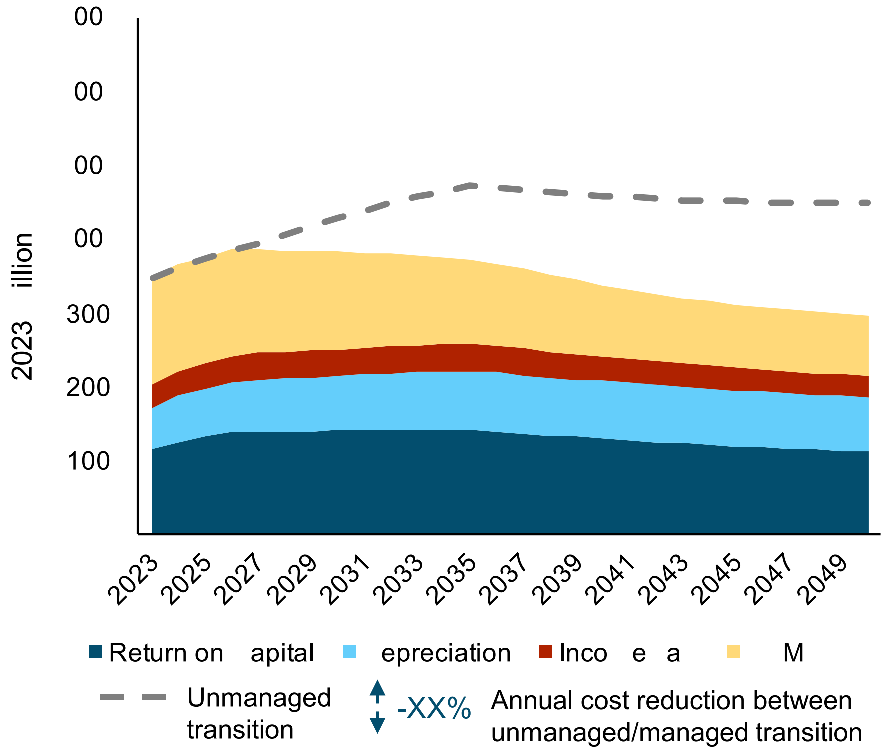


- In a managed transition, investments and incentives will be **geographically focused** to allow parts of the gas system to be decommissioned.
- To retire a gas pipeline, it must be considered ***hydraulically feasible,*** meaning the gas system maintains gas flow and the minimum allowable pressure.
- For the purpose of this study, E3 assumed that up to 50% of pipeline replacements may be avoidable in a managed transition***; this assumption is not based on input from RIE*** and needs significant additional study.
- If 50% of pipeline replacements are avoidable, up to 3,000 customers per year need to electrify their heating system in a targeted manner, with implications for customer choice.

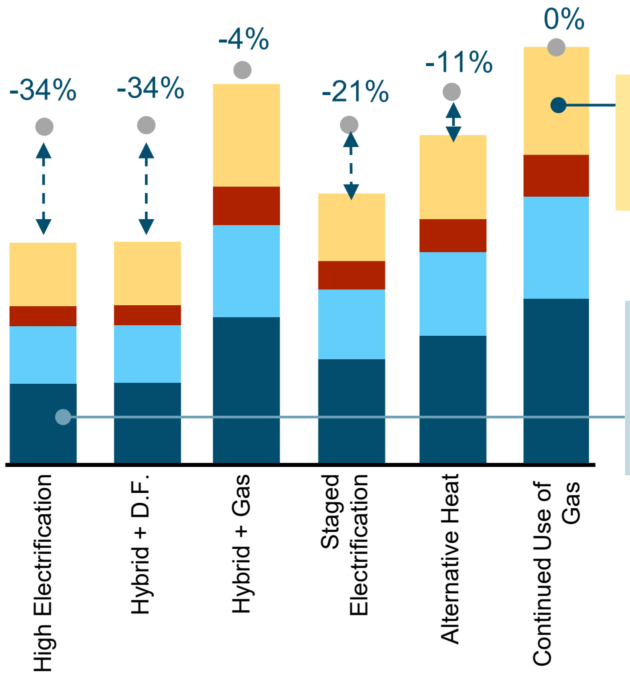
A managed transition can substantially reduce the costs of the gas system

A managed transition can reduce the costs of the gas system by nearly 35% compared to an unmanaged transition*,* primarily in scenarios that transition away from the gas system in the near term (High Electrification, Hybrid + Delivered Fuels, Staged Electrification). This translates to +/- $150 mln/year by 2050.

RIE Gas Revenue Requirement (RR) in High Electrification scenario (managed)



2050 Mitigation Scenarios (unmanaged vs. managed)



Higher O&M costs in the Continued use of Gas and Hybrid+Gas scenarios that require full maintenance of the gas system in the long term.

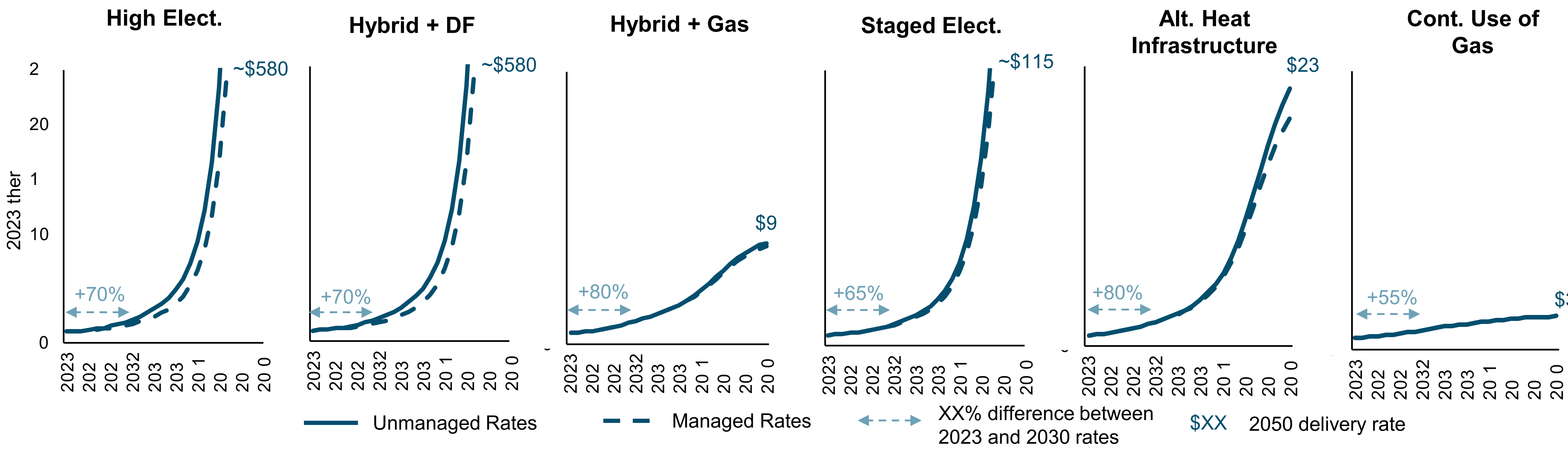
Scenarios that allow for a managed transition see a +/-50% reduction in return on capital compared to scenarios that require full maintenance of the gas system in the long term.

All mitigation scenarios lead to increased delivery rates; a managed transition can only partly mitigate this effect

Except for the Continued Use of Gas scenario, ***all mitigation scenarios lead to untenable long-term delivery rates in the long term*** for residential customers, driven by a combination of increased gas system costs and throughput decline. This effect mostly starts to materialize post-2035. A managed transition has a relatively small impact on this dynamic.

In the near-term, gas system cost increases combined with gas demand efficiency leads to substantial unit rate increases.

Residential gas rates in a managed versus unmanaged transition

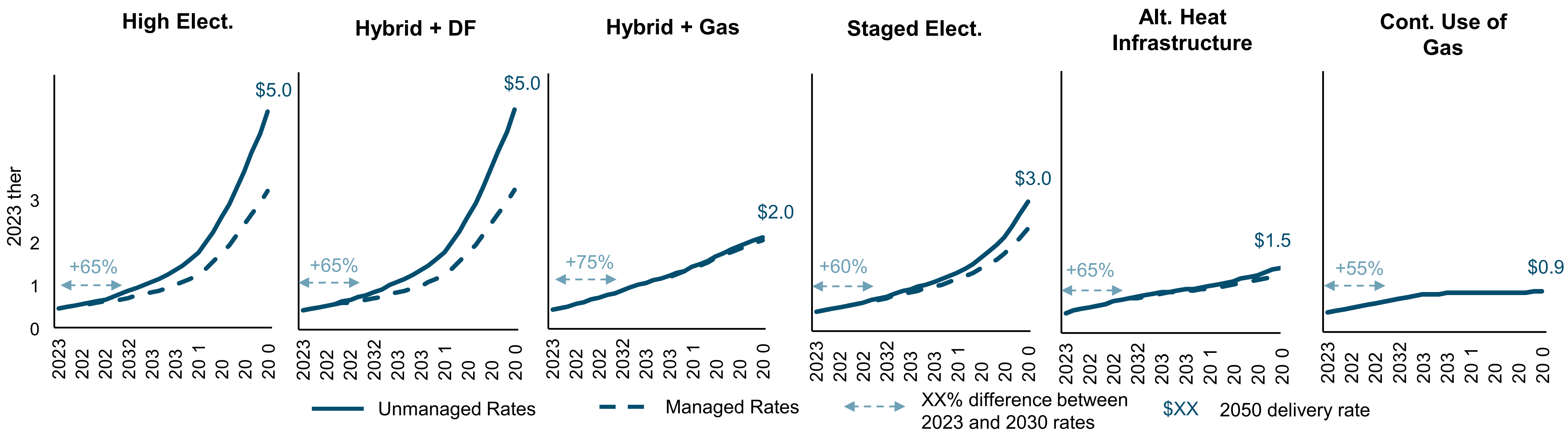


All mitigation scenarios lead to increased delivery rates; a managed transition can only partly mitigate this effect

Also for C&I customers, ***most scenarios lead to an increase in long-term delivery rates***, driven by a combination of increased gas system costs and throughput decline. This effect is not as significant as for the residential sector and mostly starts to materialize post-2035. A managed transition has a higher impact than for residential customers.

In the near-term, gas system cost increases combined with gas demand efficiency leads to substantial unit rate increases.

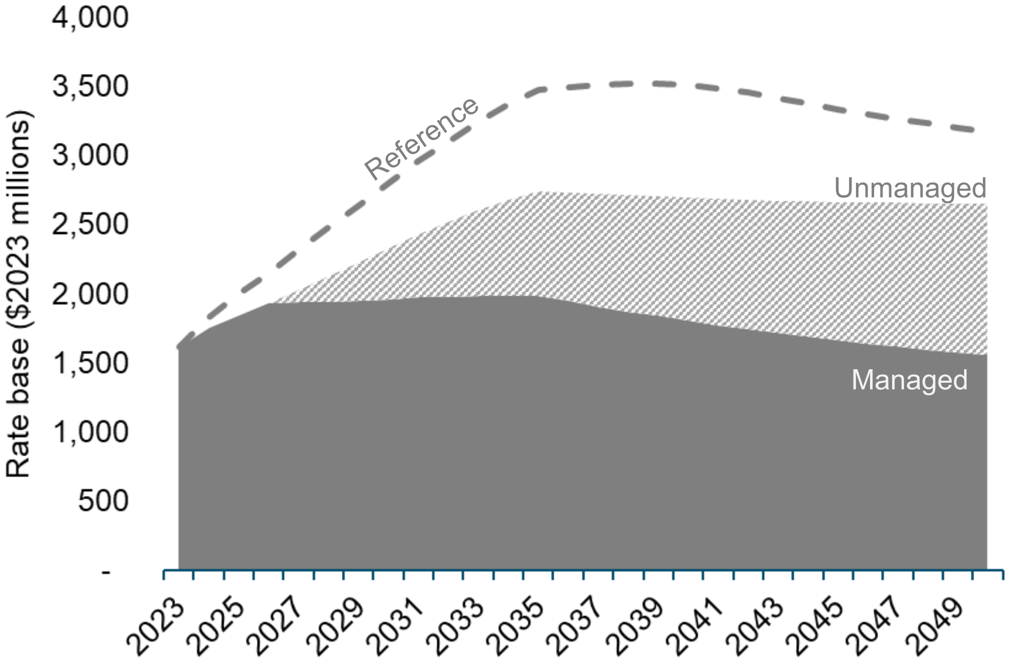
C&I gas rates in a managed versus unmanaged transition



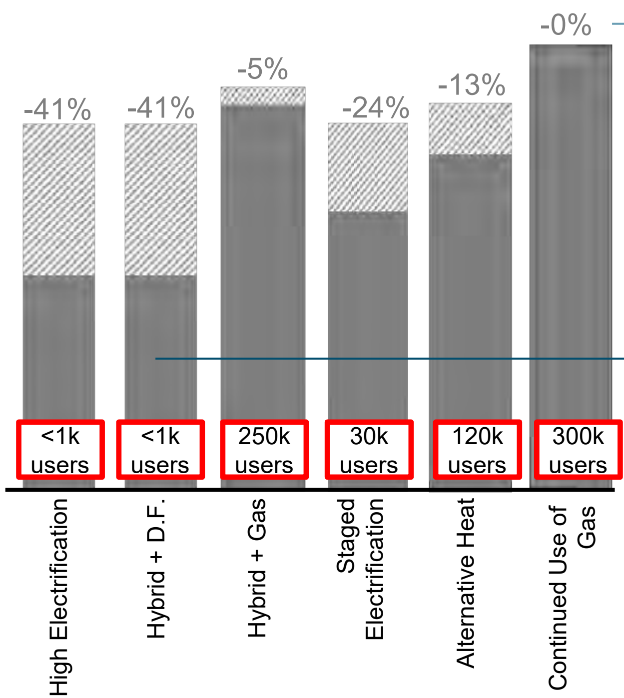
A managed transition could mitigate risks related to potential unrecovered costs in scenarios with customer departures

As the number of gas customers in a scenario declines, the **risk of unrecovered costs** on the system increases. In scenarios with high levels of electrification, remaining customers may not be able to shoulder the remaining system costs. A managed transition can help reduce remaining system costs (= rate base) by +/- 40% by 2050.

RIE Gas Rate Base in High Electrification scenario (managed vs. unmanaged)



2050 Mitigation Scenarios Rate Base (unmanaged vs. managed)



XX users — Number of gas customers remaining on the system that can participate in cost recovery

Difference in 2050 remaining rate base between unmanaged and managed transition

Continued use of Gas scenarios does not have opportunity for reduced gas system costs

A managed transition can reduce remaining rate base by 2050 by 41%. These scenarios have the lowest number of gas customers by 2050, and therefore the highest risk of unrecovered costs.

Decarbonization Pathways Technical Results

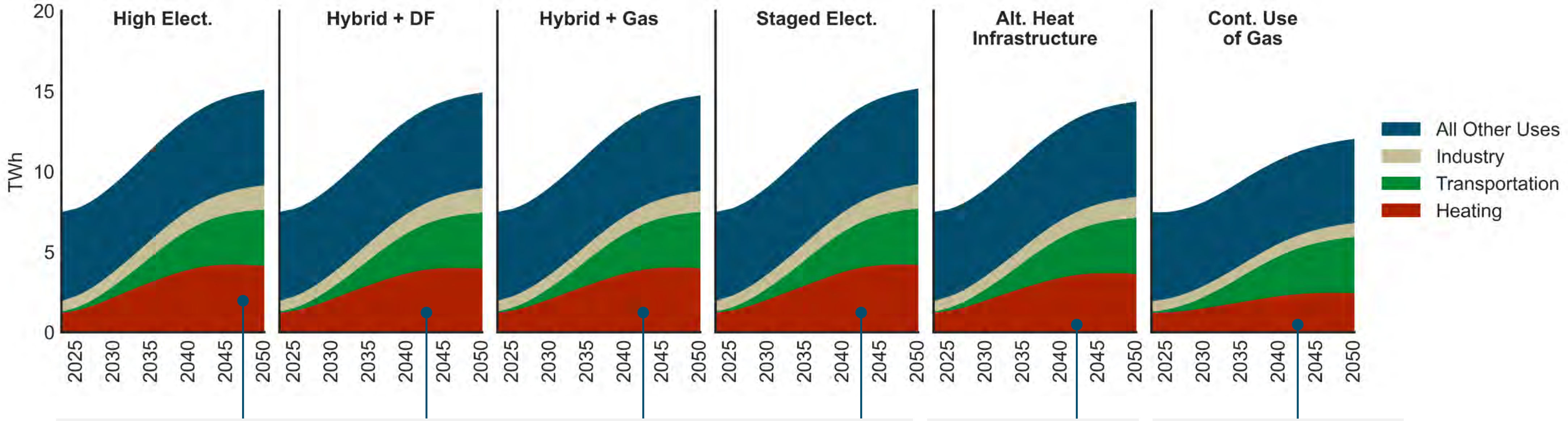
Impact on Electric System

Energy+Environmental Economics

Scenarios see varying levels of annual electric load growth, driven by heating and transportation electrification

Scenarios with high levels of electrification ***nearly double electric system load by 2050*** co pared   to today's levels. he primary driver of load increase is electrification of heating in scenarios with high levels of heat pump adoption, followed by transportation electrification (equal across scenarios).

Annual Rhode Island Electric Loads (TWh)



Scenarios with high reliance on either whole-home or hybrid HPs have similar amounts of total heating load growth. Hybrid heat pumps only have a minor impact on load growth.

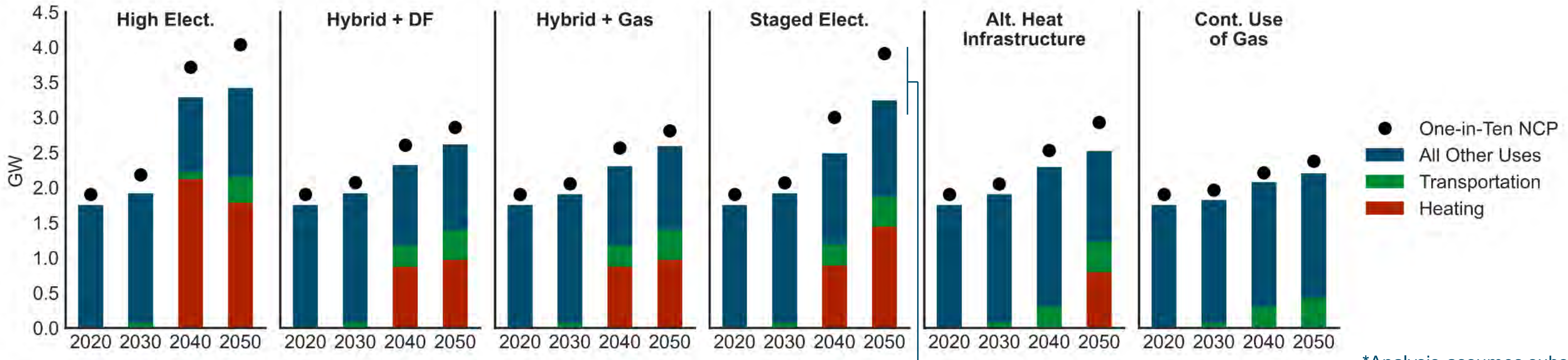
Networked geothermal mitigates some annual heating load growth

A lower pace of heating electrification results in lower heating load growth

Peak demands in RI may double towards 2050, scenarios with backup systems reduce electric impacts

Scenarios with high adoption of heat pumps switch to winter peaking in the 2030s. Median peak demand doubles in the High Electrification scenario – this effect is substantially mitigated in the hybrid scenarios that see an approximately 1 GW reduction in median peaks.

Post-Flexibility* Median Peak Loads by Contribution and 1-in-10 Total Noncoincident Peak (GW)



Scenarios with high reliance on either whole-home or hybrid HPs become winter peaking in 2030s

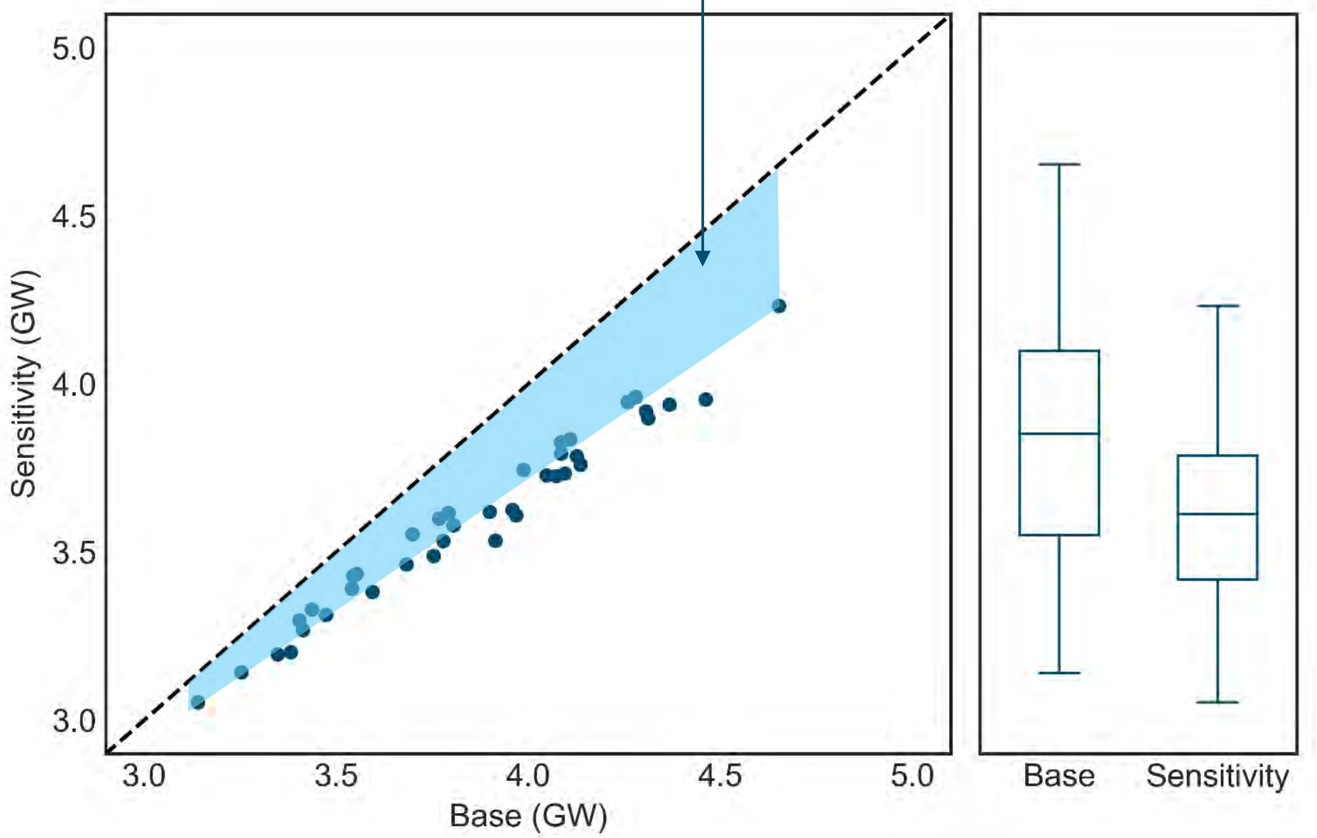
Peak loads in scenarios with high reliance on whole-home HPs are more sensitive to changes in weather. The High and Staged Electrification scenarios' 1-in-10 peaks grow more quickly than the Hybrid scenarios.

Scenarios with fewer ASHPs transition to winter peaking later or remain summer peaking.

*Analysis assumes substantial levels of load flexibility that allows peak contributions for several categories to shift load to different hours of the day. Assumptions include 50% LDV flexibility, 25% water heating flexibility, 5% space heating flexibility.

High-efficiency, whole-load heat pumps help to avoid peak load in the High Electrification scenario

Sensitivity analysis shows that ***higher efficiency heat pumps can avoid system peak impacts by approximately 250-300 MW*** under median peak heating conditions. High-efficiency heat pumps increasingly avoid peak load under increasingly extreme conditions by (1) avoiding supplemental electric resistance and (2) operating the compressor itself at higher levels of efficiency.



Loads shown in the chart are for 2050 and are *before load flexibility.*

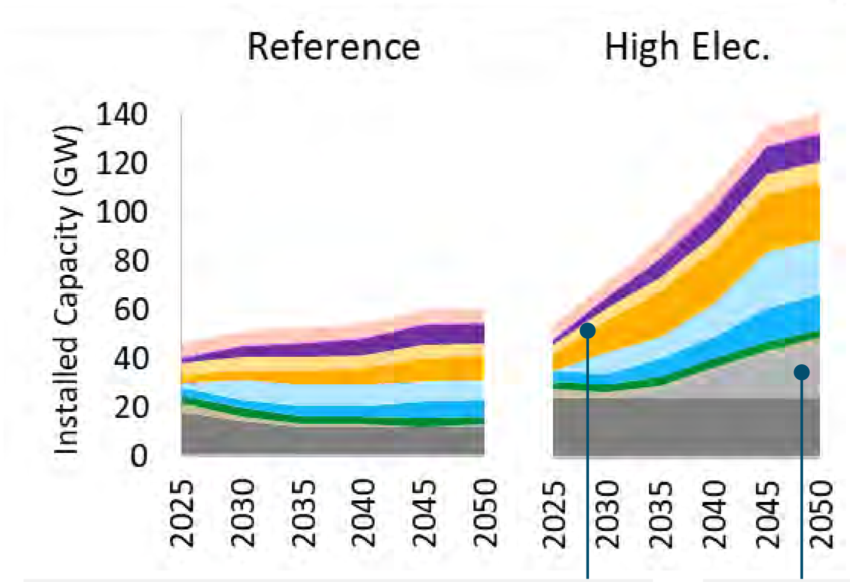
Under the most extreme conditions, high-efficiency heat pumps can avoid up to 500 MW of peak load before load flexibility.

Under median conditions, high-efficiency heat pumps can avoid up to 250-300 MW of peak load before load flexibility.

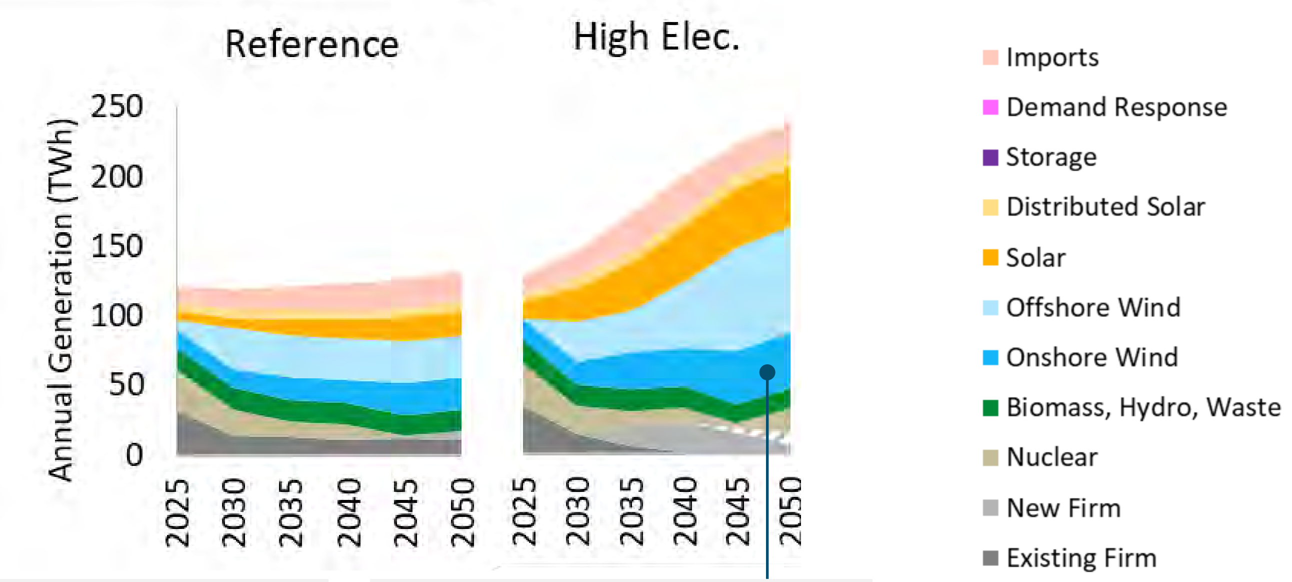
The New England electric system is expected to see transformational changes in generation and capacity

Renewables become a major source of electricity across all scenarios in New England, including in the Reference Scenario.
The need for firm (gas) capacity drops in Reference due to relatively flat load profiles, ***while new firm capacity is required in the other scenarios*** to reliably serve increasing demand from electrification.

Installed Capacity across ISO NE (GW)



Generation Mix across ISO NE (TWh)



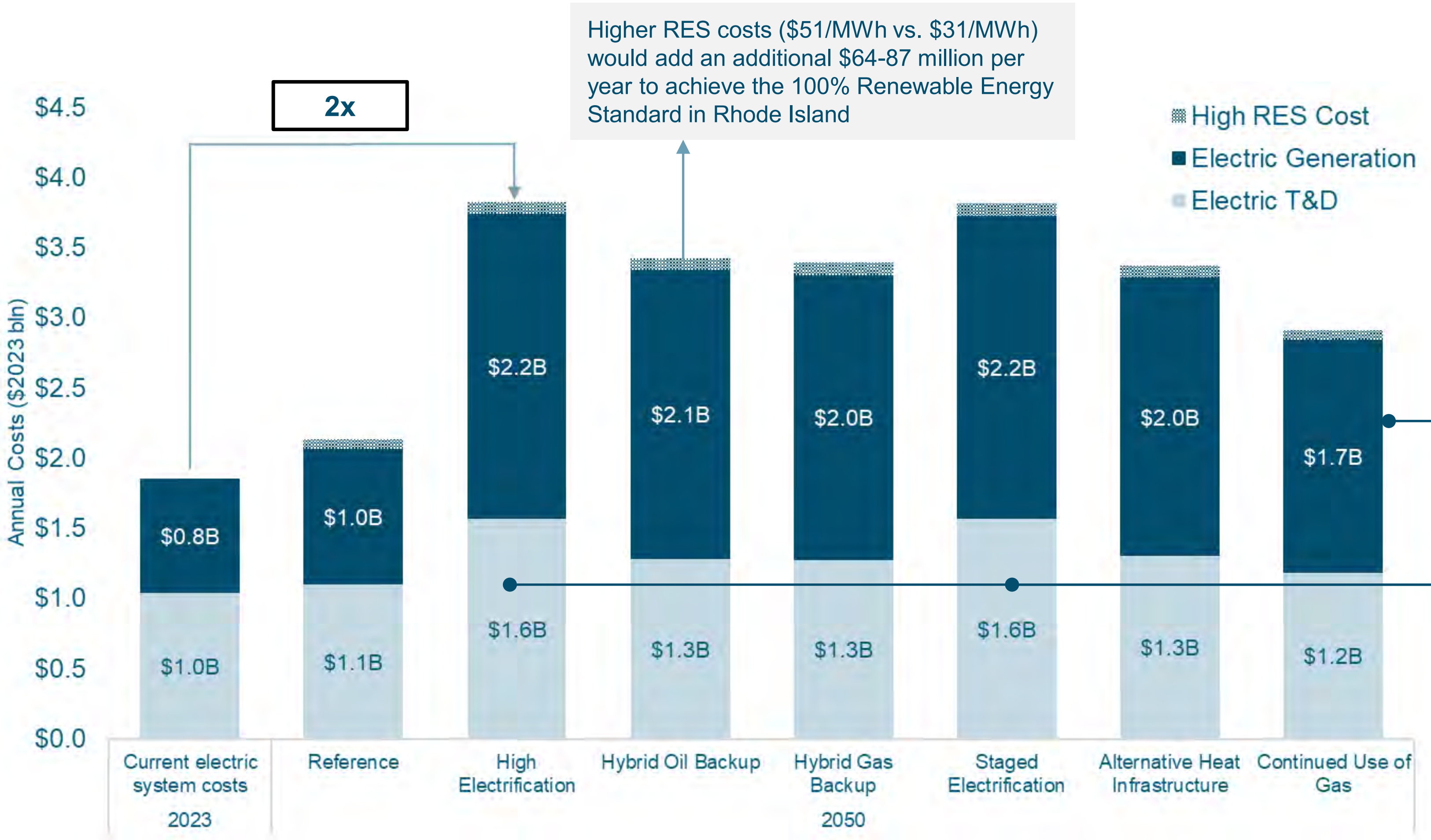
Substantial increase in renewables lead to nearly 3x higher installed capacity needs by 2050.

High Electrification increases the need for firm capacity to serve electric peak needs

Renewable generation in NE dominated by wind and solar

Total cost of electric service in Rhode Island approximately doubles by 2050 due to increased renewables & capacity needs

Current and 2050 Total Cost of Electric Service (2023$ Billion)



Total cost of electric service increases across all scenarios driven by (1) higher electric demand and (2) higher cost of electric generation to meet the 100% Renewable Energy Standard.

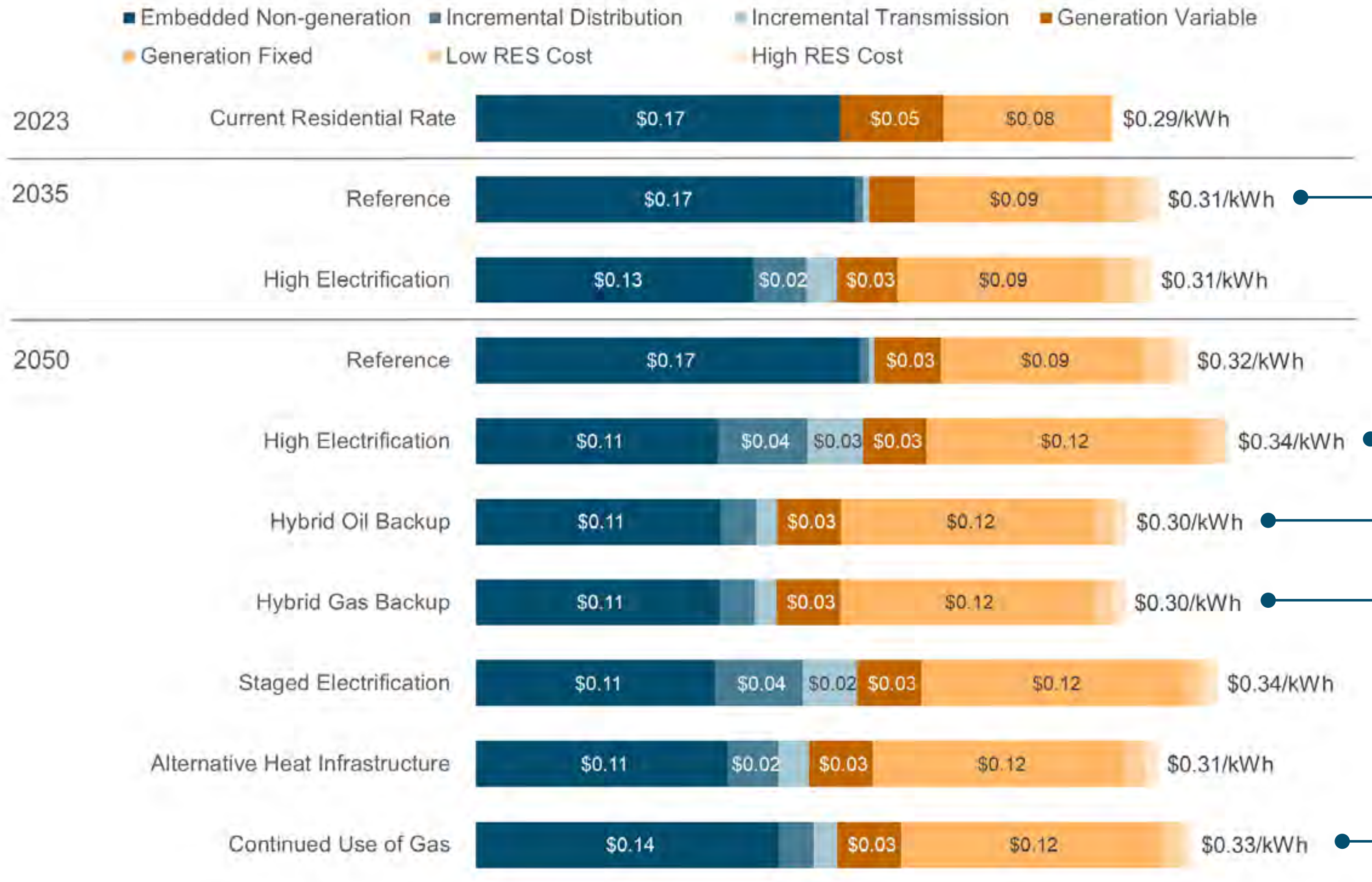
Continued Use of Gas scenario sees lowest costs of generation

Higher levels of T&D in the long term due to heat pump capacity needs

Cost of service increases are largely offset by increased loads, especially for scenarios with high load factors

CLF-1-3

Residential Electric Rates by Scenario and impact of RES



Residential rates increase across scenarios but are mitigated through load growth.

Achieving RES increases rates by ¢1.3-2.3/kWh* by 2035. By 2050, unit costs of RES are lower in mitigation scenarios due to load growth (¢0.9-1.5/kWh)

Higher heating load from all-electric heat pumps requires more capacity resources per MWh increase in load to ensure system reliability, thus driving up rates

Alleviated peak impacts reduce the need for capacity resources, increasing scenario load factors and therefore lowering the cost per MWh to serve electrification load

Relatively high rates due to lower levels of load increase with similar RES requirements

*Range represents REC prices of $31-51/MWh

Decarbonization Pathways: Assessment and Implications

Energy+Environmental Economics

Implications of scenarios can be viewed across multiple evaluation criteria to assess risks, benefits and challenges

Quantitatively assessed

Metric	Units
Economy-wide Costs (E3)	• Total incremental resource costs compared to reference scenario (cumulative NPV and annual costs) • $/ton abated by subsector

Customer Impacts (affordability, cost shifts) (E3)	• Number of targeted electrification projects in 2035 (customer choice)
	• Monthly customer bills for migrating and non-migrating customers (including amortized appliance costs)
	  ◦ *Migrating = customer adopting the decarbonization technology representative of the respective scenario*
	  ◦ *Non-migrating = customer not adopting a decarbonization technology that remains reliant on gas for heating*

Workforce Impacts (supported by RI Dept. of Labor & Training)	• # of jobs lost in gas sector • # of jobs gained in clean energy sectors • Job quality (wage) impact **Note: workforce impacts are not yet assessed in this presentation**

Qualitatively assessed based on quantitative outcomes

Metric	Evaluation	Based on
Air quality impacts (E3)	Air quality impacts tied to variations in fuel combustion	Levels of fuel combustion across scenarios
Reliance on (out-of-state) fuels (E3)	Reliance on level of renewable fuel that, given Rhode Island's footprint, will likely need to be imported from and producers that are out of state	Volume of renewable fuels
Technology Readiness (E3)	Reliance on commercially available technologies	Range of TRLs that are likely going to needed in scenario to comply with AoC.
Pace of electric system expansion (E3)	Pace and scale of electric sector infrastructure needs	Near-term (up to 2035) T&D investments and new installation of electric generation resources (e.g. offshore wind).

Implications of scenarios can be viewed across multiple evaluation criteria to assess risks, benefits and challenges

Scenarios see different levels of benefits, risks and challenges across multiple evaluation criteria. The matrix below provides a first step in assessing the implications of scenarios across the evaluation criteria discussed with the Stakeholder Committee.

Evaluation Criteria	Key Metric		Detail on slide	High Electrification	Hybrid + Delivered Fuels Backup	Hybrid + Gas Backup	Staged Electrification	Alternative Heat Infrastructure	Continued Use of Gas
Economy-wide Costs	Cumulative NPV in $bln*		62-65	$16-20	$15-20	$14-19	$15-19	$17-23	$16-26
Customer choice	Number of targeted electrification customers in 2035	*Unmanaged*	46-48. 66	0	0	0	0	0	0
		Managed	46-48. 66	3,000	3,000	0	1,200	700	0
Long-term affordability	2050 monthly total cost of ownership for migrating customer		67-68	+/- $800	+/- $800	+/- $800	+/- $800	+/- $900	+/- $800
Cost shifting to non-migrating customers	2050 monthly total cost of ownership for non-migrating customer		67-68	> $3,000	> $3,000	+/- $1,500	> $3,000	> $3,000	+/- $800
Workforce Impacts	*Not yet assessed*								
Air Quality Impacts	Change in statewide fuel combustion between 2020-2050 (%)		69	-85%	-82%	-81%	-85%	-82%	-65%
Reliance on (out-of-state) fuels	Total annual volume of renewable fuel required by 2050 (Tbtu)		70-71	11	15	15	11	13	33
Technology Readiness	Likely range of Technology Readiness Levels required to achieve AoC**		72-73	8-10	7-10	7-10	8-10	6-10	6-11
Pace of Electric System Expansion	Total increase in distribution system capacity by 2035 (GW)		74	1.2	0.5	0.4	0.5	0.4	0.2

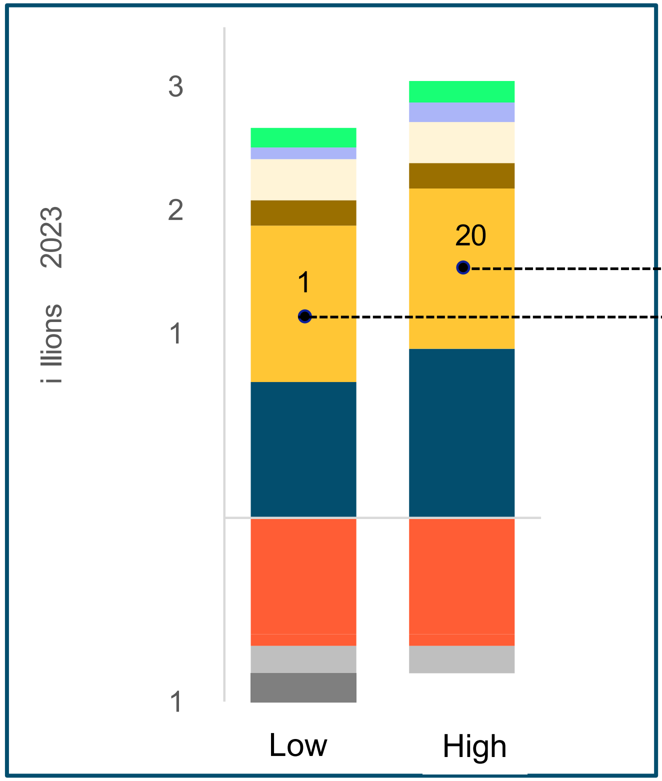
Initial considerations:

- Higher cost risk due to uncertainty in costs of large-scale renewable fuels
- High customer choice impacts if managed transition is achieved
- Relative affordability of heat pumps improves as delivery & supply costs of gas rise. Cost shift risk exist for scenarios with high levels of customer departure.
- Air quality benefits across scenarios, lower benefits for scenarios with more fuel combustion
- Higher risk of out-of-state fuel reliance for scenarios with higher levels of renewable fuels
- Reliance on networked geothermal or synthetic fuels to meet AoC targets
- Rapid electric capacity needs increase risk of system congestion

* Expressed as cumulative Net Present Value (NPV) between 2023-2050, incre ental to a reference scenario. osts shown for “un anaged” transition.
** Detail on Technology Readiness Level (TRL) ranges provided on slide 72.

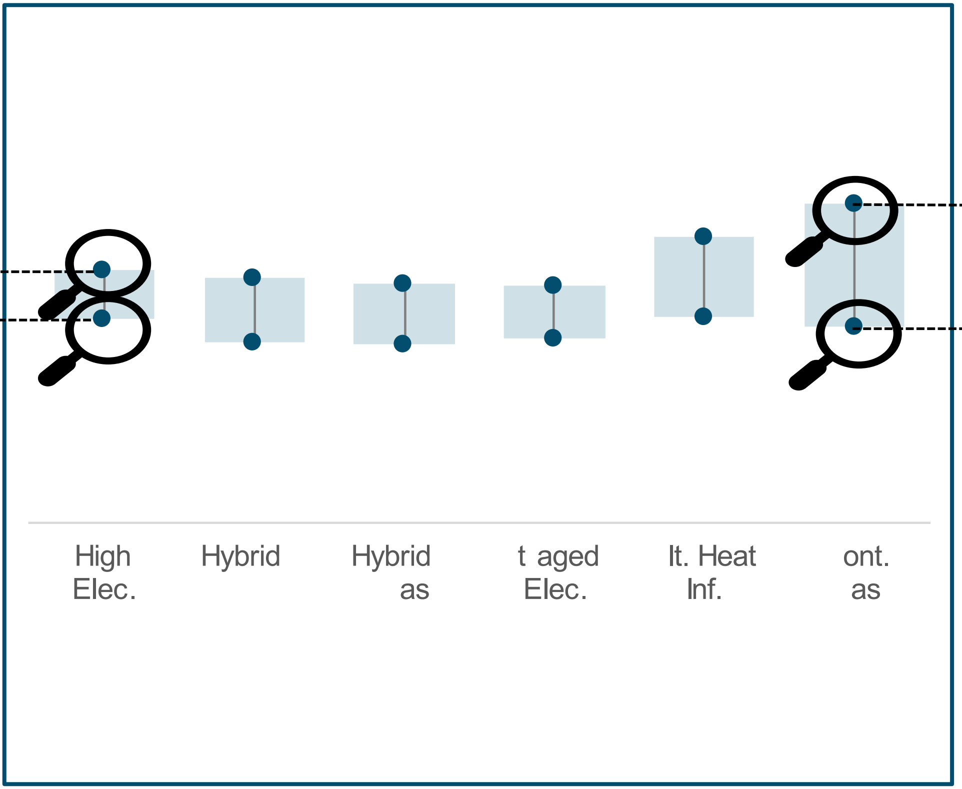
Economy-wide costs: Economy-wide costs show similar ranges with highest uncertainty in cost of renewable fuels

Detail by category: High Electrification



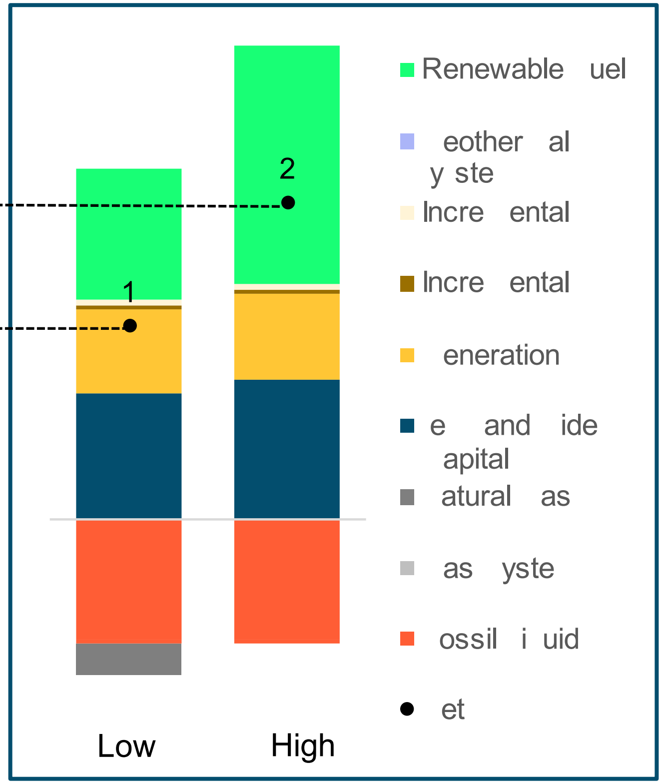
Device adoption and electric sector drive cost. Scenario shows the smallest range between optimistic and conservative cases due to limited role of fuels

Range of cumulative net NPV* costs across scenarios



Scenarios with a role for hybrid heating are favorable under both conservative and optimistic parameters

Detail by category: Continued Use of Gas



Uncertainties in renewable fuel costs drive highest variability in Continued Use of Gas scenario.

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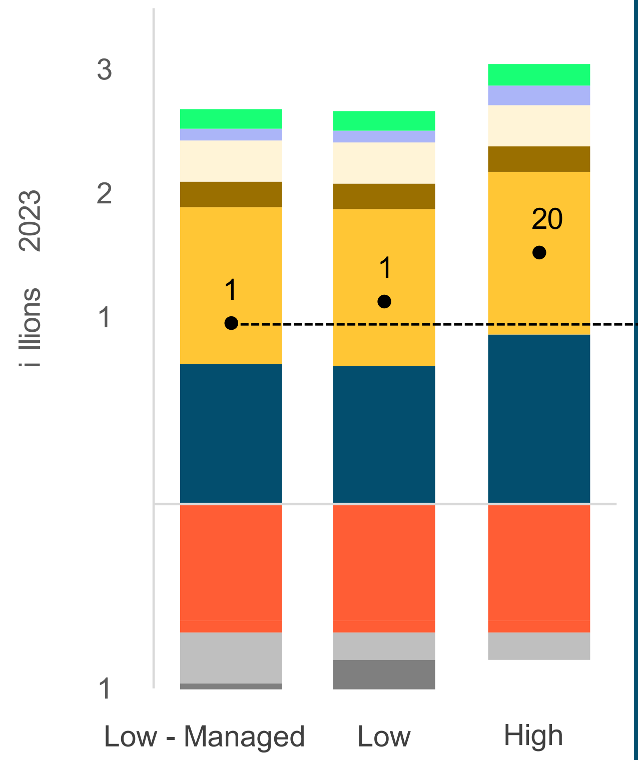
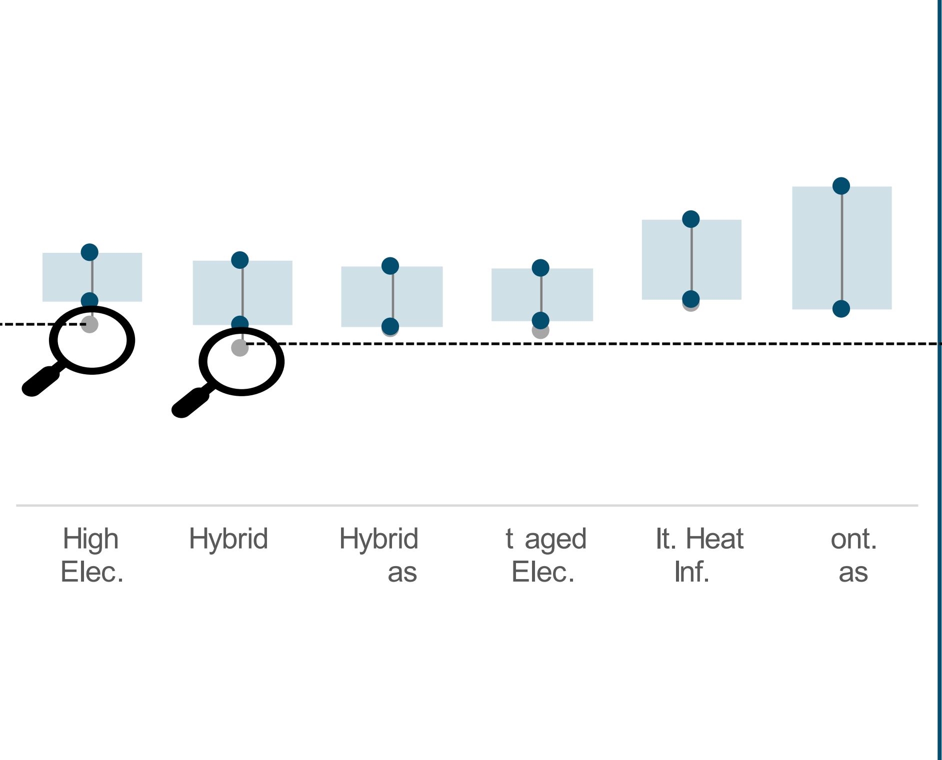
* Expressed as cumulative Net Present Value (NPV) between 2023-2050, incremental to a reference scenario. Discount Rate = 1%.

Economy-wide costs: A managed transition can reduce costs if long-term gas infrastructure is avoided

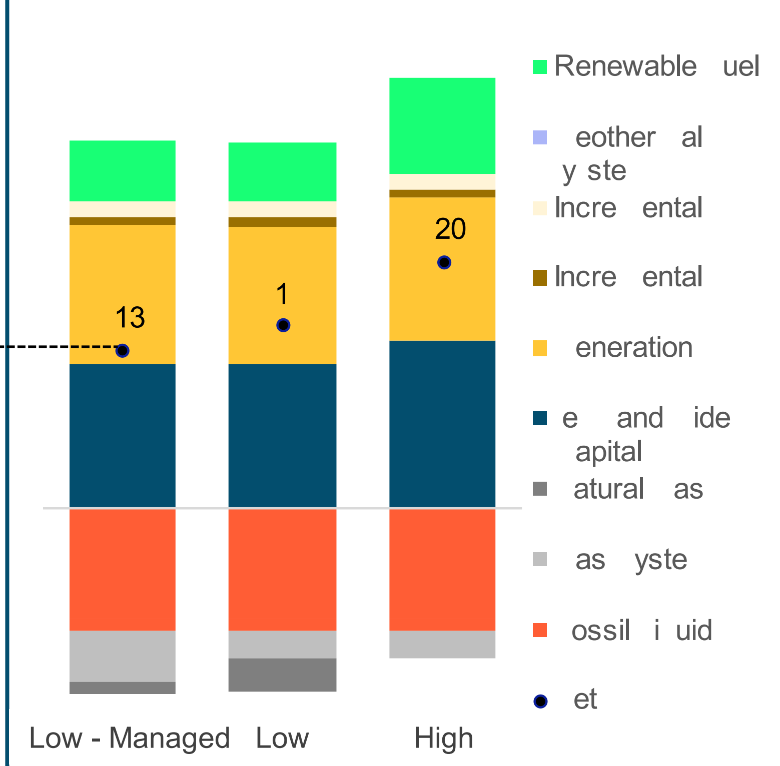
Detail by category: High Electrification



Range of cumulative net NPV* costs across scenarios



Detail by category: Hybrid + Delivered Fuels Backup



A managed transition reduces economy-wide costs, mostly in scenarios that are able to avoid long-term gas infrastructure.

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* Expressed as cumulative Net Present Value (NPV) between 2023-2050, incremental to a reference scenario. Discount Rate = 1%.

Economy-wide costs: Uncertainty analysis shows highest levels of risk for renewable fuels and networked geothermal

CLF-1-3

Sensitivity →

↓ Scenario

Incremental cost above Reference ($2023 billions cumulative NPV)							
	Low bound	Man. Trans.	High Heat Pump	High RECs	High Renew Fuel	High Net. GSHP	High bound
High Electrification	$16.4	$14.6	$19.1	$16.8	$16.8	$17.0	$20.3
Staged Electrification	$14.9	$14.1	$17.2	$15.2	$16.4	$14.9	$19.1
Alternative Heat Infrastructure	$16.7	$16.3	$18.6	$17.0	$18.7	$18.9	$23.1
Continued Use of Gas	$15.8	$15.8	$16.9	$15.9	$24.5	$15.8	$25.8
Hybrid Gas Backup	$14.5	$14.3	$16.5	$14.8	$16.9	$14.5	$19.3
Hybrid DF Backup	$14.6	$12.7	$16.6	$15.0	$17.5	$14.6	$19.8

Uncertainty across scenarios and sensitivities ($2023 billions cumulative NPV)							
	Low bound	Managed Trans.	High Heat Pump	High RECs	High Renew Fuel	High Net. GSHP	High bound
High Electrification	$1.9	$1.9	$2.5	$2.0	$0.4	$2.5	$1.2
Staged Electrification	$0.4	$1.4	$0.7	$0.4	$0.0	$0.4	$0.0
Alternative Heat Infrastructure	$2.2	$3.6	$2.1	$2.2	$2.3	$4.4	$4.0
Continued Use of Gas	$1.3	$3.1	$0.4	$1.1	$8.2	$1.3	$6.7
Hybrid Gas Backup	$0.0	$1.6	$0.0	$0.0	$0.6	$0.0	$0.2
Hybrid DF Backup	$0.2	$0.0	$0.1	$0.2	$1.1	$0.2	$0.7

Uncertainty analysis is based on Regret Analysis from Decision Theory[1]. "Regret" is defined as the e tra cost of a given scenario above the lowest cost scenario within each sensitivity (column). A regret of zero indicates that scenario was the lowest cost scenario within that sensitivity. All sensitivity costs are shown as incremental to the lowest costs values, changing one variable at a time.

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[1]Peterson M. *An Introduction to Decision Theory.* Cambridge University Press, 2013.

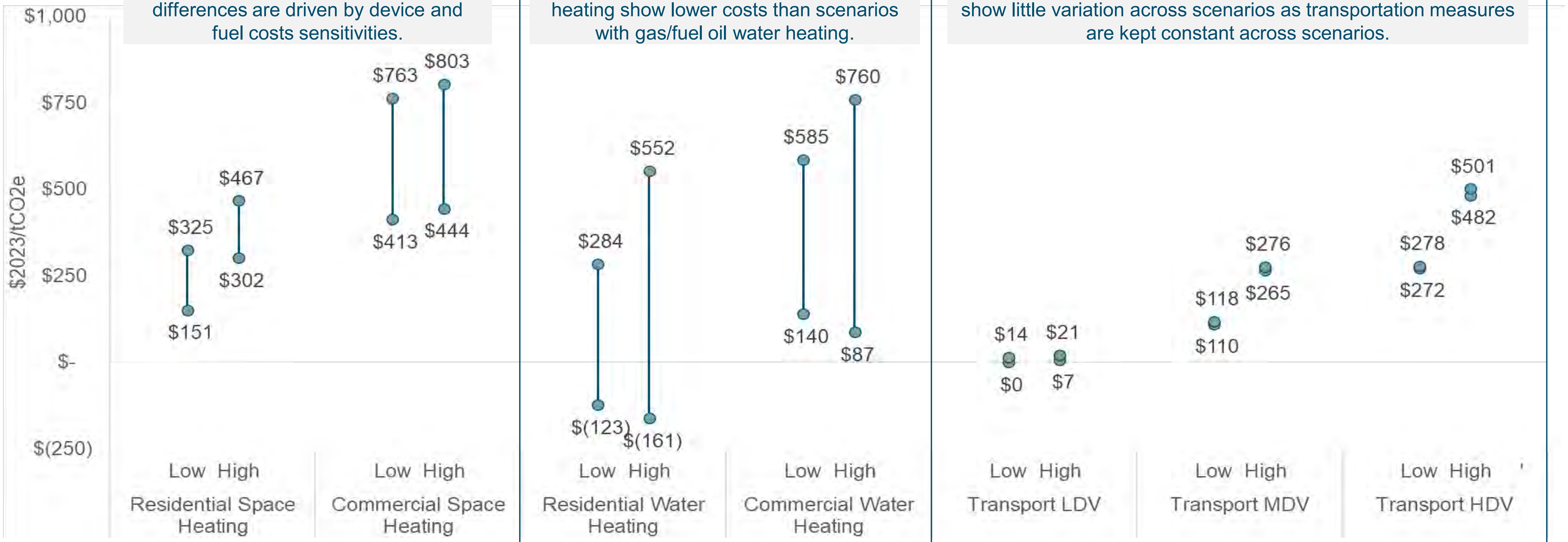
Economy-wide costs: abatement costs show differences in cost-effectiveness across subsectors

Range of abatement costs* for each subsector found across scenarios, broken out by low/high cost parameters

Space heating electrification shows lower cost for the residential than commercial sector. Low/high differences are driven by device and fuel costs sensitivities.

Large variation in costs is driven by technology adoption differences across scenarios. Scenarios with electric water heating show lower costs than scenarios with gas/fuel oil water heating.

Across categories, LDV electrification is most cost-effective. Differences between low and high MDV and HDVs costs are due to the cost uncertainty associated with renewable fuels. Ranges show little variation across scenarios as transportation measures are kept constant across scenarios.



% economywide emissions reductions	24%	10%	6%	1%	25%	3%	7%

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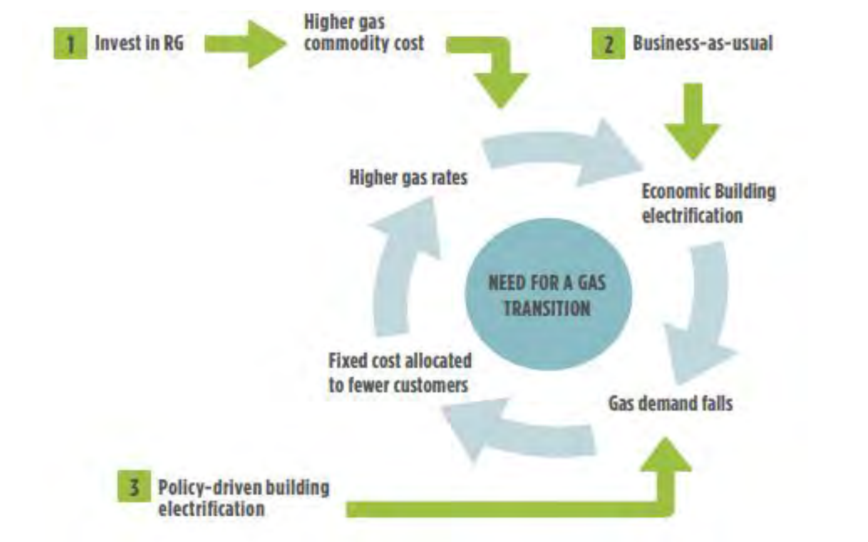
* Based on cumulative NPV of costs and emissions reduced between 2023-2050. The bars represent the range of abatement costs found across scenarios. The difference in low/high represent sensitivities in cost input parameters (low = optimistic, high = conservative).

Customer impacts: Unmanaged transition creates higher cost-shift risks; managed transition harms customer choice



In an ***unmanaged transition***, a reduction in gas demand leads to higher gas rates for remaining customers, which could lead to a spiraling effect as the cost-effectiveness of electrification increases.

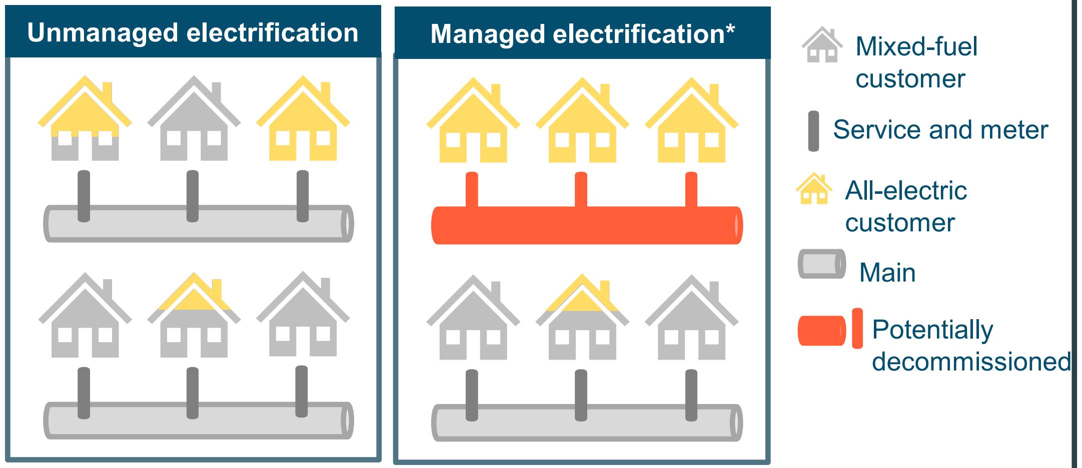
As the upfront cost of electrification are high, this effect could create ***equity issues*** as low-income customers are less likely to be able to afford electrification.

Scenarios with higher levels of customer departures, such as ***High Electrification and Staged Electrification*** see more equity risks; although hybrid scenarios may lead to similar impacts without ***rate design adjustments***.

In a ***managed transition***, neighborhood-specific targeted electrification projects are based on gas mains replacement schedules are required in order to avoid gas system costs.

This strategy requires a 100% opt-in from customers ***or*** has significant implications for ***customer choice***, as customers will need to agree to convert from gas to electric and or/geothermal systems.

The customer choice risk is only applicable to scenarios with ***near-term gas system departures***.

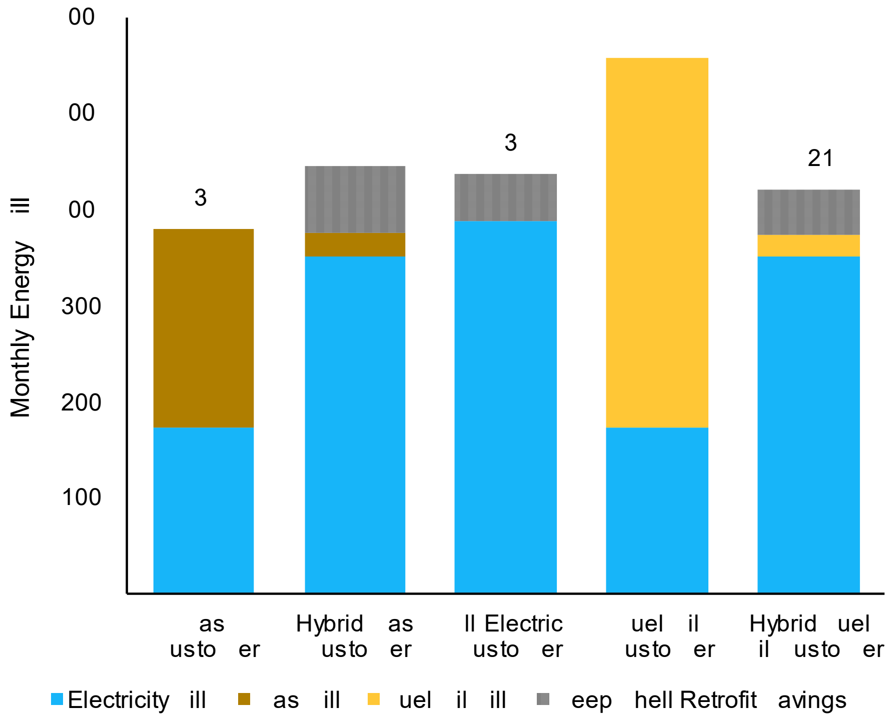


* Is o referred to as "**targeted/zonal electrification and gas decommissioning**"

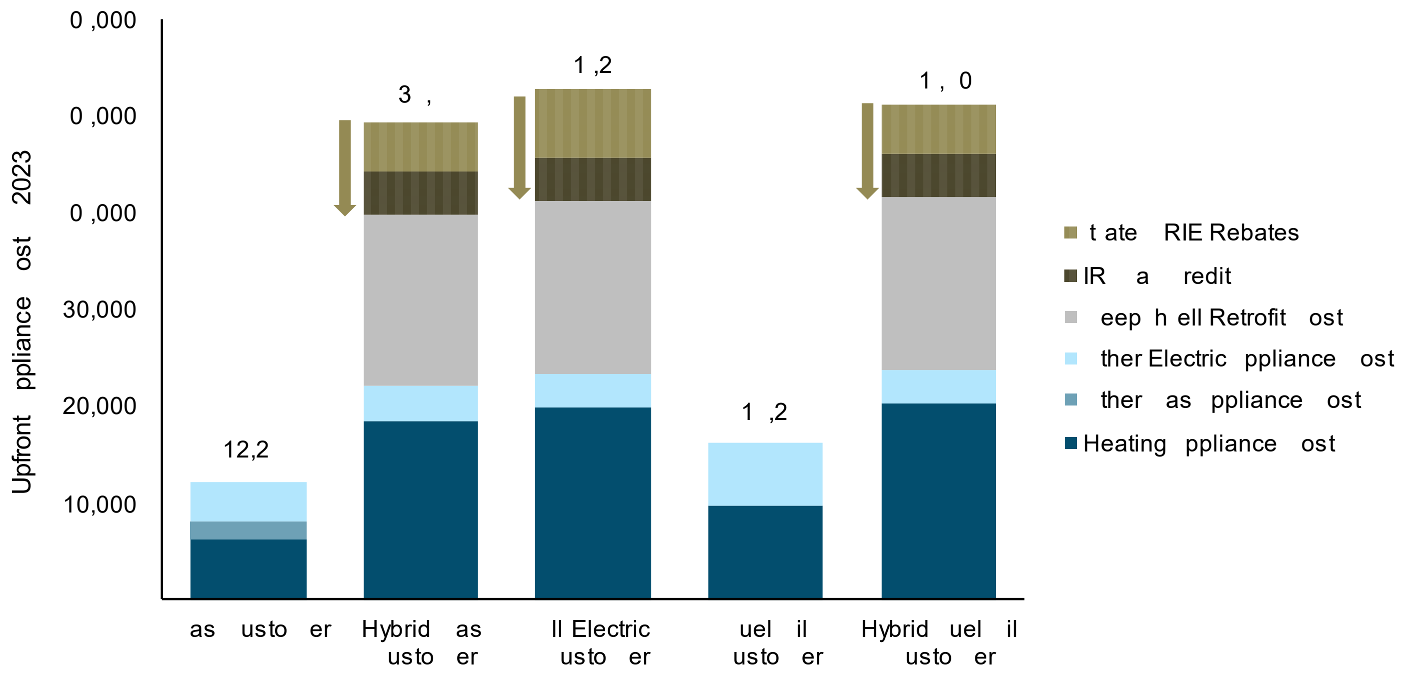
Customer impacts: Energy affordability is going to be key in understanding customer decisions

At current rates, **electrification is more expensive than using natural gas for heating and cooking purposes**, looking at energy bills only. This excludes the significant upfront costs associated with all-electric conversions. Energy bills could be reduced with deep shell retrofits, requiring larger upfront investments.

Energy Affordability in 2023 (residential monthly energy bills for Single Family pre-1960s home)



Upfront Cost in 2023 (residential appliance costs for single family pre-1960s home)

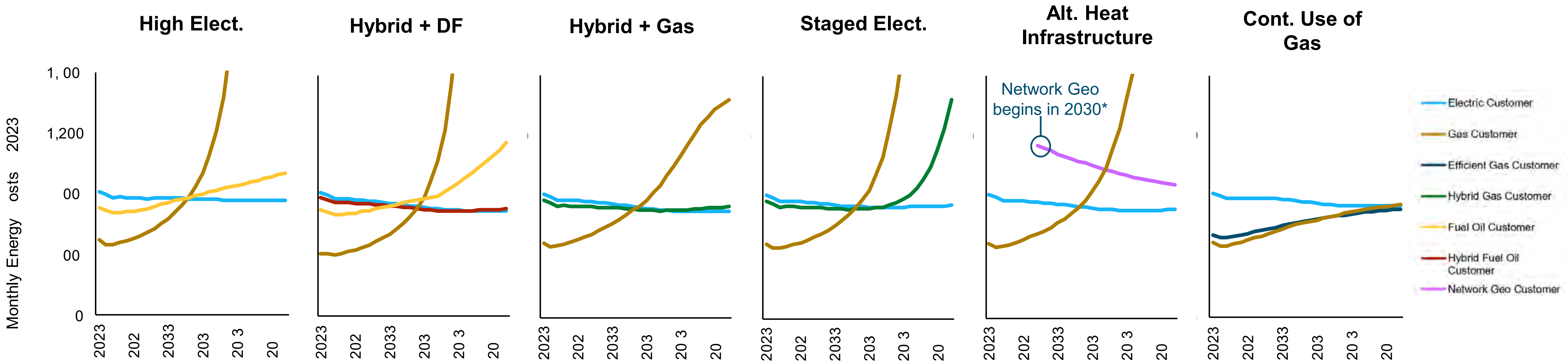


Note: Costs and energy impacts are shown inclusive of deep shell retrofits. In the PATHWAYS analysis, by 2050 34% of customers are assu ed to receive a deep shell retrofit, and % a “basic” cheaper shell retrofit. hese nu bers are si ilar across scenarios.

Customer impacts: Scenarios with gas customer reductions see a significant risk of cost-shifting

- Energy affordability is a challenge across all scenarios
- Gas customers face the highest energy costs in the long-term in all scenarios except Cont. Use of Gas
- The upfront cost of electric appliances and a building shell retrofit draws out the payback period for electric and hybrid customers

Monthly energy costs (energy bills + levelized upfront costs) for a residential single-family household under each scenario's rates

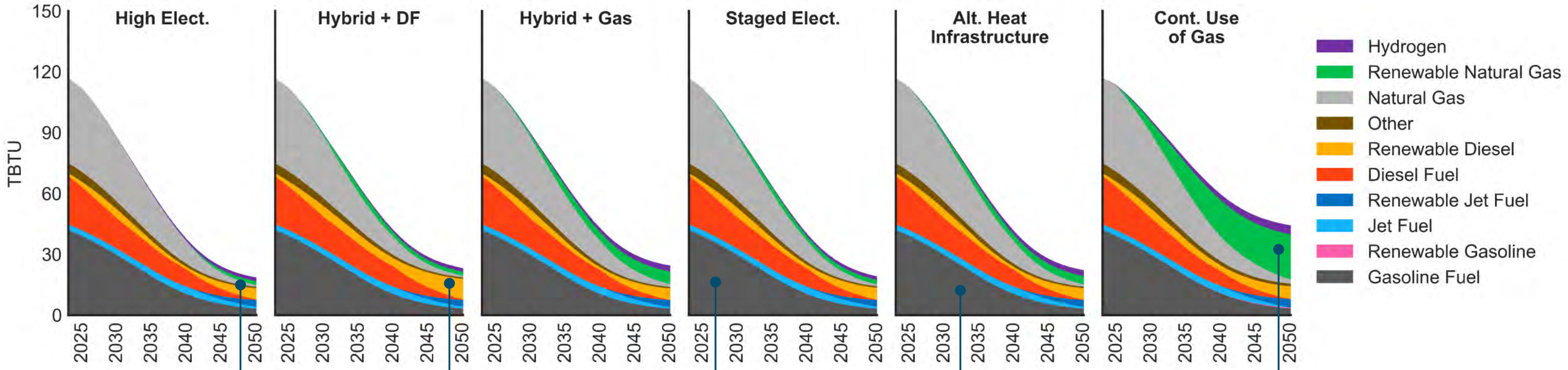


*Network geothermal costs are not socialized among geothermal and gas customers. The costs are assumed to be borne by geothermal customers only.

Air quality: Fuel combustion will decrease across all scenarios, greatest improvements in scenarios more electrification

The combustion of fuels produces emissions of pollutants, such as PM 2.5 and NOx. E3 assumes that the reduction of fuel combustion positively impacts air quality in Rhode Island. **Across scenarios, fuel combustion declines as a result of efficiency and electrification** in the transportation and buildings sector, implying air quality improvements. Scenarios with lower levels of electrification leave more fuel combustion.

All fuel combustion over time: (2023-2050)

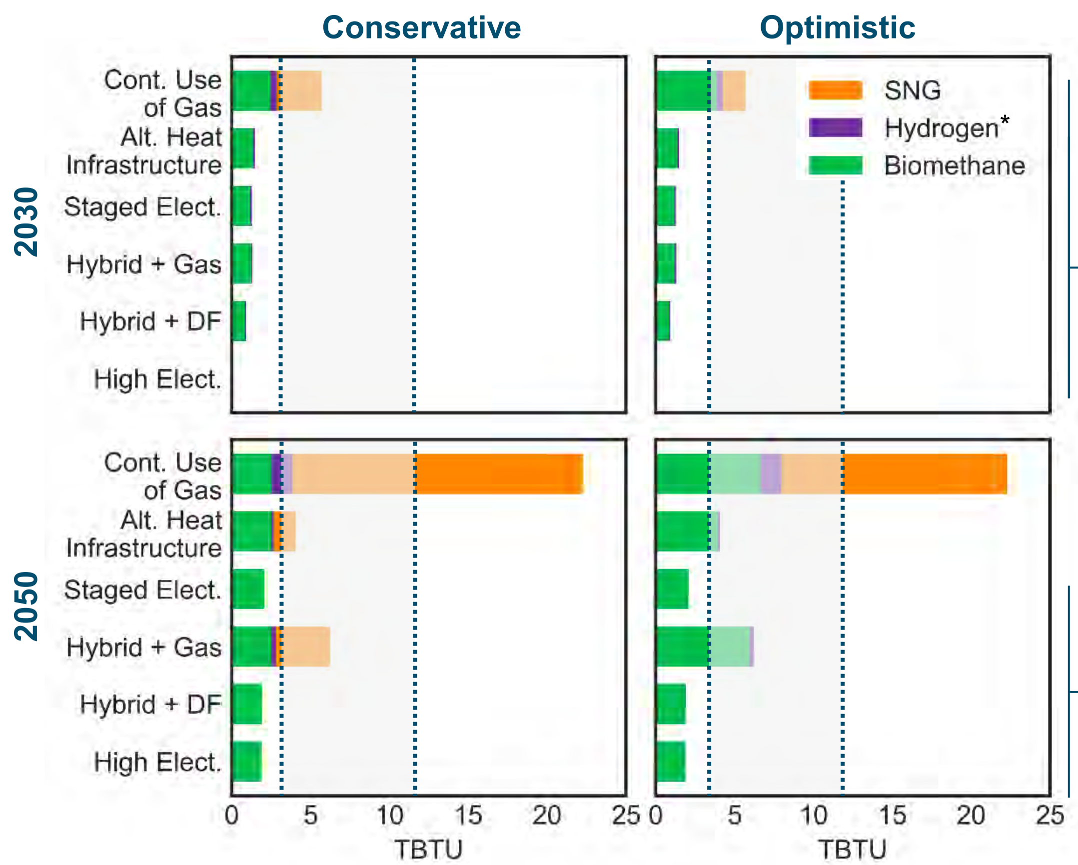


Scenarios with the largest reductions in combustible fuels are assumed to have the highest benefit in air uality i prove ent scored as "lower level of challenge" on the assess ent atri .

The Continued Use of Gas scenario reduces combustion of fuels substantially, but leaves more fuel combustion by 2050 compared to other scenarios.

Reliance on out-of-state fuels: Reliance on high amounts of renewable gas likely requires more synthetic fuels

Renewable pipeline gas demand: Conservative/optimistic availability



Shaded range represents a "fair share" of east-of-Mississippi biomass potential if all biomass would be converted to renewable natural gas. This range is not a cost-effective, market-based, or policy-driven allocation, but is instead based on industry natural gas demand (low end) or population (high end) weighted share.

E3 developed "conservative" and "optimistic" estimates of biofuel availability.

- Conservative: Thermal gasification is not commercialized within the timeframe of the study, leading to lower amounts of biomethane availability
- Optimistic: Thermal gasification is commercialized after 2030, resulting in higher amounts of biomethane availability

Scenarios with high amounts of direct decarbonization, such as electrification, will likely require relatively small amounts of biomethane and hydrogen.

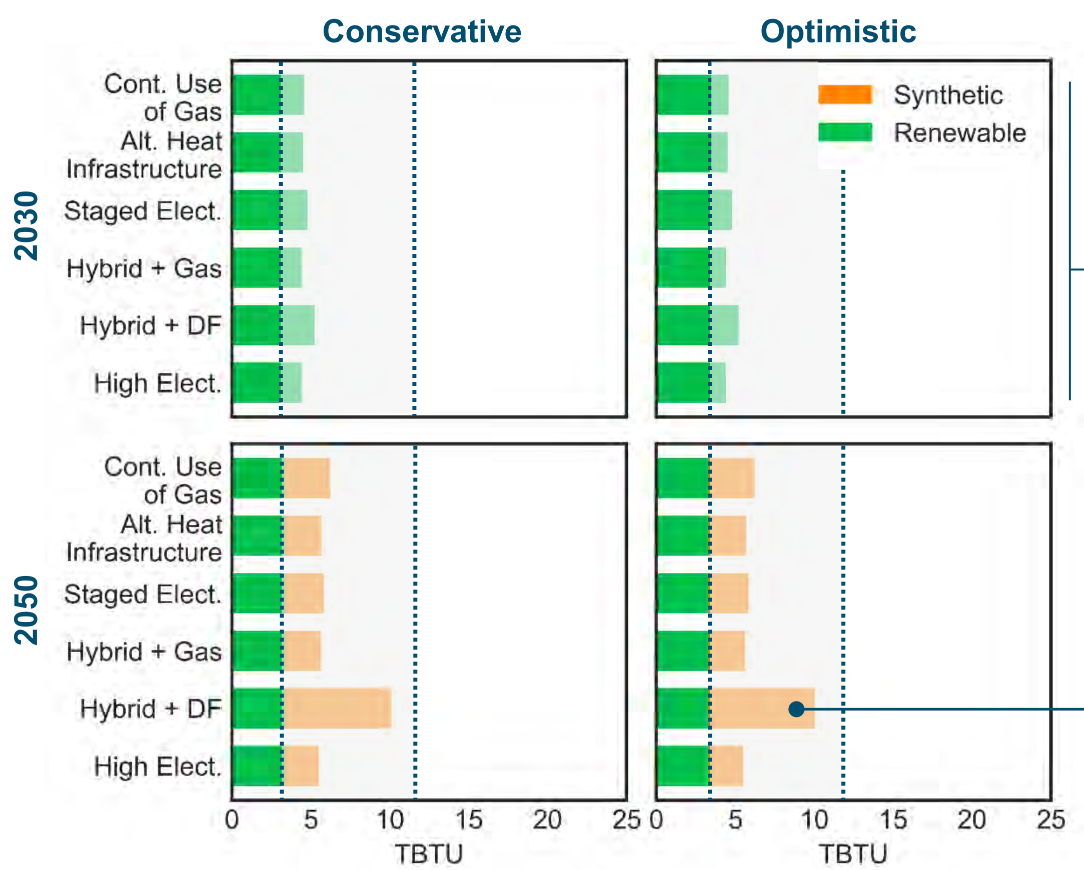
Full electrification can mitigate or entirely avoid the potential for synthetic gas.

- While not shown here, the **Hybrid Delivered Fuels Backup** scenario requires an increased amount of synthetic diesel to hit the economywide emissions target.
- The **Staged Electrification** scenario "threads the needle" by accelerating full electrification after 2030 and avoiding high synthetic fuel demand.

*Use of "pure" hydrogen H2 in gas network, as opposed to H and bio et hane

Reliance on out-of-state fuels: Reliance on high amounts of renewable diesel likely requires more synthetic fuels

Renewable diesel demand: Conservative/optimistic availability



Shaded range represents a "fair share" of east-of-Mississippi biomass potential <u>if all biomass would be converted to renewable diesel</u>. This range is not a cost-effective, market-based, or policy-driven allocation, but is instead based on industry natural gas demand (low end) or population (high end) weighted share.

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All scenarios rely on similar amounts of renewable diesel to satisfy the Biodiesel Act requirements.

The Hybrid Delivered Fuels Backup scenario requires an increased amount of synthetic diesel to hit the economywide emissions target.

Technology Readiness: Technology readiness is a key dimension to assess the risk of decarbonization options

Scale of Technology Readiness Levels as defined by IEA

Category	TRL	Description
CONCEPT	1	**Initial idea** Basic principles have been defined
	2	**Application formulated** Concept and application of solution have been formulated
	3	**Concept needs validation** Solution needs to be prototyped and applied
SMALL PROTOTYPE	4	**Early prototype** Prototype proven in test conditions
LARGE PROTOTYPE	5	**Large prototype** Components proven in conditions to be deployed
	6	**Full prototype at scale** Prototype proven at scale in conditions to be deployed
DEMONSTRATION	7	**Pre-commercial demonstration** Solution working in expected conditions
	8	**First of a kind commercial** Commercial demonstration, full scale deployment in final form
EARLY ADOPTION	9	**Commercial operation in relevant environment** Solution is commercially available, needs evolutionary improvement to stay competitive
	10	**Integration needed at scale** Solution is commercial and competitive but needs further integration efforts
MATURE	11	**Proof of stability reached** Predictable growth

Decarbonization scenarios rely on technologies with varying levels of readiness.

IEA has established a Technology Readiness Level (TRL) scale for decarbonization measures. A technology with a TRL of 11 is ready to scale, options lower than that need R&D and/or commercialization support.

Portfolios of decarbonization options that rely on lower TRL measures carry additional risk. For example, some scenarios may need to rely more strongly on synthetic fuels (see previous section), a technology that is still in prototype/demonstration phase.

E3 and other deep decarbonization researchers generally screen out technologies that are low (<5) on the TRL scale because of their speculative nature and the short time horizon of mid-century climate goals.

Technology Readiness: Decarbonization technologies need to reach maturity in order to meet the scale of RI’s climate goals

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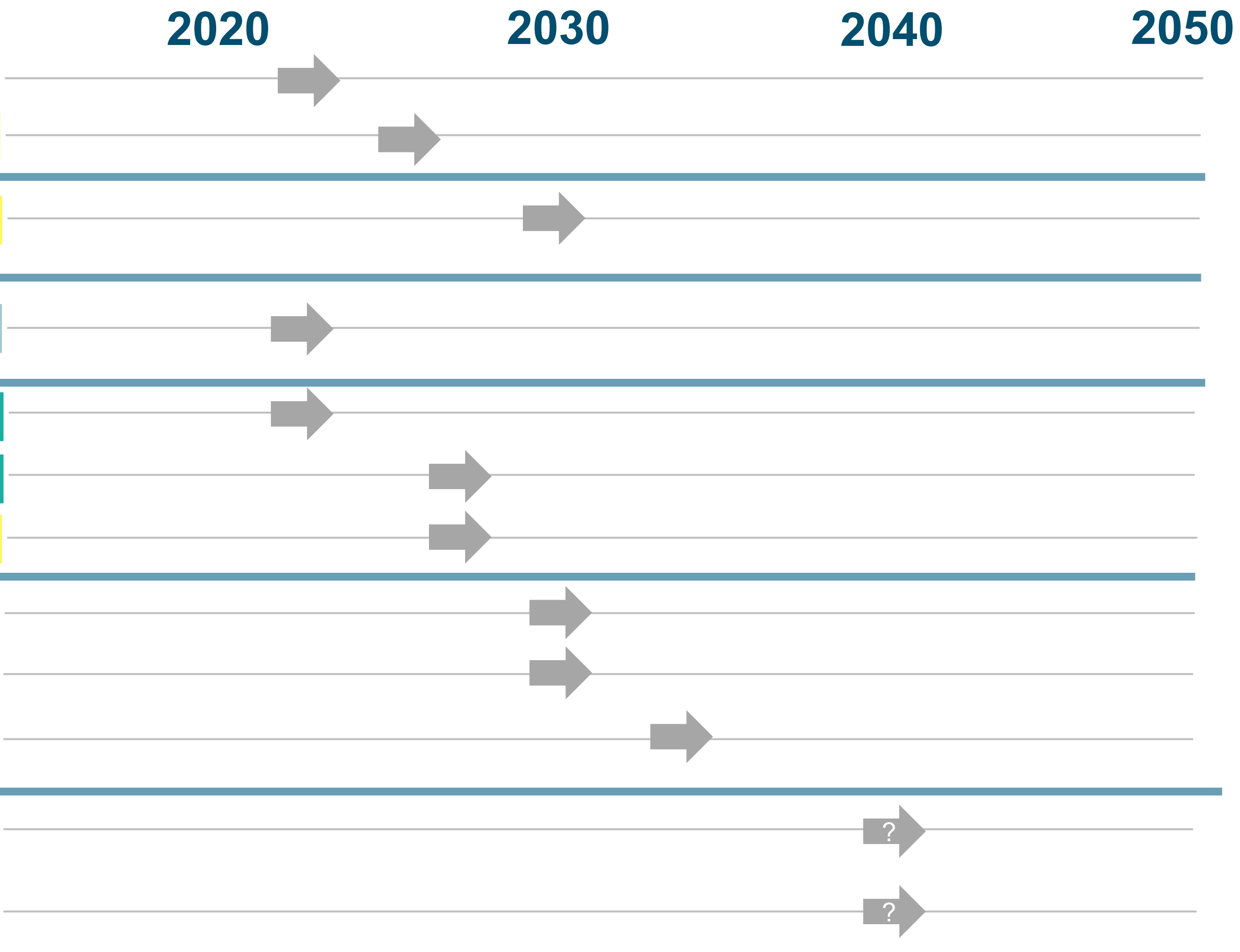
TRL = Technology Readiness Level

		oday’s R
Cold-Climate ASHP Most scenarios	Res/Small Commercial	10
	Large Commercial	8
Networked Geothermal In Alternative Heat Infrastructure scenario	Residential/commercial	7
Efficient Gas Appliances Continued Use of Gas scenario	Condensing furnaces	11
Biofuels All scenarios	Biodiesel	10
	RNG - Anaerobic digestion	10
	RNG - Bio-gasification	7
Hydrogen All scenarios for power gen and transportation sector, some scenarios for dedicated pipeline delivery	Alkaline electrolyzers	9
	H2 blending	7
	Dedicated hydrogen network & use	6
Synthetic Fuels Likely required in Continued Use of Gas, Hybrid + DF, Hybrid + Gas	Synthetic biodiesel	6
	Synthetic gas with climate-neutral carbon source	6

Expected timing of technology ramp-up in scenarios



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Note: TRLs are based on values from an IEA database, modified in some cases by E3 based on our professional judgement, including an assessment of RI specific context.

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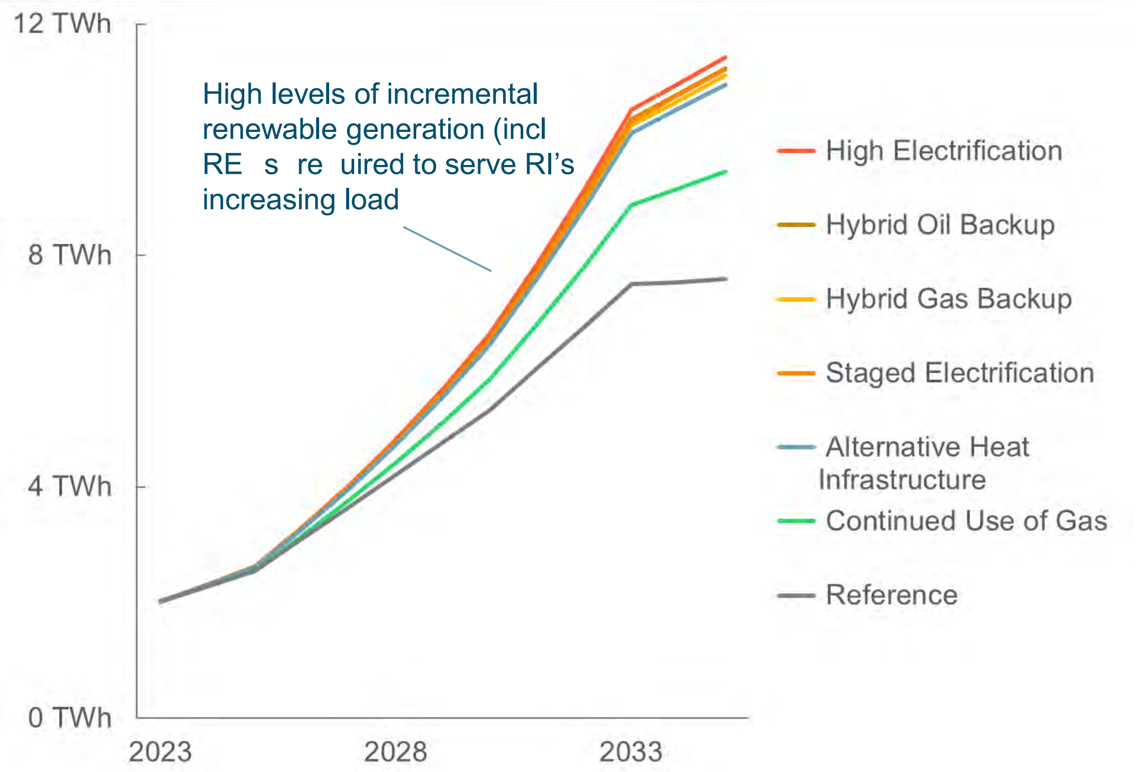
Pace of Electric System Expansion: All scenarios require significant renewable buildouts to comply with 100% RES

CLF-1-3

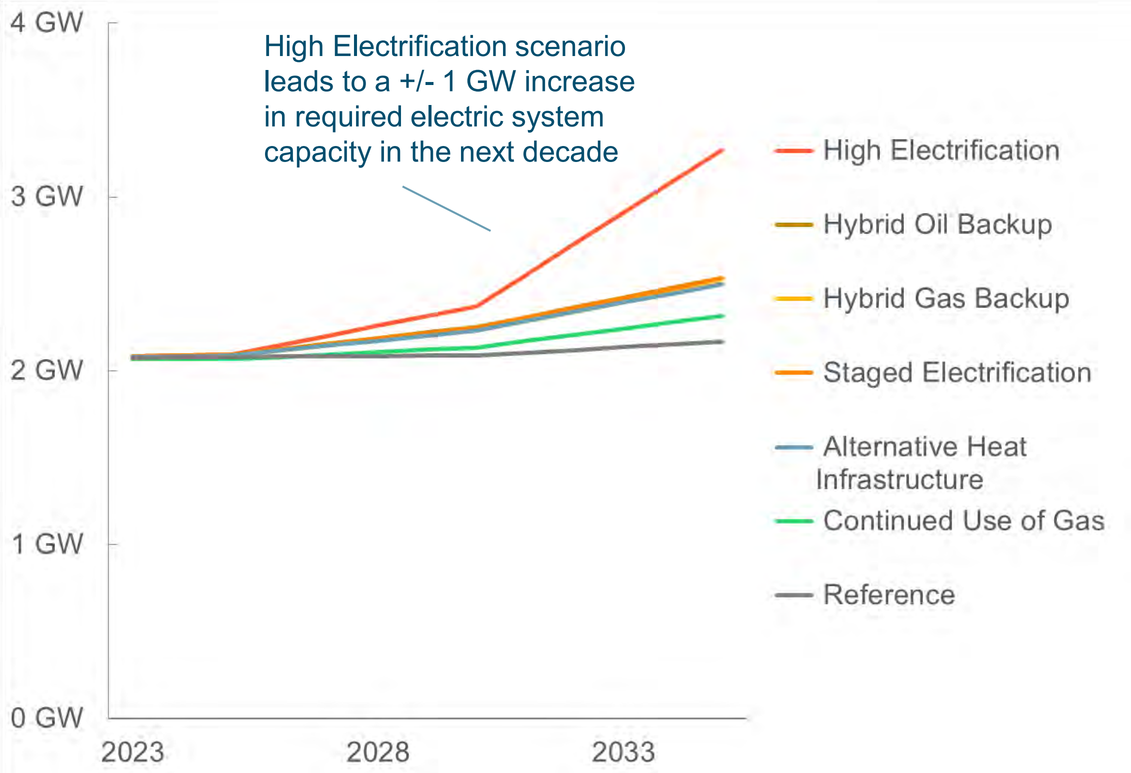
+ **All scenarios require rapid expansion of renewables to achieve 100% Renewable Energy Standards by 2033**

+ **Expanding T&D infrastructure build is driven by higher peak demand from electrification**

Annual Renewable Energy Generation by Scenario (TWh)



One-in-Ten Noncoincident Peak by Scenario (GW)



Appendix

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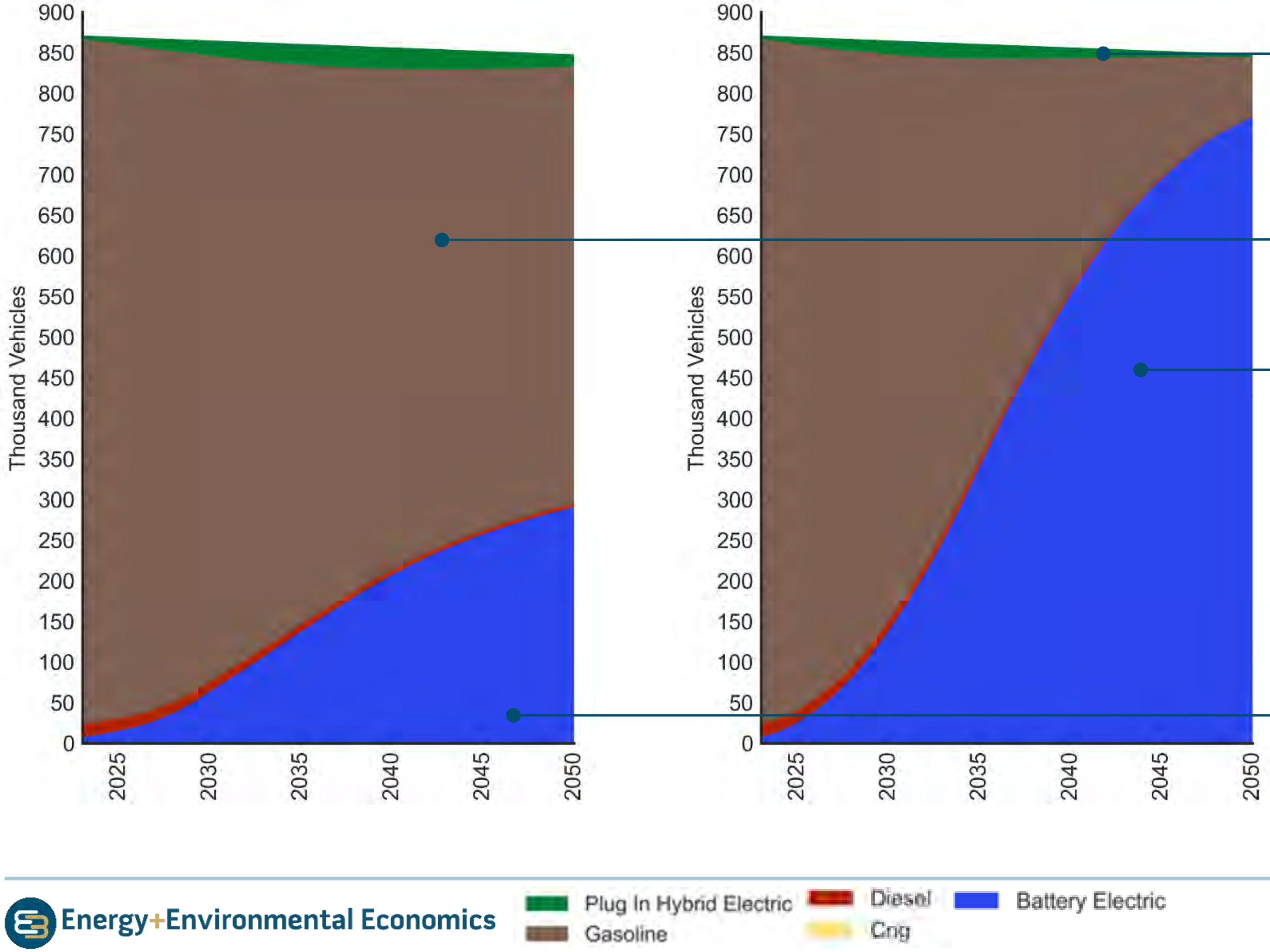
LDV ZEV adoption in all scenarios is driven by ACCII/ACT; Reference trajectory consistent with historical growth

Reference | **Mitigation Scenarios**



Long-term ZEV growth in both Reference and mitigation scenarios is **driven primarily by all-electric EVs** rather than plug-in hybrids

Reference LDV stocks are dominated by gasoline ICE vehicles

Mitigation **scenario growth in LDV ZEV penetration is consistent with ACCII/ACT**

Reference case growth in **LDV ZEV penetration is consistent with historical levels** and EC4 target (10% of stocks by 2030)

No adoption of ACCII/ACT in Reference

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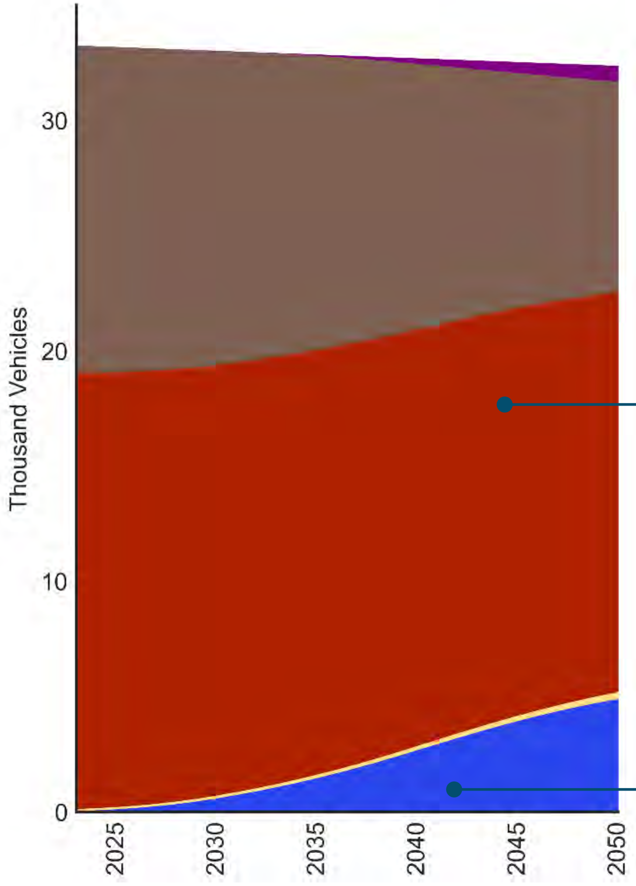
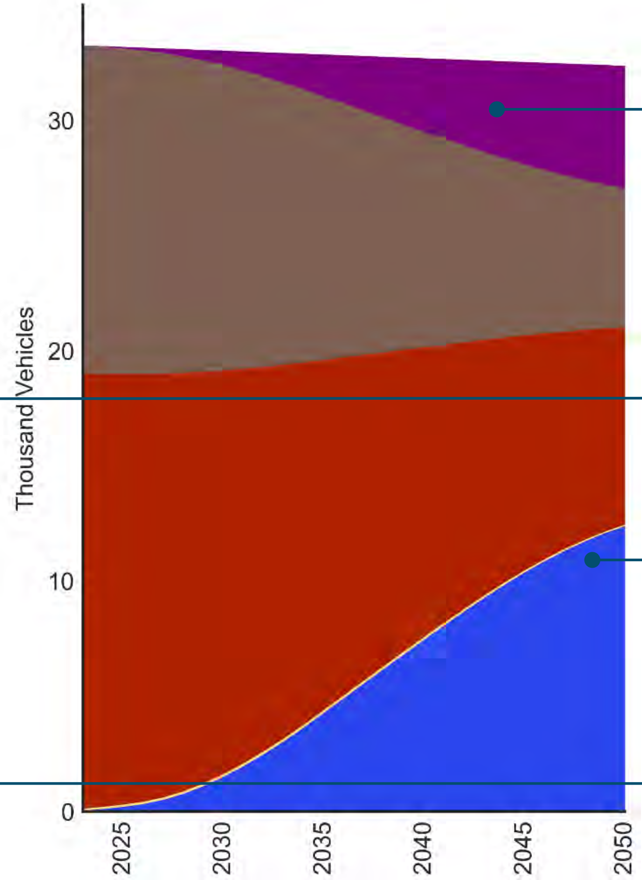
LDV = Light-Duty Vehicle
ZEV = Zero-Emission Vehicle

MHDV ZEV adoption in all scenarios is driven by ACCII/ACT; Reference trajectory consistent with historical growth

Reference



Mitigation Scenarios



Hydrogen fuel cell vehicles are classified as ZEVs under ACCII/ACT; growth in MHDV ZEV penetration is consistent with ACCII/ACT

Reference MHDV stocks are dominated by diesel and gasoline ICE vehicles

Mitigation **scenario growth in MHDV ZEV penetration is consistent with ACCII/ACT**

The **Reference case includes modest growth MHDV ZEVs**

No adoption of ACCII/ACT in Reference

Hydrogen Fuel Cell | Diesel | Battery Electric | Gasoline | Cng

MHDV = Medium- and Heavy-Duty Vehicle

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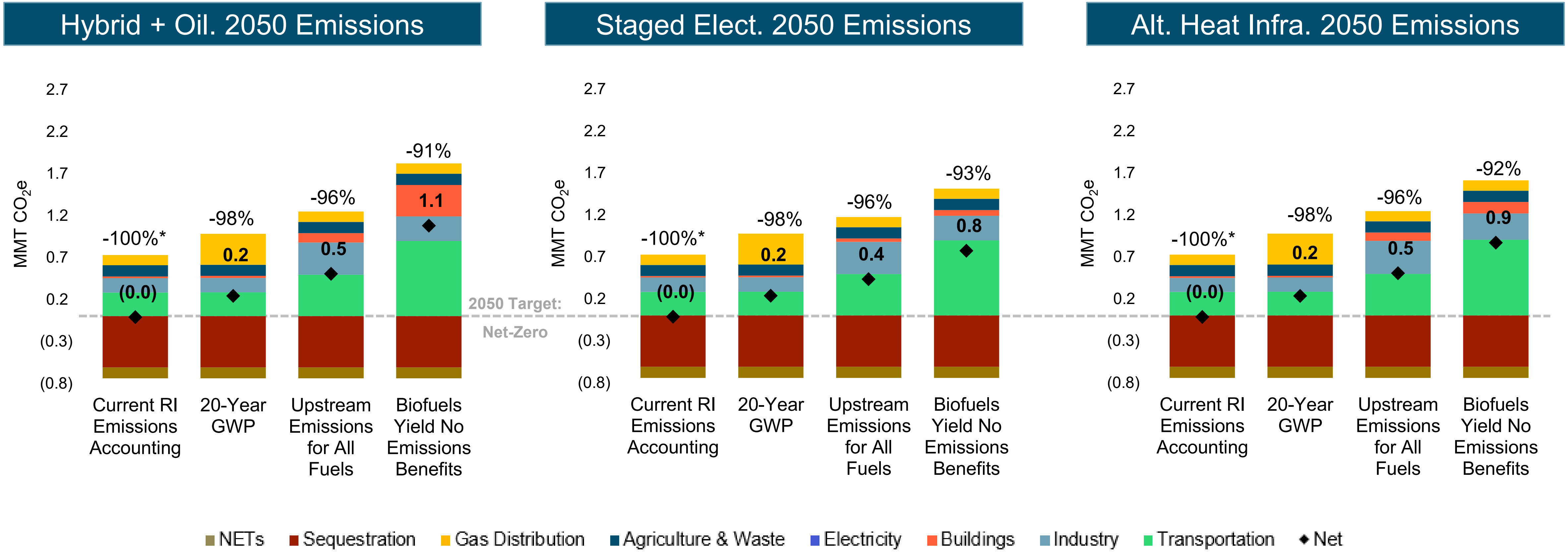
Scenarios with higher levels of renewable fuels may have higher emissions under alternative accounting frameworks

The Technical Analysis is based on emissions accounting **consistent with federal and RI's accounting standards**.

Through **sensitivity analysis**, E3 assessed scenario-specific risks of other types of emissions accounting methodologies. Results for High Electrification, Hybrid + Gas, and Continued Use of Gas are shown on Slide 30. The sensitivity analysis results for remaining scenarios are shown below.

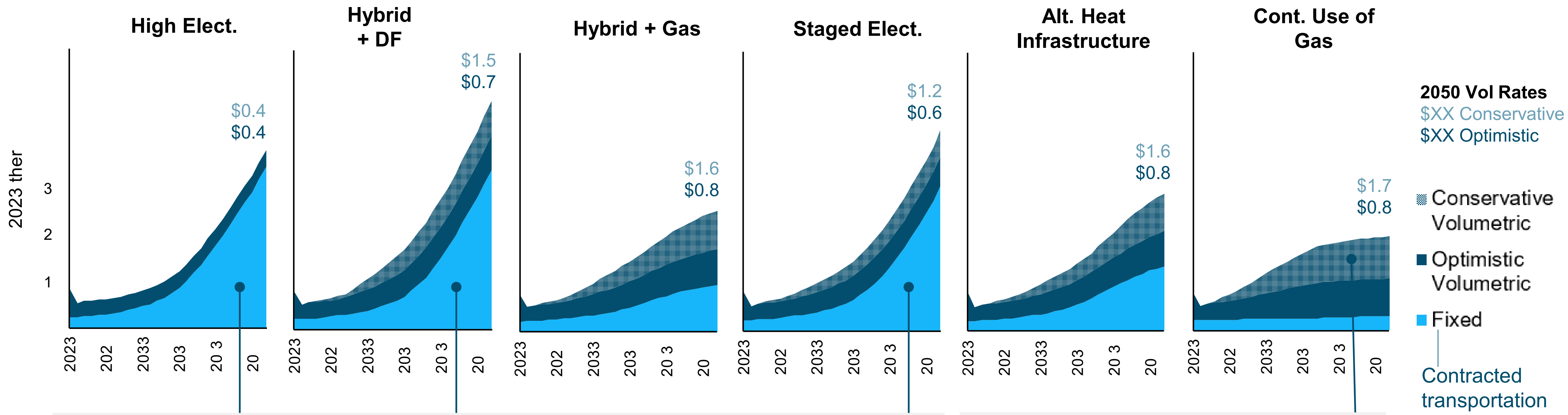


* Compared to 1990 emissions levels

Supply costs of gas are expected to rise for residential customers as a result of increased RNG blending

As a result of increased blending of renewable fuels and a decline of system throughput, **the cost of gas is expected to rise**. In scenarios with high levels of electrification, cost increases are due to fixed (transportation & storage) costs shared over a lower volume of customers.

Costs of residential gas supply across scenarios, distinguishing fixed & volumetric components*: 2023-2050

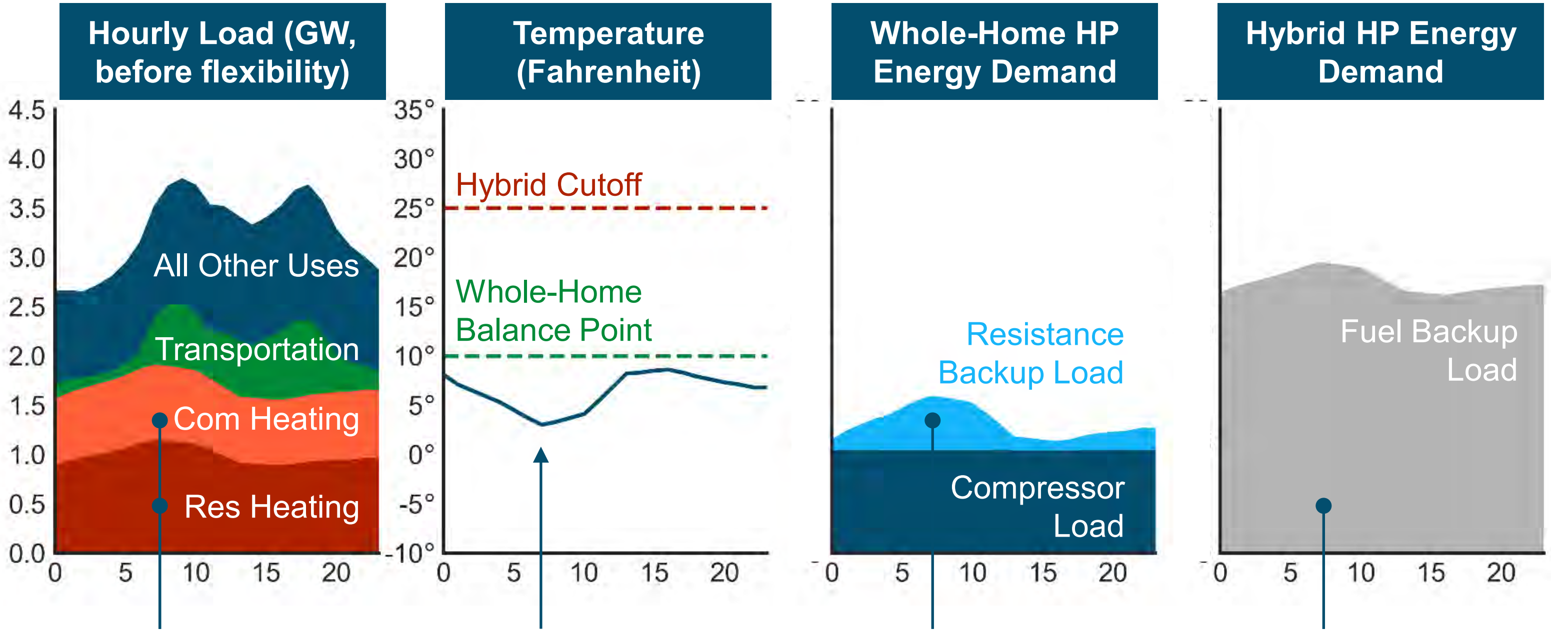


Scenarios with high levels of customer departures see a per-unit increase of fixed costs used for transportation & storage. The extent to which these costs can be avoided is uncertain.

Scenarios with higher levels of renewable fuels see an increase in the volumetric (commodity) component of the costs of gas.

In scenarios with high penetrations of all-electric heating, low temperatures drive peak load

System dynamics in High Electrification scenario on 2050 peak day



The system peak is driven by higher residential and commercial space heating.

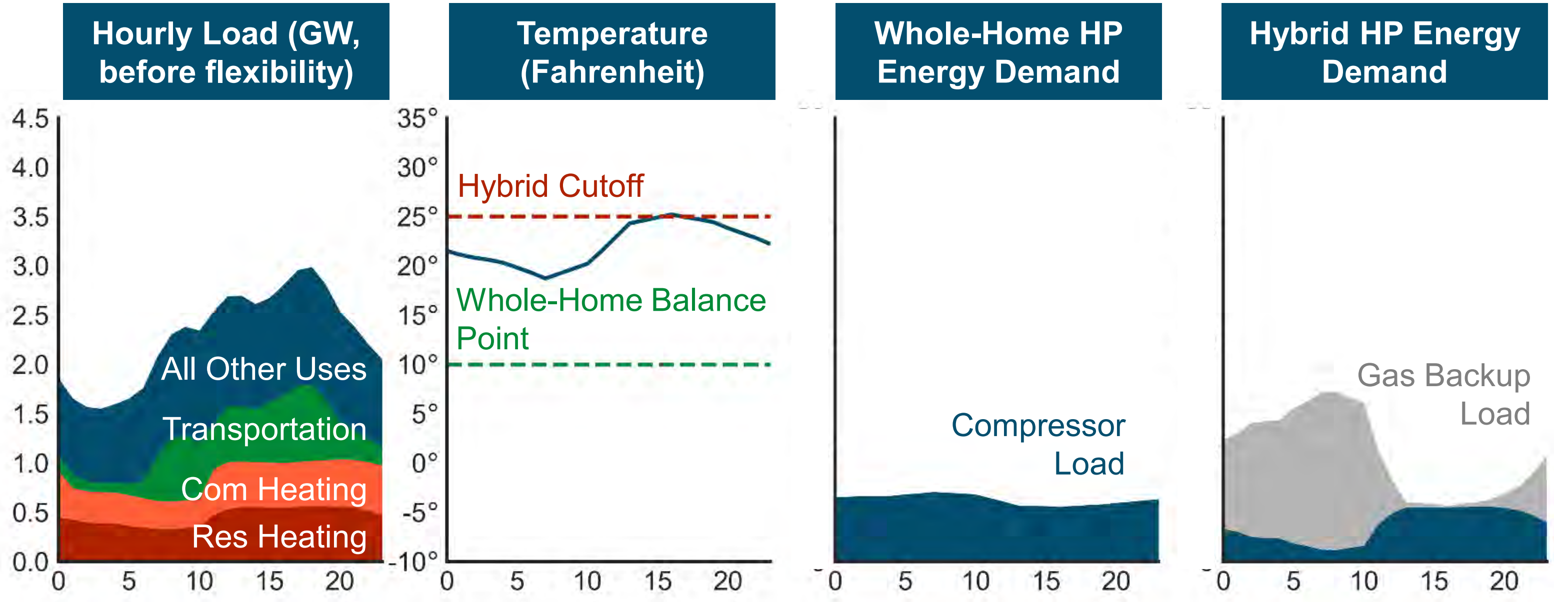
The temperature at peak is below both whole-home and hybrid HP balance points.

As a result, whole-home heat pumps rely on backup resistance to supplement compressor output.

Because hybrid compressors are not operating, whole-home heat pumps drive the entirety of the space heating contribution to the peak.

In scenarios with high penetrations of hybrid heating, transportation/peak hybrid heating coincidence drives peak

System dynamics in Hybrid + Gas Backup scenario on 2050 peak day



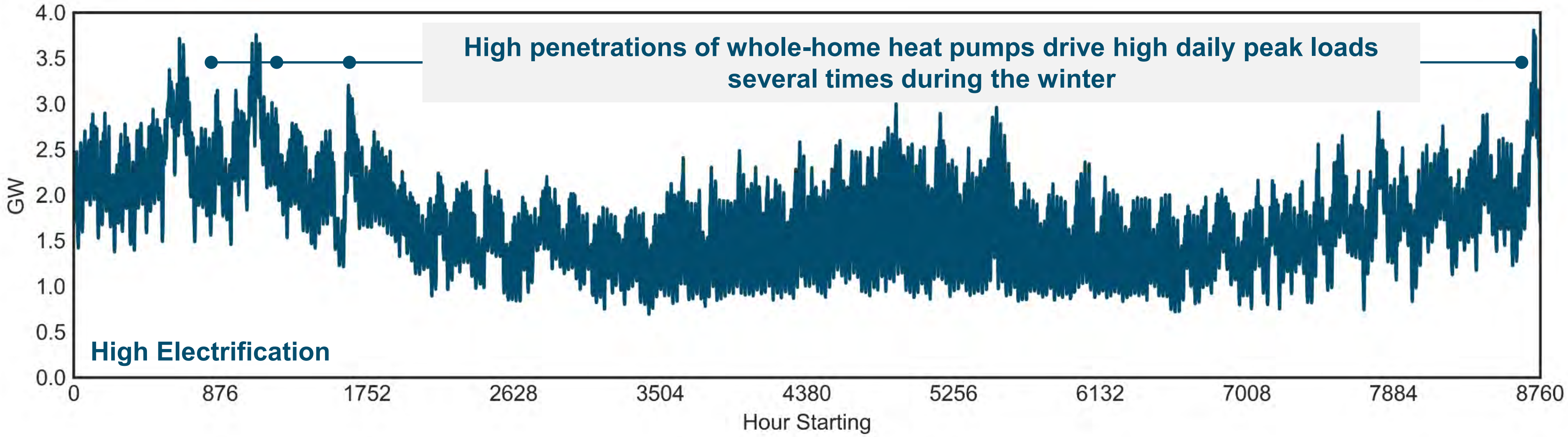
The system peak is driven by the coincidence of transportation and evening hybrid heat pump compressor operation.

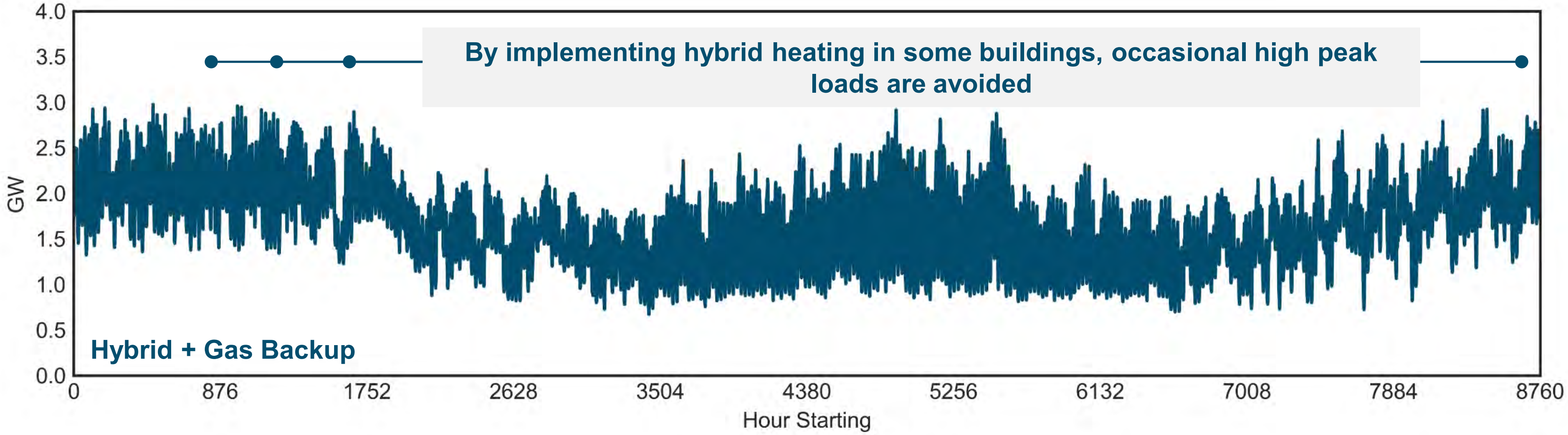
The temperature at peak is very close to hybrid heat pump cutoff.

As a result, whole-home heat pumps are operating below capacity but are still contributing to the peak.

Combined with hybrid heat pump compressor operation near its cutoff, both types of heat pumps contribute to the peak.

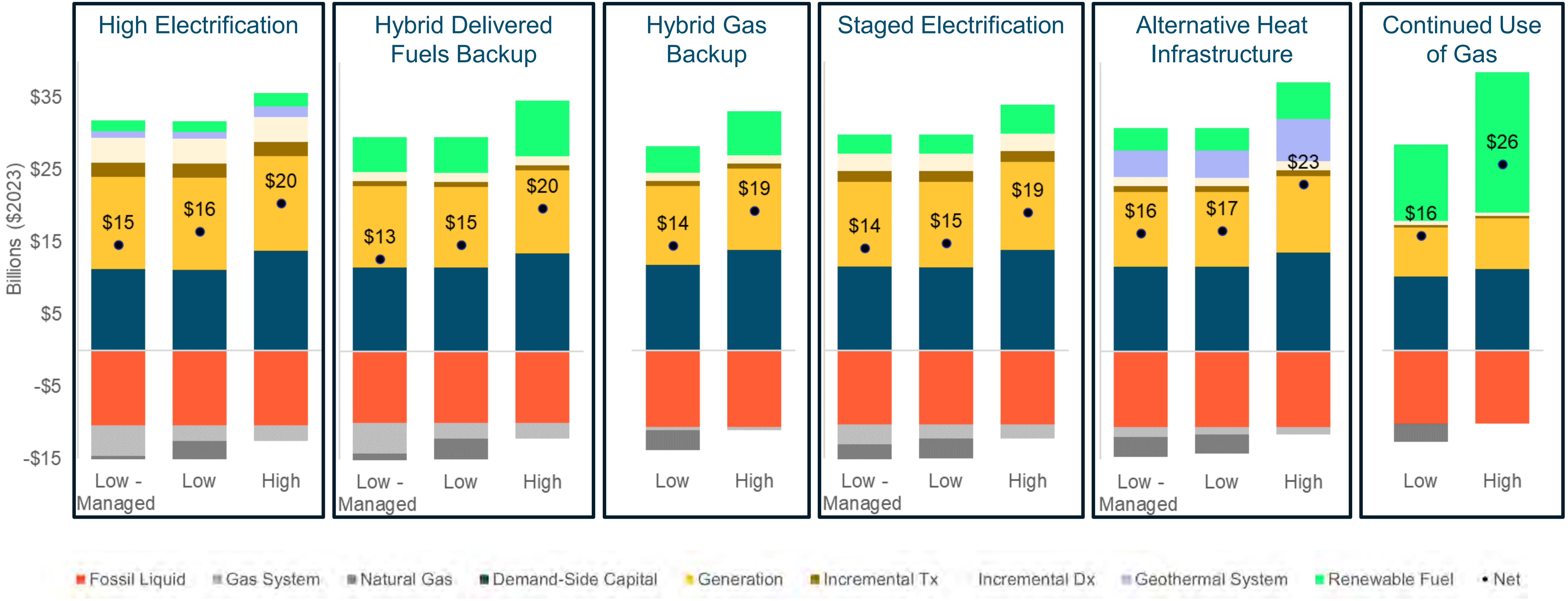
Hybrid heating avoids high system peaks driven by whole-building heating electrification





Economy-wide costs show similar ranges with highest uncertainty in cost of renewable fuels

Detailed Cumulative NPV Costs by category:



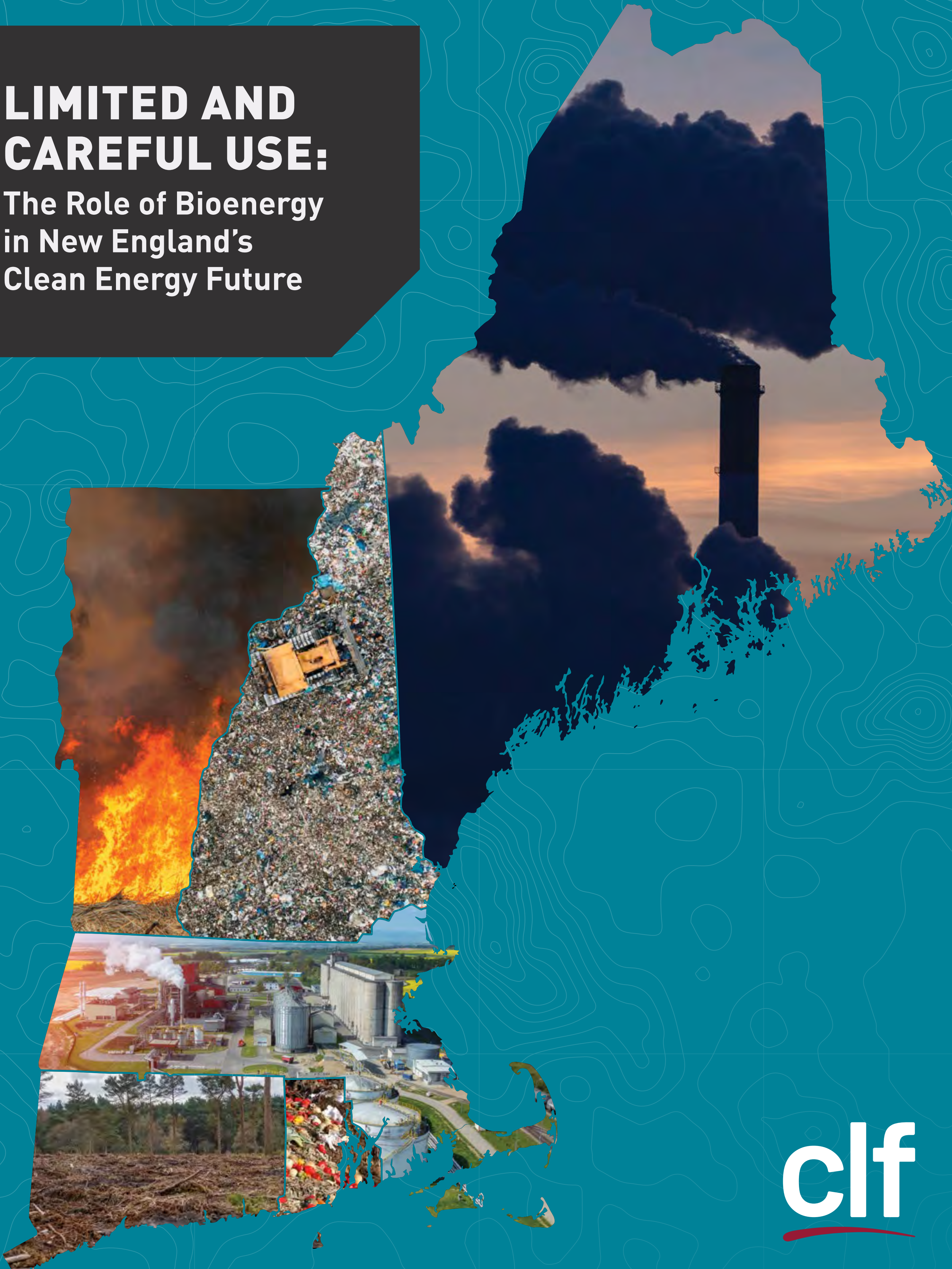
Economywide costs shower highest level of variations in the long term under annual cost projections

Annual economywide costs across scenarios (snapshots for 2030 and 2050)

Thank You

LIMITED AND CAREFUL USE:

The Role of Bioenergy in New England's Clean Energy Future



clf

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ABOUT CLF

Conservation Law Foundation (CLF) creates comprehensive long-term solutions to environmental challenges. CLF is a critical mover in building a new energy infrastructure, restoring the health of our oceans, countering climate change, and safeguarding the health, quality of life, and economic prosperity of our families and neighbors for generations to come. CLF protects New England's environment for the benefit of all people. We use the law, science, and the market to create solutions that preserve our natural resources, build healthy communities, and sustain a vibrant economy.

Contents

EXECUTIVE SUMMARY

What role will our natural resources and waste systems play in the energy system as New England moves toward 2050?

From blistering heat that aggravates air pollution and respiratory illnesses to mild winters devoid of the classic snow New England economies depend so heavily on – climate change is affecting us here and now. **The good news is our region has made its voice clear: We want climate action.** That is why nearly every New England state has passed mandatory climate laws and policies to slash polluting emissions, with targets for 2025 all the way to 2050. We need to end our reliance on fossil fuels, and that presents a pressing question: what role will our natural resources and waste systems play in the energy system as New England moves toward 2050?

As each state implements its climate law, it is critical that government and business leaders invest in the policies and strategies that will drive down climate-damaging emissions the fastest and the cheapest. They must also ensure an energy transition that accommodates vulnerable and already burdened communities and individuals. Foundational to all such strategies will be a heavy investment in energy efficiency and clean energy.

As such investment is pursued, states, communities, and institutions will need to be vigilant about avoiding misguided and ineffective solutions that may conflict with these broadly defined decarbonization goals. Such discipline is particularly needed around the application of alternatives to fossil fuels that enable the continuation of entrenched industries and activities that conflict with the region's codified emissions and social goals. Generally referred to as "bioenergy," these alternative resources are produced from organic matter such as agricultural crops, wood, sewage sludge, food waste, and animal waste.

Fossil fuels are not the only source of climate-causing emissions: agriculture and land use currently contribute to a quarter of the planet's warming.

While bioenergy resources are not of fossil origin, their use has significant potential for climate damage. Fossil fuels are not the only source of climate-causing emissions: agriculture and land use currently contribute to a quarter of the planet's warming. Likewise, large-scale bioenergy cultivation and processing have the potential to exacerbate climate change through various mechanisms.

It is common sense that directly replacing all of our current fossil energy systems with those derived from forests or from energy crops would create unbearable economic, ecological, and climate costs. Such costs are one of the many reasons why New England's, and the world's, clean energy goals focus on rapidly scaling wind and solar electricity generation to power electric end-uses. Despite this direction, questions remain about the modest application of bioenergy that need answers.

In this report, we analyze bioenergy's role in New England's clean energy future and provide guidance to decisionmakers who are considering bioenergy to meet their mandatory climate targets. The appropriate role of bioenergy is a limited and targeted one. Indiscriminate use of bioenergy in the electricity and heating sectors can undermine efforts to decarbonize and in some cases results in emissions that are more climate-damaging than fossil fuels. Particularly when it comes to fuels that might replace natural gas in end-uses that will be electrified, it could be both cheaper and cleaner to continue using fossil fuels until the use can be electrified, instead of temporarily adopting a bioenergy strategy.

But, of course, we must end our use of fossil fuels as quickly as possible by transitioning to clean electric alternatives.

Bioenergy may have a role to play in industries and transportation that are hard to electrify, such as aviation or shipping. But even in these limited scenarios, policymakers and investors must use a holistic lens beyond life-cycle analysis to scrutinize the climate-damaging emissions and other impacts from the fuels' production, transportation, and ultimate use.

When implemented with the appropriate safeguards, the production of bioenergy from waste resources delivers some modest climate benefits. However, we must avoid depending on intentionally cultivated sources (such as corn, soybeans, or wood) whose overuse of agricultural lands can impact food production or result in the clearing of forests and reduction in forests' inherent ability to soak up carbon. We also should be careful to use currently abundant waste materials in an efficient way without creating demand for waste streams, like food waste, that could be eliminated by better waste policies.

We are in the process of fighting climate change and securing a livable and healthy future for New England. We don't have time or resources to waste on costly and ineffective solutions. The economic, environmental, and public health of our communities and businesses demands that we invest substantially in energy efficiency and clean energy resources while moving with caution and care on bioenergy resources.

1. NEW ENGLAND’S CLIMATE LAWS AND POLICIES

As New England looks to fulfill the mandates of its climate laws and the global climate policy consensus, the role of bioenergy has become a key issue. The last several years have seen the emergence of plans and studies for how the region should evolve to achieve its net-zero goals, including cutting gross emissions as deeply as possible and strategic continued use of emitting technologies only where it is not possible to eliminate the emissions. Table 1 summarizes these actions using examples of key strategies.

Table 1.

COMMON NET-ZERO ACTIONS AND EXAMPLES OF SUCH ACTION THAT APPEAR IN VARIOUS NEW ENGLAND-FOCUSED DECARBONIZATION STUDIES [1–6]

NET-ZERO ACTION	EXAMPLE
CLEAN ELECTRICITY	• Deploy wind and solar as aggressively as possible.
ENERGY EFFICIENCY AND CONSERVATION OF RESOURCES	• Reduce energy losses across all energy uses. • Reduce demand for energy by smart dense growth while reducing reliance on personal vehicles.
ELECTRIFICATION	• Electrify fuel-consuming end-uses in buildings, transportation, and industry. • Deploy electric heat pumps to capture and use renewable ambient heat from the air, earth, and water.
INTEGRATION	• Build transmission to share renewable energy resources between regions. • Construct local integrated energy systems, such as microgrids and thermal networks, to better share energy resources across space and time for efficiency and resiliency. • Pursue systems emissions reductions rather than relying on credit or offset programs.
LIMITED USE OF ALTERNATIVE FUELS IN HARD-TO-ELECTRIFY SECTORS	• Prioritize green hydrogen use for chemical feedstocks and high-temperature heat demands. • Use bioenergy from wastes and residues in aviation, shipping, high heat industry, and chemical feedstocks.
MODEST USE OF FOSSIL FUELS WHERE ALTERNATIVE FUELS ARE NOT PRACTICAL	• Rightsize and leak-manage pipeline gas systems to support energy system reliability. • Wind down existing paid-for fossil infrastructure rather than building temporary alternative fuel infrastructure.
CARBON DIOXIDE REMOVAL	• Preserve and enhance natural carbon stocks. • Engineer removal of carbon dioxide via direct air capture or bioenergy carbon capture and storage.

It is important to emphasize that the actions listed above are complementary – not competitive – actions that play a role at different scales and in specific ways. However, the need to deploy a diverse solution set to meet ambitious emissions reduction goals does not mean that these strategies achieve equal scales: **combustion of alternative fuel is not a substitute for clean electrification.**

Non-Combustion Strategies

Integrating the strategies of renewable electricity, efficiency, and electrification reduces the region's reliance on imported fuels, replacing them with locally available energy resources like wind, solar, and ambient heat. This transition delivers remarkable benefits by replacing the combustion of fuels with clean local energy resources. Instead of being spent on volatile out-of-state energy imports, such as imported biofuels and fossil fuels, money is invested locally in energy-producing assets, more-efficient vehicles, and healthier and better buildings. Improvements in air quality from reduced air pollutants are realized across the energy system, from inside the home to environmental justice communities adjacent to dirty power plants.

While these benefits will be achieved across all sectors, the mechanics and the pace of how this deployment proceeds will vary by sector.

LOW-CARBON CLEAN ELECTRICITY

New England's coastline is rich with wind energy resources and the region has ample solar potential.[7] Wind and solar electricity are on track to be cost-competitive with fossil fuel-based power and can meet the bulk of the region's current and future electric demands. However, the electricity sector faces challenges in *eliminating* emissions because of the region's large winter heating demand and the variable nature of wind and solar generation. Where storage, demand shifting, and imported electricity from other regions cannot cover the full scope of our electricity generation needs, the best available modeling acknowledges a minor role for maintained combustion-based electricity generation[8,9] at a fraction of today's use – at least until cleaner technological options emerge. Such technologies could include green hydrogen combustion, hydrogen fuel cells, enhanced geothermal, small modular nuclear, and carbon capture and storage, all of which currently face significant cost and practical barriers in the region. Woody biomass electricity generation faces long-term challenges due to its inefficiency,[10] inflexibility, lack of sustainable scalability,[11,12] and relatively high generation of harmful air pollutants.[13]

ELECTRIFICATION AND EFFICIENCY IN THE TRANSPORTATION SECTOR

Electrification of the light-duty vehicle sector has become all but certain as policy incentives,[14] regulations, and manufacturers[15] are aligning on a phase-out of new internal combustion engine vehicle sales by the 2030s. All New England states except New Hampshire are in the process of adopting[16] California's Zero Emissions Vehicle Mandate.[17] The electrification of larger vehicles is also gaining traction on these fronts. While electrification slashes fossil fuel consumption and demand for corn ethanol and biodiesel,[6,8] the current limits of electrification in some heavy-duty vehicles, aviation, and shipping leave open the need for targeted uses of combustible fuels for the foreseeable future. Overall, transportation system efficiency will benefit from a focus on minimizing the use of personal vehicles where possible.

ELECTRIFICATION AND EFFICIENCY IN THE BUILDINGS SECTOR

Electrifying building heat and appliances has emerged as the consensus strategy for eliminating emissions from the building sector. The ability of heat pumps to capture renewable ambient heat from the nearby air, water, and earth offers significant efficiency advantages over combustion fuel technologies. Modern heat pump technology provides more energy than it consumes the majority of the time and thus *reduces* fuel consumption. This reduction occurs even when relatively inefficient combustion-based power plants supply the heat pump's electricity. As the grid becomes more renewable as new wind and solar generation facilities come online, the trio of wind, solar, and ambient heat can displace most fuel consumption for heat. Even partial electrification of most building heat has been recognized by regional gas utilities as necessary for achieving the region's decarbonization goals, given the challenges associated with scaling strategies for decarbonizing pipeline gas such as renewable natural gas (RNG) or green hydrogen.[18]

With currently available technologies, there would likely remain a residual amount of non-electrified heat demand in 2050. While heat pumps operate at the coldest temperatures, they require more electricity to do so at very cold temperatures when heat demand is high. And some buildings (e.g., hospitals) and processes require a backup or high-temperature heat source for which electricity may not be sufficient. As such, and while it is in decline, a limited amount of combustion may play an important role in the clean energy transition by supporting thermal reliability at the building scale and electric reliability at the grid scale.

It is important to move beyond conversations that equate electrification and RNG as future building heat options. Electrification of heat and other end uses have the potential to benefit New Englanders with improved comfort and air quality. Despite a supporting transitional role for combustion, it is also clear that even a modest degree of electrification will severely challenge the long-term financial viability of the gas system.[1,19,20] Transitioning away from gas use in a coordinated way will be important to avoid utility death spirals, in which an unmanaged transition results in fixed gas system costs being borne by the few likely-lower-income consumers who are unable to migrate to clean technologies. Managing the implications of such a transition is beyond the scope of this report, but it is being actively explored in Massachusetts[21] and Rhode Island.

This transition will need to proceed on three fronts. First, given the emerging cost-effectiveness[22] of all-electric, high-performing buildings, it is clear that continued expansion of the gas system is misguided and could lock in combustion infrastructure that will be costly to convert in the future. Second, New England states currently accelerating the process of replacing leak-prone pipes should seek out opportunities to avoid reinvestment in gas distribution systems, given that the increasing cost of pipeline replacement projects typically exceeds the cost of electrifying connected buildings on affected street segments.[23] Finally, given an increasingly electrified and efficient building stock, coordinated zonal transition strategies – such as those being implemented in parts of Europe[24] – will be needed to leverage local energy thermal resources, construction of energy networks, and optimized upgrading of the electrification system.

Achieving decarbonization of buildings is a systems problem that requires planning for the transition of multiple connected energy assets. The assumption that buildings can be decarbonized by simply dropping in a substitute fuel (whether it be delivered by pipe or by truck) ignores the opportunity and planning needs of non-combustion strategies, along with the scalability challenges associated with alternative fuels discussed in this report.

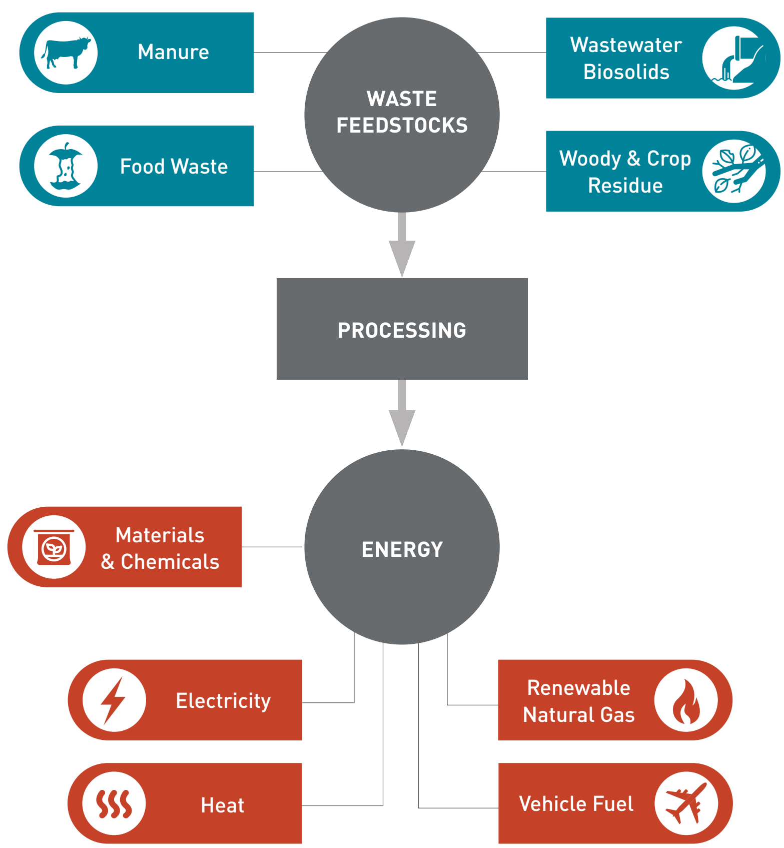
Managing Residual Combustion Uses in Pursuit of Net Zero

The balance of this report focuses on the question of what fuels New England's policymakers should be planning to combust in those residual use cases that cannot be electrified with current technology as the region moves toward 2050, recognizing the overarching directionality and primacy of solar, wind, and ambient heat in driving decarbonization.

Generally, locally available bioenergy should be prioritized for hard-to-electrify end-uses like aviation fuel (Figure 1). Limited strategic use of fossil fuels will be a preferable transition strategy in other cases where combustion is still necessary. Pipeline-quality RNG, for example, has a very high production and purification cost that, relative to the cost of fossil gas, exceeds the social cost of carbon and the emissions abatement costs of other fuels. Its production and use require infrastructure that will be increasingly underutilized over time as the buildings sector, writ large, electrifies. A policy assumption that gas can be decarbonized will delay necessary decisions to rightsize the gas system to manage its costs better. RNG production assets and gas distribution infrastructure are significantly at risk of being underused in a deeply electrified future, at the expense and responsibility of ratepayers.

The feedstocks for RNG can instead be used to produce higher-value fuels and products, and such feedstocks are of limited supply.

Figure 1.
BIOENERGY PRODUCTION



Summary for Policymakers

There is consensus among state climate plans,[1,2,4,5,25] utilities,[26–28] and ISO New England[29,30] on the large-scale deployment of renewables and the electrification of most transportation and heat end-uses. There remain outstanding questions surrounding the scale of certain strategies relative to others, the pace of implementation, and the role of future technologies. For example, the gas utilities have argued for a continued role of the gas system at its current size but with lower throughput to serve as a "backup" to the widespread deployment of heat pumps.[26–28] Other studies have argued that rightsizing the gas system may be a more cost-effective strategy.[1,20]

Compared with efforts to reduce fuel consumption, overreliance on biofuels will increase consumer energy costs and make it difficult to impossible to achieve the region's climate goals.

Despite such outstanding questions, fuel-saving strategies have clear economic, social, and environmental benefits. States, the federal government, and other decision-makers should embrace a fuel-saving industrial policy that advances these strategies as aggressively as possible:

1. New all-electric building standards for most building classes (buildings that may require fuels for resiliency or high-temperature uses should carefully evaluate whether or not such fuels are best met with pipeline gas or an alternative like propane to avoid stranded asset risks associated with expanding the gas system).
2. Firm yet adaptable zero emissions vehicle, appliance, and heating equipment targets (e.g., policies implemented by California and New York[17,31,32]).
3. Sufficient incentives to bridge funding gaps between conventional combustion-based equipment and electric and efficient buildings.
4. Modernization and decarbonization of the electrical grid to support and respond to increasing consumer demand for electrification (increase distribution capacity, add renewables, and enhance reliability and resiliency).
5. Aggressive energy efficiency (e.g., building shells, thermal networks) and flexible electric system measures to moderate the costs of grid modernization and electrification while improving building habitability.
6. Workforce and supply chain development to support the above strategies.
7. Gas system rightsizing to reduce costs associated with maintaining aging and, because of electrification, increasingly redundant utility infrastructure.

Careful and strategic consideration of biofuels is necessary to ensure that New England reduces its greenhouse gas emissions, secures affordable energy for its residents, and prevents harmful air and water pollution.

2. FROM FIELDS AND FORESTS TO USABLE FUELS: BIOENERGY PRODUCTION

Like fossil fuels, any kind of bioenergy needs to be processed from an initial resource into a usable form and then transported to the location where it is combusted. Table 2 on page 11 segments the components of the bioenergy production chain.

Bioenergy production begins with collecting energy-rich raw organic material known as *feedstock*. The feedstock is then converted into a usable energy carrier or fuel at a production facility, such as a biorefinery for liquid fuels. The fuel may then be transported, stored, and finally delivered to a particular energy application. Each of these steps incurs both a cost and an energy penalty that can significantly influence the relative efficacy and cost-effectiveness of bioenergy as a tool in decarbonization.

This section reviews these components.

BIOENERGY TERMINOLOGY

The language surrounding bioenergy can be confusing, even for experts in the field. Many terms are often used interchangeably and inconsistently. For example, "biofuel" and "biomass" are often used interchangeably with "bioenergy" to describe all energy produced from bioresources. Sometimes "biofuel" is used to refer to liquid fuels, while "biomass" refers to solid fuels used in electricity generation. Likewise, the term "bioproduct" is often used interchangeably with "bioresource" to be inclusive of energy but is used in this report explicitly to refer to biologically derived materials and chemicals derived from biological feedstocks. Similarly, the term "organic" is sometimes used interchangeably with the prefix "bio-." Use of the term "organic" in this report does not connote organic farming cultivation practices but is used to describe waste of biogenic origin.

Bioenergy Feedstocks

In general, feedstocks fall into one of two categories:

- **Purpose-grown feedstocks** are derived from intentionally cultivated crops. Examples include corn or soy crops and harvested trees.
- **Waste feedstocks** result from some other activity. Examples include forestry and agricultural residues, animal manure, food processing residues, food scraps, and wastewater treatment plant sludge.

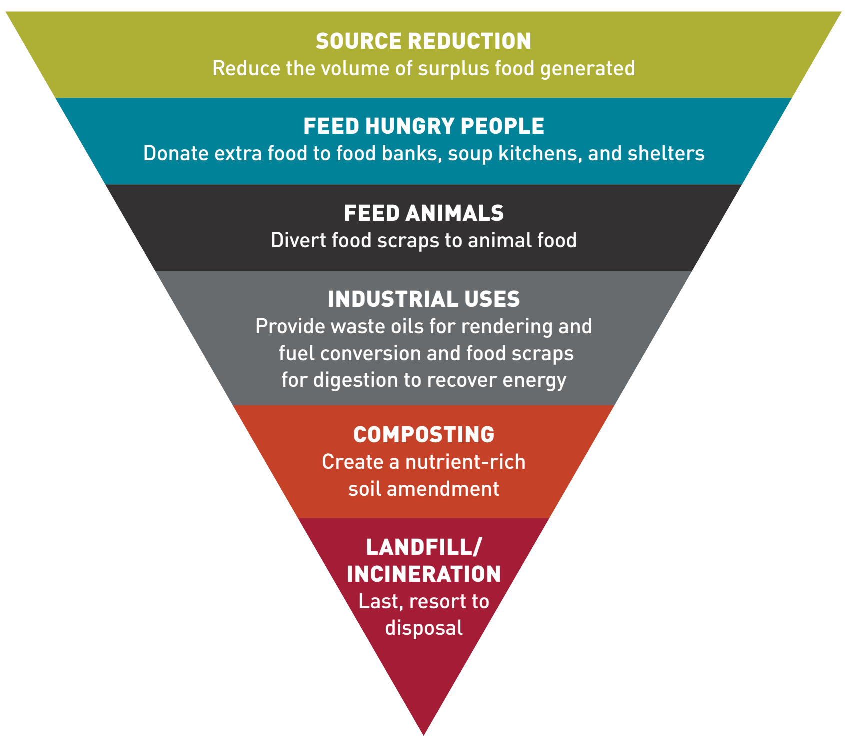
Using purpose-grown feedstocks to produce bioenergy requires the dedication of various inputs. These include land, water, nutrients, energy for cultivation, capital, and labor. Using purpose-grown bioresources also results in ecological impacts that vary greatly depending on the resource and how it is cultivated.[33] The use of these resources thus has the potential to incur climate and other ecological, economic, and social impacts.

Using waste feedstocks for specific, targeted energy uses may be preferable to incinerating them or dumping them in methane-producing waste-handling places like landfills or manure lagoons, but it is critical to first prioritize waste reduction.

WASTE MANAGEMENT HIERARCHY

While energy recovery from organic waste generates an energy resource alternative to fossil fuels, other waste management strategies can deliver greater environmental benefits and tend to be preferable depending on the circumstance. This concept is commonly referred to as a "waste management hierarchy" (Figure 2) and has been used in various forms to guide waste management.

Figure 2.
WASTE MANAGEMENT HIERARCHY



Reducing waste generation by consuming fewer goods is universally regarded as the first step in sustainable waste management. Such source reduction avoids waste generation by avoiding unnecessary consumption or diverting products to places where they can be reused (e.g., food donations).

Where practical, recycling is often preferable over energy recovery. With paper recycling, there is less need to extract and process wood for producing paper, resulting in both resource and energy savings. Alternative business models are emerging seeking to recover food waste that is unsuitable for human consumption and repurpose it as animal feed.[34] These may obviate the need for food waste energy recovery but are energy-intensive due to the heat demand needed for drying food wastes.

Burning solid waste in incinerators and landfilling organic waste are the least preferable options. If reduction and recycling are not options, finding a way to extract energy from the waste before incineration should be considered.

Where practical, recycling is often preferable over energy recovery.

Conversion of Feedstocks into Usable Energy

Biomass is barely usable in energy applications in its raw form. Even combustion of raw biomass requires some aggregation, cutting, and/or drying before actual use. To render them usable as fuel, raw feedstocks undergo a conversion process, or a series of conversion processes, that usually entails:

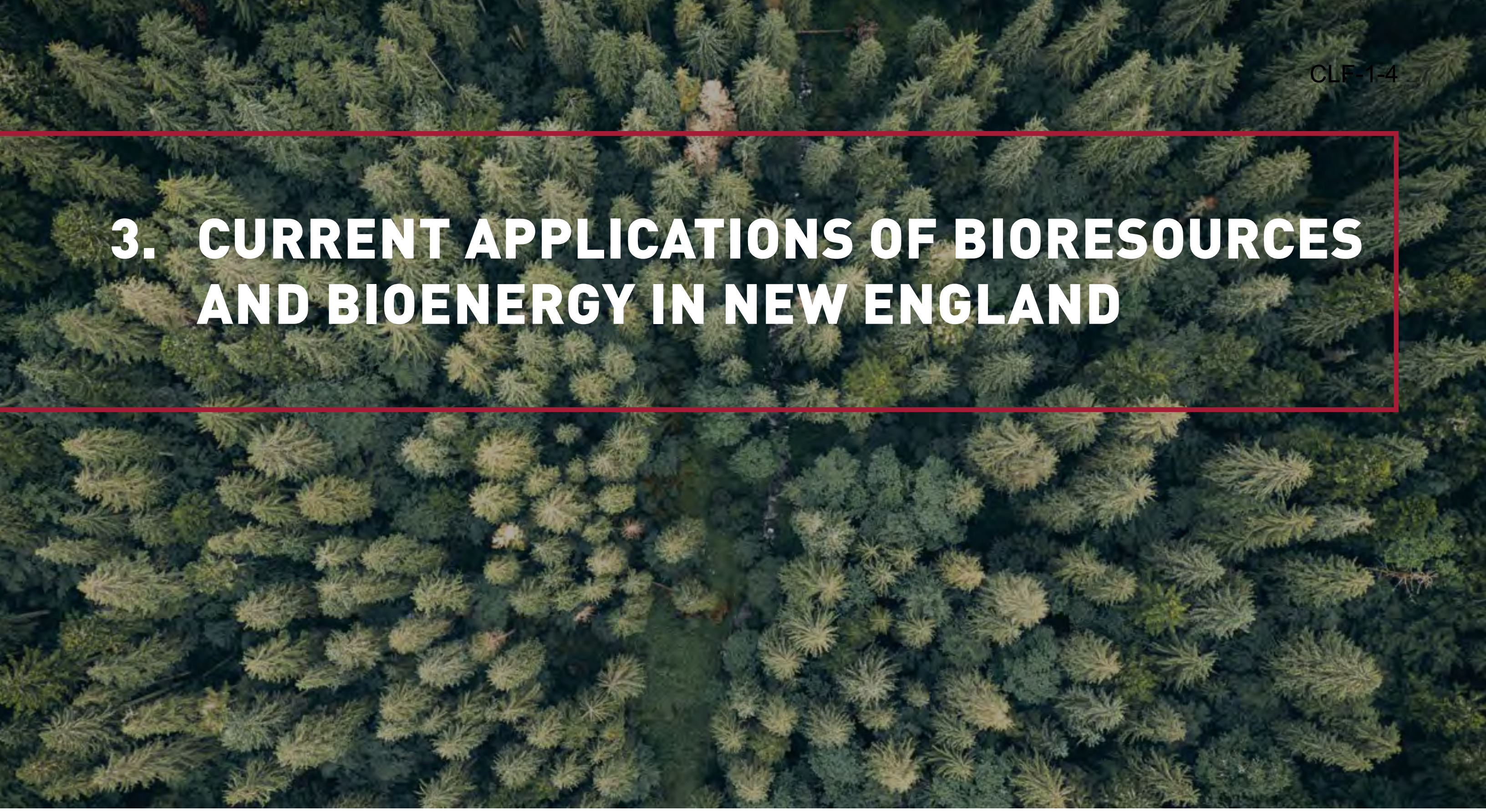
- Collecting the feedstocks and transporting them to a conversion facility.
- Transforming the biomass at the facility into a usable energy carrier or fuel.
- Distributing that energy carrier to specific uses.

Usable energy carriers include biomass ready for combustion, pipeline-quality RNG, hydrogen, liquid fuels, and electricity. Generally, almost any feedstock can be converted into a solid, liquid, or gaseous fuel – although some pathways are more advantageous than others in terms of yield, input energy demands, and distribution. These, in turn, influence the economic viability and the greenhouse gas impact of the final fuel product.

Table 2.

BIOENERGY CONVERSION PROCESSES, THEIR FEEDSTOCKS, PRODUCTS, AND RELEVANCE TO NEW ENGLAND'S ENERGY CONTEXT

PROCESS TYPE	PROCESS NAME	BIOENERGY FEEDSTOCKS	PRIMARY PRODUCTS	PROCESS DESCRIPTION	NEW ENGLAND CONTEXT
SOLID FUEL CONVERSION PROCESSES	Mechanical	Roundwood, wood waste	Cordwood, woodchips	Wood scraps are cut or chipped down to scales suitable for combustion based on the needs of the combustion system.	Northern New England's wood industry generates sufficient biomass to support a small portion of the region's heat and electricity demand (~3%).[35]
	Pelletization	Scrap, sawdust	Biomass pellets	Wood scraps are pulverized and pressed into pellets.	
LIQUID FUEL CONVERSION PROCESSES	Fermentation	Sugar crops (corn, sugar-cane, kelp)	Ethanol	Simple sugars are biologically converted to ethanol that is then distilled to fuel-grade concentrations.	New England currently consumes Mid-West corn-derived ethanol in its gasoline.
	Transesterifi-cation / hydrogenation	Oil crops Waste fats, oils, and greases Bio-oils from HTL (see below)	Liquid hydrocarbon fuels	Various plant and animal-derived fats and oils are processed to usable liquid fuels.	Several small biodiesel producers collect oil waste and upgrade it for blending into heating fuel and transportation diesel.
THERMAL CONVERSION PROCESSES	Gasification	Any dry biological material	Methane, hydrogen, liquid hydrocarbon fuels	Biomass is burned at high temperatures with varying degrees of oxygen and steam to produce the desired fuels.	A Fischer-Tropsch gasification facility is proposed in northern Maine to produce sustainable aviation fuels.[36,37] Production of RNG by gasification has been proposed by the gas industry.[38,39]
	Pyrolysis	Any dry biological material	Methane, hydrogen, liquid hydrocarbon fuels	Biomass is burned at medium temperatures in a low-oxygen environment to produce the desired fuels.	Biomass pyrolysis for energy has not yet emerged in the region.
	Hydrothermal liquefaction (HTL)	Any wet biological material	Liquid hydrocarbon fuels	Biological material is treated with high pressure and temperature to create a biocrude oil that can be refined to higher-value fuels.	HTL for energy has not yet emerged in the region.
ORGANIC WASTE MANAGEMENT	Landfilling	Municipal and commercial organic waste	Methane	Anaerobic decomposition of organic waste buried in land-fills leads to the production of methane-containing biogas, some of which is captured via collection systems, with the remainder leaking into the atmosphere.	About 20 New England landfills currently capture and burn their landfill gas for electricity.[40] Several utilities have explored upgrading the methane to pipeline quality at local landfills.[41]
	Anaerobic digestion	Food waste Biosolids Manure Some dry biomass	Methane	Controlled decomposition of organic waste without oxygen produces methane-containing biogas.	Several digesters across the region burn manure, biosolids, and food waste. At most sites, biogas is combusted to generate electricity and heat.
WASTE INCINERATION	Waste incineration	Municipal and commercial organic waste	Heat, electricity	The combustion of organic wastes produces heat and electricity.	Approximately 15 incinerators in the region burn municipal and commercial solid wastes.



3. CURRENT APPLICATIONS OF BIORESOURCES AND BIOENERGY IN NEW ENGLAND

Bioenergy resources, both local and imported, are currently used across the electricity generation, building heat, and transportation sectors in New England. While local feedstocks are harvested for those uses, it is important to consider first the value provided by these resources when kept in place.

Forest Carbon Sequestration

New England's forests cover 75% of its land and store carbon equivalent to 12 billion metric tons of CO_2 in its trees, other above-ground biomass, and soils.[42] If released into the atmosphere, it would equal two years of the entire United States' greenhouse gas emissions. Each year, the region's forests sequester carbon equivalent to 24 million metric tons of CO_2 to this stock, removing it from the atmosphere. This is equivalent to 21% of the region's fossil greenhouse gas emissions.

New England's forests are a sink for CO_2 because they have meaningfully regrown after the deforestation of the 1800s.[43] This capability to sequester emissions will likely continue for some time and is likely to be enhanced by factors like warmer temperatures and longer growing seasons.[44]

Such sequestration is at risk of climate-driven extreme storm events, drought, fire, and pestilence like the emerald ash borer.[45,46] Given such increasing threats to the region's forests, efforts to enhance the natural carbon stock should also integrate best practices in forest resilience.

Further, poor historical management practices have hampered the forests' pace of carbon storage.[47] Unsustainable logging and land conversion limit New England's natural forests' storage of carbon.[48] According to a report from Highstead, titled *New England's Climate Imperative: Our Forests as a Natural Climate Solution*,[42] New England could sequester an additional 11 million metric tons of CO_2e annually through better forest management and preservation practices.

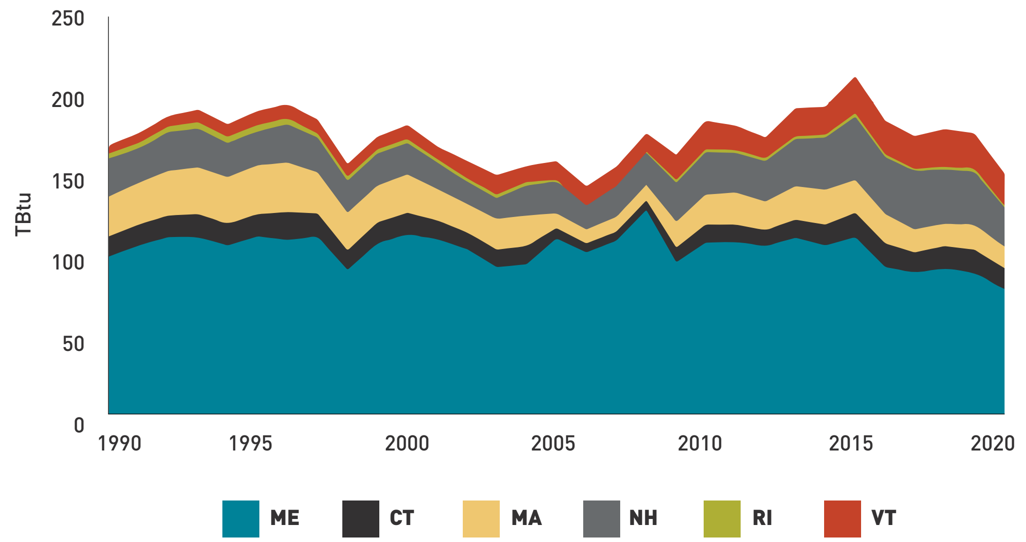
Wood Bioenergy

New England has a long relationship with wood as an energy resource. Today, the existing paper and lumber industries drive the harvest and collection of wood for lumber and paper products. While tree harvesting seeks to maximize high-value lumber production, it also generates a stream of collected residues, sawdust, and other wood-processing byproducts that are diverted to energy uses. Land development for commercial or residential use also creates a source of woody biomass feedstock.

This waste feedstock produces pellets, wood chips, and firewood that provide heat and electricity across the region. Figure 3 shows the distribution of New England's biomass demand, noting that the bulk of this use has been in Maine – the region's largest stock of wood and home to most of its wood products industry. Maine's industrial paper and wood products industry is a big driver of such consumption, using a significant portion of its wood waste to power its facilities. A modest amount of dedicated roundwood harvest also exists in New England and is used for heat.

What is notable about this figure is the flat and recently declining levels of consumption across most feedstocks and end-uses despite a push by some states in the early 2000s to promote the use of this resource for energy.

Figure 3.
NEW ENGLAND (1990–2020) WOOD CONSUMPTION BY STATE
Source: EIA.[35]



Wood consumption for electricity has dropped significantly since 2015 in both relative and absolute terms on New England's grid. This reflects a recent policy move away from woody biomass for electricity generation.

The conversion of solid woody biomass into electricity faces future challenges. Conventional biomass-combustion facilities function best when operating continuously, providing a consistent power output. While such facilities can be used seasonally, they will be challenged operationally and economically in a future grid dominated by variable renewable electricity such as wind and solar. Unlike modern gas-fired electric generation facilities (combined cycle turbines) that are effective *peaking* or *load-following* plants, New England's conventional woody biomass plants[10] face operational challenges in supporting the variable output inherent in wind and solar energy. Advanced biomass load-following facilities could conceivably be built but at a higher cost, limiting their competitiveness in the region's energy markets.

The other major use of wood is in home heating. Approximately 3% of homes in New England use wood as their primary heating fuel, with an additional 13% of households using it to provide supplemental heat. Most of these homes are in northern and rural New England, where they are closer to forestry and lumber industries, largely beyond the extent of pipeline gas distribution systems, and otherwise reliant on expensive oil, kerosene, or propane delivery. Pellet and cord wood stoves have efficiencies that top out at 80%.[49] The direct combustion of biomass at home and at the generator level incurs significant harmful air quality impacts[13] (discussed in Chapter 5). There may, however, be limited use cases where wood heat may provide some value, as, for instance, with highly efficient stoves supporting heat pumps in rural areas.

On the whole, burning wood may be customary in some parts of the region, but it negatively impacts air quality and does not pair well with the growing energy system of the future.

Crop Biofuels

Bioenergy used in the transportation sector is predominantly corn ethanol blended into gasoline – with a much smaller amount of biodiesel blends and other fuels such as RNG used for transportation as compressed natural gas. A 2022 analysis of the Environmental Protection Agency's (EPA) standard corn ethanol requirement has estimated that the emissions intensity of corn ethanol is either similar to or up to as much as 24% higher than gasoline when accounting for energy inputs and land-use changes.[50] The future of the EPA's standard for bioenergy blending in gasoline is in flux, being challenged by reduced demand for gasoline as light-duty vehicles electrify. Declining demand for corn ethanol could allow the rewilding of the land or the repurposing of the land it uses toward higher-productivity energy crops for advanced fuels and other beneficial uses.[17]

Biogenergy from Waste Treatment

Various waste treatment pathways serve as bioenergy conversion processes. The crudest pathways are incineration and landfilling.

CONVENTIONAL WASTE TO ENERGY PATHWAYS

Incineration combusts solid waste to generate heat and electricity. Food waste, paper products, and wood are typically burned alongside plastic. Plastic combustion releases fossil emissions, while combusting organic material releases biogenic carbon. This process is a relatively inefficient way of generating electricity, especially for high-moisture-content food waste. The siting of several incineration facilities at or adjacent to environmental justice communities also raises concerns because such facilities generate adverse air quality impacts even with pollution control technology, to say nothing of the high concentration of heavy, diesel-burning garbage trucks serving the facilities.

There are 15 solid waste combustors in New England – approximately 20% of all such facilities in the country. These generate about 3% of the region's electricity annually.[51] Many of these facilities are reaching the end of their design lifetime. As low-cost wind and solar electric capacity continues to expand in the region, these electric generation resources will face economic challenges due to their inability to provide value to the grid.[8,52]

More than 20 landfills in New England are also considered a bioenergy resource. At these, the anaerobic decomposition of buried organic waste, largely food scraps, generates landfill gas, a mixture of CO_2, CH_4, and some minor impurities. Landfills of a particular size are required to install methane capture and destruction systems to mitigate the climate impact of produced methane.[53]

Some landfills opt to generate electricity from the captured gas to sell to the grid. Various state renewable portfolio standards provide additional revenue for these projects via renewable electricity credits. Landfill electricity generation contributes to approximately 0.4% of the region's electricity generation capacity.[51] While such generation is inflexible, fuel is provided at zero cost, and revenue generated can cover or exceed methane capture regulation compliance costs.

The methane generated from landfills will decline over the next several decades as the digestible waste in landfills is exhausted. While new landfill proposals emerge[54] and several continue to accept waste, the closure of most landfills in New England and the emergence of alternative food waste treatment pathways and regulations will mean that this resource will steadily fade away.

Landfill gas can be directly burned to generate electricity.

UTILITY EFFORTS TO PROMOTE RNG

In the meantime, several New England gas distribution companies have sought to develop projects to convert landfill gas to RNG and inject it into the gas distribution system. The purification or upgrading process requires significant energy inputs, which can reduce potential greenhouse gas emissions benefits. Alternatively, and more commonly, landfill gas can be directly burned to generate electricity. Given this common practice, it makes little sense to spend energy and capital refining that limited supply of gas for injection into the pipeline system rather than using it to directly generate electricity that would offset burning fossil gas for electricity generation.

In 2022, Liberty Utilities petitioned the Massachusetts Department of Public Utilities (DPU) to develop an RNG production facility at a landfill in Fall River, MA.[41] In December 2022, the DPU denied that request, noting that Liberty Utilities could not demonstrate clear greenhouse gas emissions reductions or benefits to its customers.

Such bioenergy projects exemplify how siloed decarbonization policy can lead to suboptimal outcomes. Utility commissions and gas distribution companies are tasked with pursuing emissions reductions solely on a greenhouse gas accounting basis and without considering more optimal uses of such bioenergy resources. A narrow focus not only places climate targets at risk but also has the potential to put the financial risk associated with such projects onto customers.

MANAGING FOOD AND AGRICULTURAL WASTE

New England has begun to get more active in its food waste treatment. Massachusetts (effective 2014), Vermont (effective 2014), Connecticut (effective 2014), and Rhode Island (effective 2016) have organic waste disposal bans of varying stringency[55] that typically cover commercial institutions such as grocery stores, food processors, restaurants, universities, and other large food waste producers. These institutions must divert their food away from conventional waste treatment (landfilling, incineration) to alternative strategies such as composting, food donation, or anaerobic digestion. In 2020, Vermont expanded its policy to cover residential food waste. Similarly, cities such as Cambridge, MA, and Boston, MA, have begun to collect residential food waste. While some of this waste is sent to composting facilities or fed to animals, siting challenges, costs, and limited compost off-takers challenge the ability of compost to scale in the region.

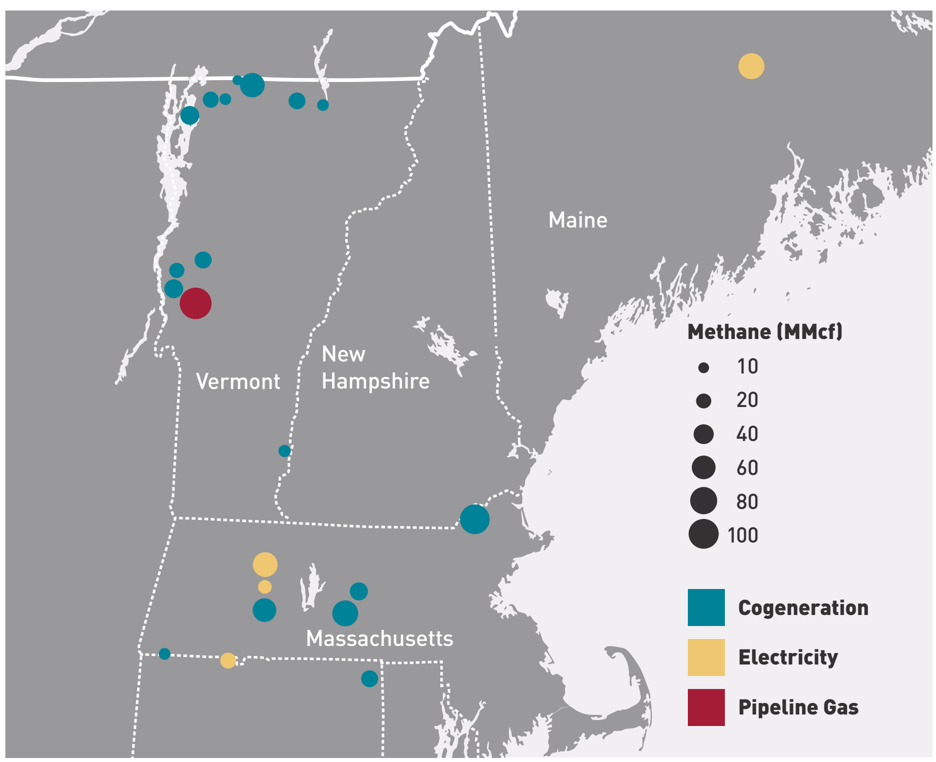
Managed anaerobic digestion has been growing as a waste management strategy, having been used for decades to treat municipal wastewater biosolids and generate energy for wastewater treatment plants. Over the past decade, anaerobic digestion has been adopted at several regional farms to manage manure from cattle (Figure 4). Several of these facilities have begun accepting food waste that can be co-digested with manure or biosolids.

Controlled digestion in tanks converts organic material to biogas and a residue digestate. The biogas is combusted directly at most facilities to generate heat and electricity, although one farm in Vermont is now refining biogas into RNG and other farms may follow suit. Excess electricity is sold to the grid – contributing a negligible amount of regional electricity in 2021.[51] The digestate is often used as a nutrient-rich soil amendment. There is increasing concern regarding various contaminants (per- and polyfluoroalkyl substances, perfluorooctanoic acid, pharmaceuticals) in digestate from municipal wastewater treatment, which can have devastating financial and environmental impacts for farmers who use them.[56] The State of Maine has subsequently banned the application of such material to land,[57] and Vermont has taken steps to reduce PFAS concentrations in food waste.[58]

Figure 4.

MAP OF ANAEROBIC DIGESTERS IN NEW ENGLAND PLOTTED BY ENERGY OUTPUT (COLORS) AND TOTAL EQUIVALENT METHANE PRODUCTION

Source: EPA Livestock Anaerobic Digestor Database.[59]



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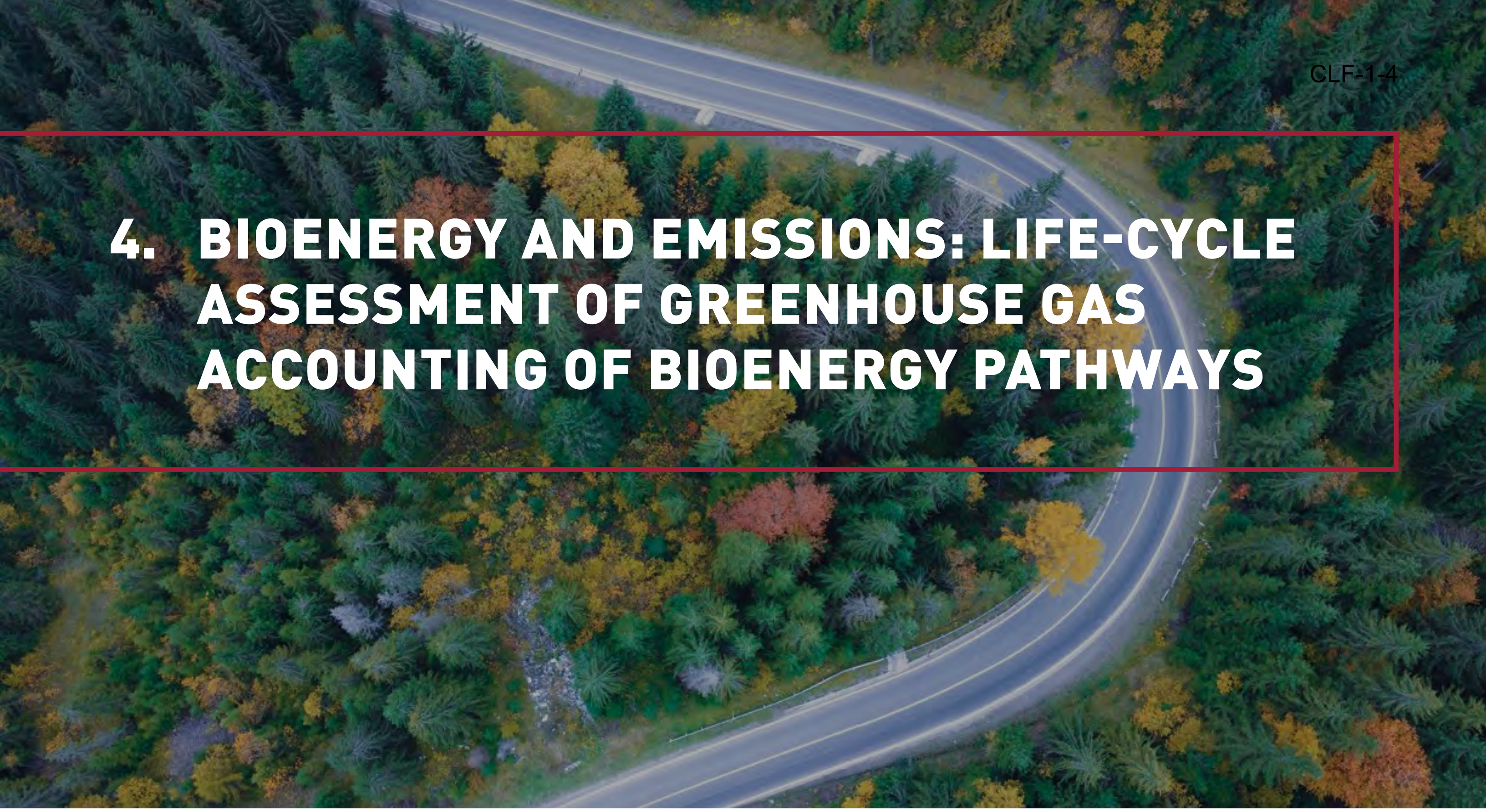

4. BIOENERGY AND EMISSIONS: LIFE-CYCLE ASSESSMENT OF GREENHOUSE GAS ACCOUNTING OF BIOENERGY PATHWAYS

The Greenhouse Gas Impacts of Bioenergy Are Often Underestimated and Misunderstood

It is often erroneously assumed that bioenergy use has no climate impact. In reality, the climate impact can be considerable – as the EPA states, "depending on the feedstock and production process, biofuels can emit even more greenhouse gases than some fossil fuels on an energy-equivalent basis."[60] This is for two key reasons.

First, like and often more so than fossil fuels, production of bioenergy resources requires significant energy inputs. These inputs come from the cultivation, collection, transport, and processing necessary to make the bioenergy usable, akin to the energy-intensive refining of crude oil into gasoline. Because bioenergy resources are more spatially diffuse and less energy dense than primary fossil resources, these energy inputs tend to be higher than those needed for refining fossil resources.[61] These energy demands generate "life-cycle" greenhouse gas emissions, given the greenhouse gas intensity of today's energy inputs. While such energy inputs could be decarbonized with renewable energy, such application of limited renewable energy would be misguided given the high energy demands and other environmental and social impacts of bioenergy production and the more beneficial uses of renewable energy, such as heating buildings and powering electric vehicles.

Second, the use of bioenergy resources and the intentional production of methane gas from some bioenergy resources can increase net accumulations of carbon dioxide and methane in the atmosphere by disrupting the natural cycling of these gases.

Like the carbon stored in fossil fuels, the carbon stored in natural resources is a stock that, if depleted and released into the atmosphere, causes an increase in atmospheric CO_2 levels, leading to increased warming. Some biomass (grasses, leaves, debris, food) rapidly decomposes and is regenerated on short, often annual, timescales.

Use of these resources for energy has little impact on the carbon cycle when viewed within a silo, but can have large impacts on the carbon cycle when bioresource cultivation drives land use changes, like the conversion of forests and grasslands to create new bioresource croplands. Harvesting a whole tree for energy, by contrast, will require decades to regenerate the stock of carbon. Changing a whole swath of land from a carbon-rich forest to a sprawled development leads to long-term to permanent releases of carbon from the biosphere. Both of these activities create a net impact to warming that can be greater than the use of coal.

Conventional methods of accounting for emissions across sectors and jurisdictions do not provide a sufficient understanding of these impacts for decision-making and robust policy design. Exacerbating this problem is the fact that these emissions from the production and use of bioenergy often cross jurisdictional boundaries. Further, nations and states may have different ways of accounting for such activities (see page 20).

The practical implications of this can lead to unfortunate outcomes. Taken to the extreme, whole forests can be felled in one jurisdiction and shipped to another that claims to be using a carbon-neutral fuel because its accounting system only tracks changes in its jurisdictional carbon stock. This approach has been common in Europe for years.[12] The lack of clarity and consistency in greenhouse gas accounting approaches can still result in undesirable outcomes.

This section details major emissions drivers in the bioenergy life cycle, including cultivation, production, transportation, and combustion. Such an understanding of *life-cycle processes* is needed to inform robust policy design in economy-wide strategies (e.g., carbon tax or cap and trade), sector-specific strategies (e.g., clean heat or renewable transportation fuels standards), institutional climate planning, and the pursuit of individual projects.

It will take years to regenerate the stock of carbon released when a tree is harvested.

BIOENERGY AND NEW ENGLAND STATE GREENHOUSE GAS INVENTORIES

Across the board, New England states do not count direct bioenergy emissions in their reporting of total state-wide greenhouse gas emissions inventories. States generally use the EPA's State Inventory Tool,[62] following the greenhouse gas accounting methodology used in the *U.S. Greenhouse Gas Inventory*, in which "net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for Land Use, Land-Use Change, and Forestry."[63] These approaches are informed by and seek to align with practices established by the Intergovernmental Panel on Climate Change, although some practices differ.

Even though this approach is an analytically sound way of tracking changes in emissions at aggregate levels, it severs the relationship between the consumption of bioenergy, upstream emissions, and perturbations to the biological carbon cycle. The EPA addresses this gap by reporting emissions from wood biomass and biofuels separately from fossil fuels, yet it does not provide guidance in the tool for doing the same at the state level.

In New England, three states (Maine, Massachusetts, and Vermont) maintain accounts for bioenergy emissions. These states, along with Rhode Island, calculate land-use emissions, although, at the state level, there is no expectation that this approach will accurately account for the net emissions from bioenergy use since there is considerable interstate trade in energy. There is no expectation that the state that burns the biofuel will be the same state to grow replacement biomass. Since these greenhouse gas inventories are defined geographically, this ambiguity can lead to a mismatch between bioenergy emissions and the bioenergy-related fraction of land-use emissions reported by any given state, to say nothing of the vast uncertainty in land-use emissions accounting generally.[64]

States present bioenergy emissions in various ways to try to mitigate the confusion, including offering total emissions inventories with and without bioenergy (Maine) and displaying bioenergy and land-use emissions together (Vermont and Massachusetts). Rhode Island acknowledges the emissions from bioenergy but does not present any data; Connecticut excludes both bioenergy and land-use sectors; and New Hampshire appears to rely solely on EPA data rather than maintaining its own state-level accounts.

The constraints of the state-level greenhouse gas inventory model are largely to blame for the shortcomings related to bioenergy emissions. One of the fundamental principles of greenhouse gas accounting is to avoid double-counting. The Massachusetts inventory warns, "to the extent that biomass harvested in MA is combusted in MA, associated CO_2 emissions are double-reported in combustion and [land-use] emissions." The biomass harvested outside of the state is (presumably) reported in those states' inventories, so if MA were to report direct bioenergy emissions, it would lead to the undesirable situation that the sum of all state- and territory-level inventories would be greater than the EPA-calculated U.S. inventory. The same concerns are raised for reporting fuel cycle and other indirect emissions associated with bioenergy. Since these emissions should be accounted for in other sector or state inventories, reporting them as bioenergy emissions too would lead to a notable overcount.

No approach is perfect and different methodologies involve tradeoffs. States must recognize the limitations of these approaches and not rely on the inventories to assess the effects of bioenergy. Rather, states should consider adopting targeted and well-informed models of bioenergy emissions based on life-cycle assessment to inform bioenergy policy.

COMBUSTION: DIRECT EMISSIONS

Direct emissions are those that occur when fuel is burned, such as occurs in vehicles, heating equipment, and electricity generation facilities. They are thus the "tailpipe," "burner tip," and "smokestack" emissions that result from burning carbon-based fuels.

Direct emissions from fossil fuels are the main driver of atmospheric CO_2 accumulation as they release carbon stored deep underground that would not otherwise enter the atmosphere ("fossil carbon"). Direct emissions from bioenergy release carbon that was relatively recently removed from the atmosphere through photosynthesis ("biogenic carbon"). Table 3 shows the direct emissions of fossil and biogenic CO_2 from the combustion of various fuels. Direct CO_2 emissions depend on both the energy and the carbon content of the fuel.

Table 3.

GRAMS OF CO_2 RELEASED PER KWH OF ENERGY IN SELECT FOSSIL AND COMPARABLE BIOENERGY FUELS

	FOSSIL	BIOENERGY
GASEOUS FUEL	Natural gas – 183	RNG – 183
LIQUIFIED GASES	Propane – 215	Renewable propane (DME) – 217
LIQUID FUEL	Diesel – 250	Biodiesel – 253
SOLID FUEL	Coal for electricity – 322	Wood – 333

CARBON STORAGE LOSS AND LAND-USE CHANGE

For most bioenergy derived from agricultural crops, the CO_2 released when the bioenergy is combusted may be temporarily restored in the next growing season, assuming a similar amount of the same feedstock is cultivated. This results in a roughly months-to-year-long fluctuation in the amount of carbon stored in these ecosystems. In the case of trees and soils that may be cut down or permanently disturbed, respectively – not only for direct biomass energy but also to clear land for food or energy crops – the carbon stored therein was removed from the atmosphere decades or even centuries ago. The release of that carbon depletes the carbon stored in ecosystems and transfers it to the atmosphere, leading to the net accumulation of CO_2 and affecting the global climate.

Accounting for such depletion of ecosystem carbon and its release into the atmosphere is an essential but often overlooked element of accounting for the impacts of bioenergy.[11,65] Biogenic emissions contribute to the accumulation of CO_2 in the atmosphere if biogenic CO_2 removal (e.g., photosynthesis) is not happening at a sufficiently rapid pace to regenerate the stored carbon.

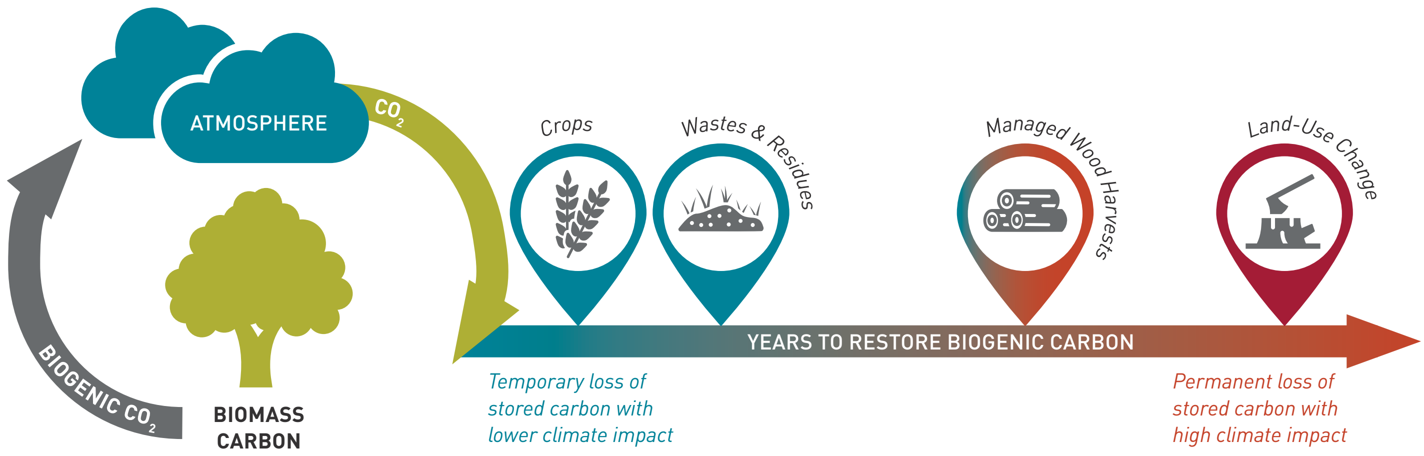

Figure 5.
Illustration of how biogenic carbon can contribute to atmospheric CO_2 accumulation if not restored in short timescales.

Young forests such as New England's are still paying back their carbon debt from the region's prior agricultural and industrial period.

Figure 5 illustrates *carbon storage loss* and the approximate storage *payback period* of different strategies. Wastes and residues that rapidly decompose and come from rapidly regenerating sources (e.g., food waste, wastewater sludge, etc.) are not long-term stores of carbon and thus have shorter payback periods. Capture and treatment – including conversion to bioenergy – of some wastes may also avoid generating methane emissions from the decomposition of organic matter if less impactful, alternative disposal methods are not available.

At the other extreme, harvested wood can take decades to pay back and regenerate, leading to a significant loss of carbon storage. Generally, fuels with decade-plus paybacks and that lead to continual depletion of ecosystem carbon contribute to the accumulation of greenhouse gases in the atmosphere.

Activities that result in permanent land-use change, such as deforestation for energy crops or food, never restore ecosystem carbon. Land-use change not only depletes ecosystem carbon but also makes it impossible for these ecosystems to grow their carbon stock. This *loss of sequestration potential* counters global goals to enhance natural carbon stocks as part of ambitious climate pathways.[66]

A stand of trees will continue to sequester more and more carbon as the trees grow. Trees in cultivated forests are removed when doing so maximizes economic returns. Had the trees been left standing, they would have continued removing CO_2 from the atmosphere for decades more. The carbon storage opportunity cost of *not harvesting* thus defines the carbon debt that results from their harvest and combustion.[67] Not only does it take decades for the harvested carbon to be restored but, due to changes in soil carbon resulting from dead trees being removed from the forest instead of decomposing into the ground, the forest carbon storage can never catch up to the no-harvest counterfactual. This is especially relevant with young forests such as New England's that are still paying back their carbon debt from the region's prior agricultural and industrial period.

Land that is not being directly harvested for bioenergy resources can also contribute to net greenhouse gas emissions through *induced* or *indirect land-use change*.[68] Bioenergy resources compete for land with food crops, leading to food price increases. These price increases are often sufficient motivation to bring more land into agricultural cultivation. The net greenhouse gas emissions from permanent land-use change from forest or grassland to farm are allocated to the bioenergy demand that stimulated it. The specific values of this indirect land-use change can be difficult to ascertain, however, especially because the effects can happen internationally.

METHANE LEAKS

Methane leaks are a pernicious problem in fossil natural gas, biogas, and RNG systems due to the high global warming potential of methane. Leaks occur at every step of gas production, transmission, storage, delivery, and use.

Using organic wastes for energy can generate varying levels of fugitive methane emissions depending on facility design, feedstocks, and conversation processes. Measurements of fugitive emissions indicate that loss rates in agricultural bioenergy facilities may range between 0.5% and 8%, and may be as high as 15% in wastewater treatment plants with biogas production.[69] A small number of super-emitter facilities may also be responsible for a significant portion of the overall methane leaks.[70] A 2% leakage rate increases the climate impact of methane consumption by 25% to 64% relative to emitted CO_2 based on 100-year and 20-year time horizons, respectively. An 8% leakage rate increases the climate impact of methane consumption by 108% to 273% on those same time horizons. As such, policy pathways contemplating RNG must ensure that fugitive methane loss is accurately measured. In addition to these production leaks, leaks in older gas distribution systems can be as high as 2.5%, half of which may come from stoves, furnaces, and other equipment behind the meter.[71] There is no strategy for mitigating these leaks. Despite six years of accelerated replacement of old distribution lines, the gas system in the Metro-Boston region has not exhibited any noticeable leak reduction. Thus, while RNG has been proposed as a drop-in substitute for fossil gas, continued reliance on the pipeline distribution of methane – of fossil or biological origin – creates significant challenges for the elimination of greenhouse gases.

Methane leaks are a pernicious problem due to the gas's high global warming potential.

INDIRECT AND HIGHER-ORDER EMISSIONS

Indirect emissions are those that stem from energy and material inputs to producing, refining, processing, storing, and transporting bioenergy. (Leaks are sometimes also classified as indirect emissions.) These emissions are highly variable and depend on local factors such as the emissions intensity of the local electricity supply, the energy requirements of a particular conversion process, agricultural practices, transportation distances, etc. Indirect emissions accumulate in the atmosphere and are not typically reabsorbed by new bioresource growth. They thus can cause much of bioenergies' impact on climate change. As efforts to reduce emissions across all parts of the economy proceed in the coming years and decades, these indirect emissions are expected to decline.

Life-Cycle Assessment Is One Way to Calculate Accurate Greenhouse Gas Emissions from Bioenergy

Accounting for all the different sources of greenhouse gas emissions from bioenergy, ranging from the cultivation of bioenergy resources through fuel production to final combustion, is the approach taken in life-cycle assessment: a technique for comparing the environmental impacts of technology choices. The term "life cycle" refers to the chain of activities that contribute to the production and use of a given product, including acquiring or cultivating raw materials and feedstocks, manufacturing, refining, transporting, using, and disposing of resources (Figure 6). By examining and quantifying all of the energy and resource inputs and greenhouse gas emissions and waste outputs in each of the life-cycle stages, environmental burdens can be calculated and compared. The currently accepted approach to life-cycle assessment has been standardized by the International Organization for Standardization as ISO 14040 and ISO 14044.

Figure 6.
Diagram of a product life cycle. The dotted line connecting the "end-of-life" box with production indicates recycling.

A life-cycle assessment can be a useful tool for calculating greenhouse gas emissions from bioenergy and other energy sources if the focus is on accurate and transparent emissions accounting with the goal of facilitating genuine decarbonization. Importantly, however, life-cycle assessments can also be misleading when constructed poorly, applied in vague situations, or used by those with the intent of promoting a particular energy strategy. They can be manipulated in ways that could cause policymakers to support or invest in polluting technologies rather than truly low-greenhouse gas technologies. If policymakers are considering adopting energy life-cycle assessments to guide technology selection, they must use caution and provide ample time, staffing, and financial resources. Policymakers must ensure that trusted experts are retained by the regulator to construct fair and accurate models and that polluting industry interests are not permitted to influence the models in ways that could make polluting technologies appear cleaner than they are. Doing so is essential if states are to adopt policies that allow them to meet their greenhouse gas reduction requirements and targets.

The following sections provide a high-level overview of life-cycle emissions from various bioenergy fuels.

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The most carbon-intensive sources of electricity involve fuels that use whole tree biomass or require substantial processing.

OVERVIEW OF BIOENERGY LIFE-CYCLE GREENHOUSE GAS EMISSIONS

Electricity

The National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy has for many years studied the life-cycle greenhouse gas emissions of different electricity sources by synthesizing and harmonizing thousands of life-cycle assessment results from the academic literature.[72] The results largely validate the common understanding of the environmental preferability of different electricity sources: fossil fuels are significantly more greenhouse gas emissions-intensive than renewables. In general, coal electricity has the highest life-cycle greenhouse gas emissions, followed by oil and natural gas. Renewable electricity is much less emissions-intensive, ranging from ocean power at the low end to biopower at the high end.

Complicating this story is the variability in emissions intensities within each energy technology. The NREL team found enormous ranges in emissions intensities, the most striking of which is for bioenergy-powered electricity. At the high end, one study calculated the life-cycle greenhouse gas emissions intensity of bioelectricity to be higher than that found in any other study except for some life-cycle assessments of coal electricity. On the other end, studies also found that bioelectricity is able to *avoid* large quantities of greenhouse gas emissions even without the use of carbon capture and storage.

The drivers of this wide range of life-cycle assessment results include differences in system boundary decisions and data sources as well as variations among different types of bioresource feedstocks that can be used to generate electricity. The most carbon-intensive sources of electricity involve fuels that use whole tree biomass or substantial processing. Alternatively, the review included carbon capture and storage pathways that generate a "negative emission" with the production of electricity. The review's quantitative approach also assigned negative carbon intensity values to pathways that avoided methane emissions in the generation of electricity, such as those from landfill gas or anaerobic digestion of manure, with the assumption that such bioenergy pathways are exclusively responsible for methane reductions – an assumption that cannot be categorically applied given a range of options for manure management.[73] Policymakers should pay particular attention to assumptions about the alternative disposition of wastes and whether the baseline is accurate before accepting a negative life-cycle assessment figure for bioenergy-powered electricity.[74]

How Bioenergy Compares with Wind, Hydro, and Solar Photovoltaics

Traditionally, bioenergy has been grouped with wind, hydropower, and solar photovoltaics as a renewable energy technology. As the costs of wind, water, and solar technologies have plummeted, a gap has formed between them and bioenergy in terms of the role they might play in the future energy system. In an NREL study, the median life-cycle emissions factors for solar photovoltaics, hydropower, and wind power were found to be 43, 21, and 13 g CO_2e/kWh, respectively, with relatively narrow ranges around those values. Bioenergy, although having a median emissions factor not much above, at 52 g CO_2e/kWh, has a range spanning from 1,300 to –1,000 g CO_2e/kWh.

These results suggest that wind, water, and solar energy represent not only a more effective pathway toward decarbonization but a more scalable one too. As production capacity for photovoltaics and wind turbines continues to expand worldwide, economies of scale and technological learning curves are driving efficiency gains, decreasing life-cycle emissions further.

Illustrative Life-Cycle Assessment of Selected Bioenergy Pathways

The NREL data are useful in visualizing the ranges in emissions intensities of the various electricity sources. However, the fact that the biopower values span nearly the entire range of emissions intensity values and beyond makes that analysis unhelpful for informing bioenergy decisions and even less so in a specific geographic region like New England. In this section, we present representative life-cycle greenhouse gas emissions results for a number of specific bioenergy pathways with the goal of comparing bioenergy pathways, identifying key emissions drivers, and highlighting sources of uncertainty.

We present the results in four main life-cycle phases (depending on the bioenergy pathway reported, there may be some variation to the scheme):

- **Feedstock preparation**, including agricultural and forestry management, chemical and fuel inputs, energy for harvesting and collection, and transportation.
- **Conversion emissions**, including the energy used to power a fuel production process and related transportation.
- **Combustion emissions**, including all CO_2 produced when burning the fuel, including biogenic CO_2.
- **Carbon uptake**, which accounts for the biogenic removal of CO_2 from the atmosphere due to replacement of crops and trees. Differences between biogenic combustion emissions and carbon uptake values can be explained by carbon storage loss. The greater the carbon uptake figure in a life-cycle emissions calculation, the more room there is for uncertainty in real-world applications.

Our presentation of these four phases is intended to better illustrate the generation of emissions for a broad audience. Is it an accurate accounting for emissions incurred at different steps in the life cycle, based on current assumptions for some products. Our presentation of these steps is novel as it seeks to emphasize the emissions debt that is incurred by the first three categories as well as the importance of ensuring near-complete carbon uptake. For a bioenergy strategy to effectively reduce emissions, the emissions from the first two categories must be minimized, while those from the last two categories must be balanced. It is important to remember that a bioenergy pathway that effectively reduces emissions on a life-cycle basis may not necessarily be the highest and best use of a bioenergy resource, effectively use input energy, or be the most cost-effective strategy.

Honest life-cycle analyses rely on transparency. Often, greenhouse gas emissions and other environmental impacts are reported as single-point values. These are easy to communicate but can obscure vital details, variabilities, and assumptions. For example, we have noted that assumptions around carbon storage loss can drastically change the environmental preferability of different biofuels. Further, we have highlighted how fuel processing and methane leaks can contribute to emissions. Carbon uptake (if present) is a negative emissions process that reduces overall carbon intensity, leading to an estimate of net emissions – the sum of the four emissions categories.

This, or similar disaggregation, can be a powerful tool for regulators and policymakers in the evaluation and application of bioenergy pathways. Understanding the magnitude and composition of conversion emissions can give insight into the efficiency of a process. Likewise, disaggregating carbon uptake places an emphasis on ensuring that the bioenergy resource is produced sustainably. This prompts regulators with the need to intentionally consider each step and provide robust data quantifying the impact in each category. It places the onus on the pathway proposer to demonstrate that the approach is consistent with broad climate goals. While such quantified disaggregation could be applied to the direct regulation of a bioenergy pathway, at minimum regulators should evaluate pathways using such multidimensional frameworks.

The following sections are used to illustrate these processes using several broadly applicable pathways. It must be reiterated that the models and values presented here are not definitive but merely representative of each pathway and the contributions of its life-cycle phases. Accordingly, the specific emissions values presented here *must not* be used to dictate a specific policy's design. Instead, along with the supporting discussions, they should be used as a guide to identifying the highest and best uses of bioenergy resources in mitigating climate warming in specific geographic and economic contexts.

SOLID FUELS

We analyzed representative life-cycle greenhouse gas emissions for four types of wood fuels – roundwood timber, forest residue, mill residue, and pellets. The results show that gross greenhouse gas emissions from wood bioenergy, without considering carbon uptake, are larger than those from fossil fuels. The degree of carbon storage loss associated with each of these fuels, which influences the carbon uptake, is therefore a key driver of the net greenhouse gas emissions from these fuels. The amount of carbon storage loss that is associated with wood energy production in New England forests is not clear; we use 20% here as a conservative figure, although it may be much higher. From these results, wood pellets appear to be 15%–25% more emissions-intensive than the other three wood fuels. The main driver of this difference is the pellet production process.

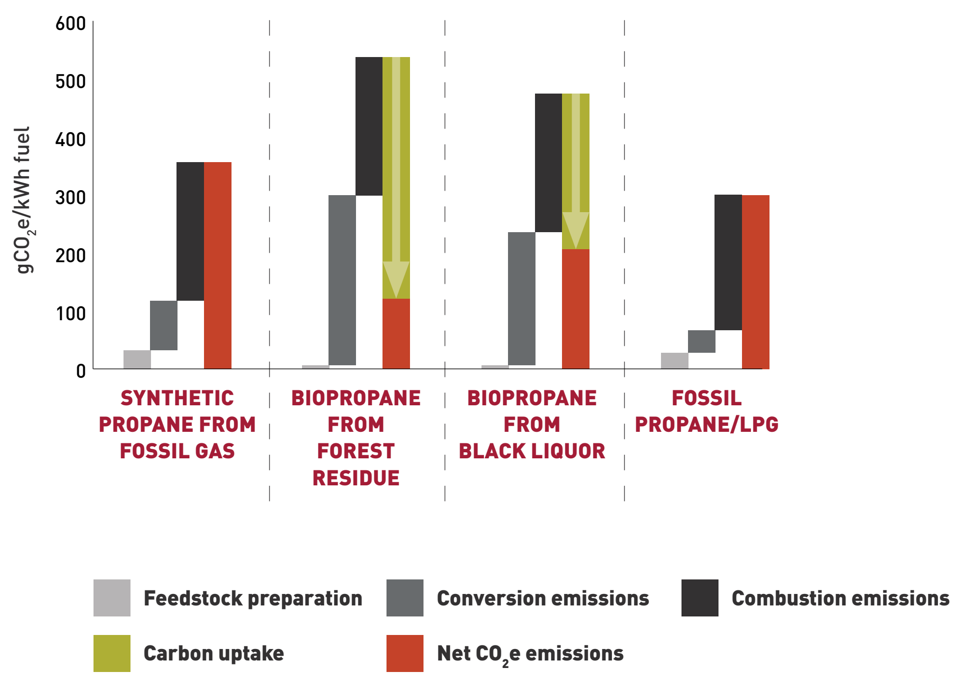
The other three fuels have lower greenhouse gas emissions intensities than pellets. Timber has the largest feedstock emissions because of the fuel and chemicals used in forest management and harvest. Forest residues and mill wastes have lower feedstock emissions because they are waste materials.

LIQUID FUELS

A bioenergy alternative for liquefied petroleum gas (LPG) is biopropane, a fuel that is functionally equivalent to fossil propane but can be produced from biological sources. Figure 7 presents representative life-cycle greenhouse gas emissions data for biopropane produced from gasification of forest residue and from gasification of black liquor, a waste product from the pulp and paper industry. This life-cycle model is based on the production of dimethyl ether (DME), a close relative of propane, for which there is much more data on the environmental impacts of production. DME is sometimes called "biopropane" or mixed into fossil LPG tanks. We assume the same conservative carbon storage loss factor of 20% that we used above. Life-cycle emissions for biopropane are presented alongside two fossil fuel-based comparisons: fossil propane and synthetic propane produced from fossil natural gas.

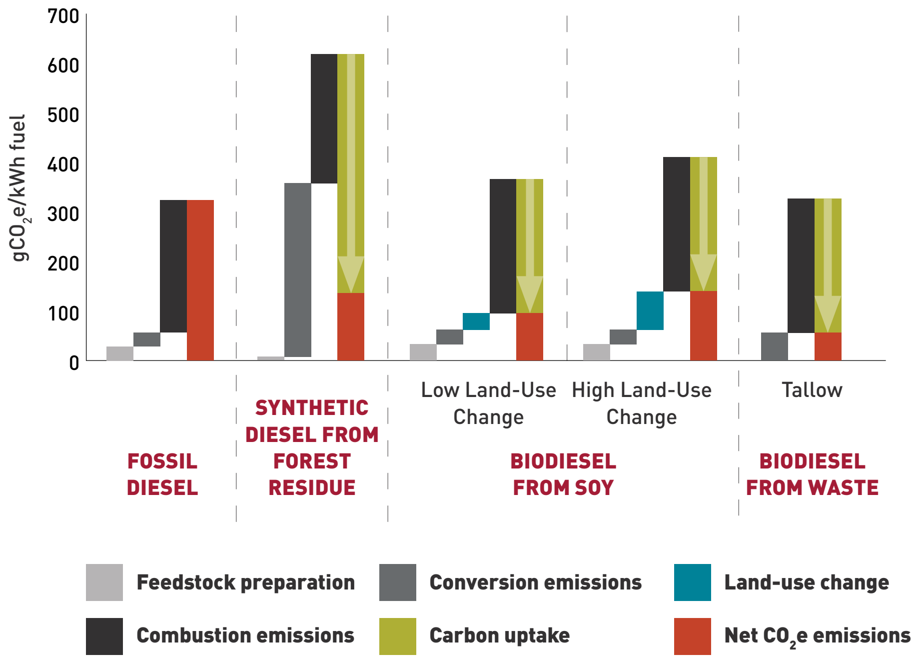
The results show that, like for wood energy, the gross greenhouse gas emissions for biopropane are much larger than for fossil propane or LPG. One major reason for this is the large consumption of bioenergy for heating the gasification processes. We assume that all the energy inputs for the forest residue case come from wood energy, while energy requirements for the gasification of black liquor are satisfied with both bioenergy and electricity. Carbon uptake offsets some of the biogenic emissions from combustion and conversion; when it is considered, the net greenhouse gas emissions range from 120 g CO_2e/kWh to 210 g CO_2e/kWh, lower than the 300–350 g CO_2e/kWh associated with fossil and synthetic propane.

Figure 7.
Representative life-cycle greenhouse gas emissions of propane/LPG based on different conversion pathways, including synthetic propane produced from fossil gas, forest residues, black liquor (a waste product from the paper industry), and fossil propane. Synthetic propane from bioresource feedstocks is called "biopropane" and assumes a conservative carbon storage loss of 20%.



There are also many bioenergy pathways for liquid fuels like gasoline, fuel oil, and jet fuel. Figure 8 presents representative life-cycle greenhouse gas emissions of diesel and biodiesel fuels. In addition to the life-cycle emissions of fossil diesel, we show data for synthetic diesel fuel produced from forest residues and biodiesel, a near-drop-in replacement for diesel fuel produced via the transesterification of soybeans and waste animal fat.

Figure 8.
Representative life-cycle greenhouse gas emissions of diesel and biodiesel fuels from a variety of production pathways. Fossil diesel refers to diesel fuel produced from crude oil. Synthetic diesel is a completely drop-in replacement for fossil diesel produced with the Fischer-Tropsch process; results are shown for production from forest residues with 20% carbon storage loss, as a conservative figure. Biodiesel, a near-drop-in replacement for fossil diesel as well as other liquid fuels like fuel oil, is produced via the transesterification of oily feedstocks, including crops and wastes. We show results for biodiesel produced from soy that includes the effect of different land-use change scenarios. The results for tallow biodiesel are also broadly applicable to other oily wastes like used cooking oil.



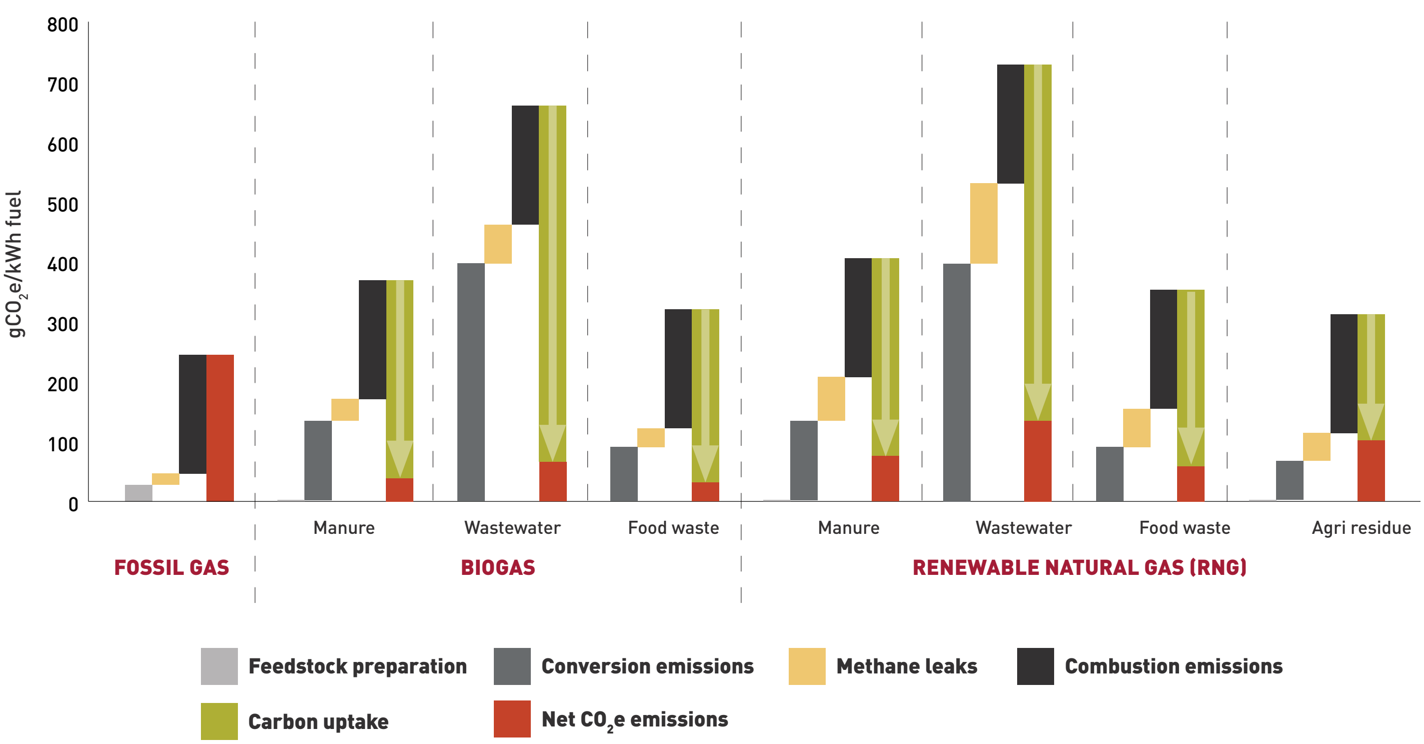
Gross greenhouse gas emissions for biopropane are much larger than for fossil propane or LPG.

GASEOUS FUELS

The bioenergy replacements for fossil natural gas are also methane-based fuels. Figure 9 presents representative life-cycle greenhouse gas emissions for two types of methane-based fuels produced from bioresources – biogas and RNG – as well as fossil natural gas as a comparison. Biogas is produced from the anaerobic digestion of organic wastes like manure, wastewater sludge, and food scraps. RNG is produced by either upgrading biogas (increasing the concentration of CH_4 to pipeline gas standards) or gasifying agricultural residue.

Feedstock emissions are largely negligible for waste resources like these. There are some transportation impacts, but they are small compared to the other emissions sources. Fuel conversion emissions can be quite large due to the energy required to operate the anaerobic digestion and upgrading facilities. All the conversion pathways examined here are at least partially self-powered, with some being completely self-powered. This means that some fraction of the fuel being produced is burned onsite to produce heat and electricity to power the process. Because these emissions are biogenic and New England is expected to see little land-use change or carbon storage loss associated with the use of these waste resources, the self-powered conversion emissions are ultimately zeroed out in the summation, along with combustion emissions. The largest net contributor to the life-cycle greenhouse gas emissions of these fuels, therefore, is methane leakage. Biogas production is conservatively assumed to have a 1% leakage rate, while RNG production is conservatively estimated to have a 2% leakage rate. As noted on page 23, fugitive methane losses can range significantly above 2%.[69] This model does not account for leakage from transmission, distribution, and end-use equipment, which can be considerable in older pipeline systems.[71]

Figure 9.
Representative life-cycle greenhouse gas emissions of methane-based fuels, including fossil natural gas; biogas produced from anaerobic digestion of manure, wastewater, and food waste; and RNG produced from upgrading biogas or gasifying agricultural residues.



The results show that biogas has an emissions intensity between 30 g CO_2e/kWh and 70 g CO_2e/kWh, while RNG has an emissions intensity between 60 g CO_2e/kWh and 135 g CO_2e/kWh, depending on the production pathway. This compares with the 245 g CO_2e/kWh life-cycle emissions intensity of fossil gas (which likely undercounts the contribution of methane leaks from natural gas production infrastructure).

There are at least two life-cycle activities that we are excluding from this analysis. First, we are not comparing these results with a waste management counterfactual scenario, as is commonly done to make RNG appear to have negative emissions. We believe this is a misleading technique, and it is more responsible to clearly identify the emissions associated with RNG production. Waste impacts can be presented in parallel if they can be reliably ascertained. For example, in New England, the management of 1 kWh-eq of manure has a life-cycle greenhouse gas emissions impact of approximately 16 g CO_2. So, we could claim that the net greenhouse gas impact of manure-based RNG in New England is 60 g CO_2e/kWh, rather than the 75 g CO_2e/kWh shown in Figure 9.

Second, we do not consider the emissions impacts of land application of digestate sludge. Depending on environmental conditions, the sludge, which contains quantities of carbon and nitrogen, can be oxidized to CO_2 and N_2O, decomposed to CH_4, and/or sequestered in the soil. The impact of this process is highly uncertain and variable across time and geography, and, as such, we exclude it from this analysis.

COMPARING ELECTRICITY AND BUILDING SECTOR LIFE-CYCLE EMISSIONS FROM BIOGAS AND RNG USAGE

Assuming 100% carbon uptake from waste-based biogas and RNG production, the life-cycle analysis conducted in this report shows that biogas has embodied emissions between 32 g CO_2e/kWh_{fuel} and 66 g CO_2e/kWh_{fuel}, and RNG has embodied emissions between 58 g CO_2e/kWh_{fuel} and 135 g CO_2e/kWh_{fuel}, depending on the production pathway. These upstream emissions figures tell only part of the story, however. Use of these fuels in different applications and different technological contexts also drives emissions.

We consider five reasonable use cases:

1. RNG used in home heating in an older, more leak-prone system (2.5% system leakage rate, 70% efficiency home furnace). Actual leakage rates in an older gas system may be significantly higher.[69]
2. RNG used in home heating in a newer, low-leak system (1% system leakage rate, 95% efficiency home furnace).
3. RNG burned in a gas turbine power plant (0% system leakage rate, 33% efficiency electricity production).
4. Biogas burned in a gas turbine power plant (0% system leakage rate, 33% efficiency electricity production).
5. Biogas burned in a reciprocating engine power plant (2% system leakage rate, 30% efficiency electricity production).

The first scenario represents a typical, older gas-burning system in Boston, where leaky gas distribution infrastructure, including home meters and appliances, has been estimated to be 2.5% or greater and older-generation furnaces have low conversion efficiency.[71] The second scenario assumes a recently constructed gas distribution system and new, high-efficiency heating appliances.

The third and fourth scenarios examine the gaseous fuels burned in a 33% efficient gas turbine power plant. These plants are often connected directly to high-pressure transmission lines with little to no fugitive emissions. The reciprocating engines contemplated in the fifth scenario, which are often used to burn biogas at landfills and other facilities that produce biogas directly, are estimated to have lower conversion efficiency and an average 2% leakage rate, but actual leakage rates may be significantly higher. Using averages of the upstream emissions factor ranges shown above (45 g CO_2e/kWh_{biogas} and 93 g CO_2e/kWh_{RNG}), we calculated the overall cradle-to-grave life-cycle emissions for the five scenarios (Tables 4a and 4b).

Tables 4a & 4b.

SCENARIO	EMISSIONS (G CO_2E/KWH HEATING)		
	FUEL PRODUCTION	LEAKAGE	TOTAL
1. RNG used in home heating (combustion) in a higher-leak gas distribution system	134	82.5	217
2. RNG used in home heating (combustion) in a lower-leak gas distribution system	98.4	24.2	123

SCENARIO	EMISSIONS (G CO_2E/KWH ELECTRICITY)		
	FUEL PRODUCTION	LEAKAGE	TOTAL
3. RNG used to produce electricity in a gas turbine	280	0	280
4. Biogas used to produce electricity in a gas turbine	138	0	138
5. Biogas used to produce electricity in a reciprocating engine	151	151	302

It is clear that system leaks and conversion efficiency play a large role in driving emissions in the use of gaseous biofuels like biogas and RNG. For large metropolitan areas with old distribution and use infrastructure, any perceived benefits of using RNG are undercut by the significant methane leakage emissions.

In electricity production, upgrading biogas to pipeline-quality RNG has a large emissions penalty. If there is the option to directly use biogas in a low-leak application such as an on-site gas turbine, that is preferable. However, if there is a high risk of leaks, directly flaring the fuel may be acceptable.

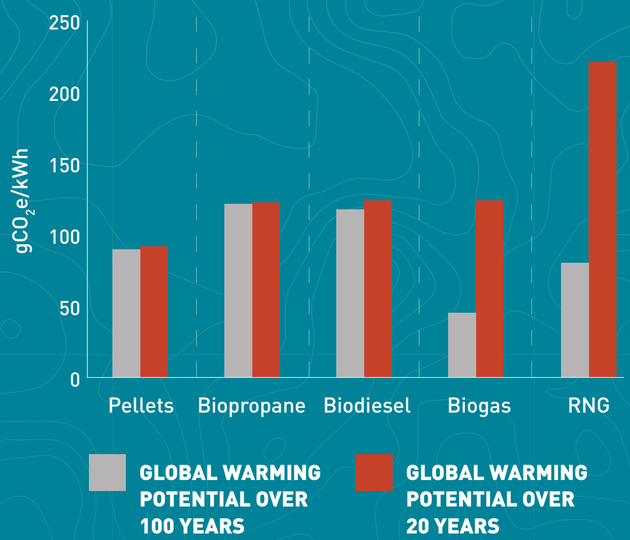
To compare the uses of these fuels across two energy services (electricity and home heating), consider a third alternative to the two provided here: heating using an air-source heat pump. If a heat pump with an average performance coefficient of 2.5 were to be powered by electricity produced by RNG, life-cycle emissions would total 112 g CO_2e/kWh heat. If it were powered by biogas burned in a gas turbine, the greenhouse gas emissions would be just 55 g CO_2e/kWh. A geothermal network system with a COP of 5 that runs on biogas electricity from a gas turbine plant would have a life-cycle emissions factor of roughly 27.5 g CO_2e/kWh heating. All of these are less than the low-leak heating scenario. With a limited supply of organic waste from which to produce bioenergy, it is usually preferable to put that resource to work producing electricity rather than burning it in homes.

WHAT IS THE "CORRECT" TIMESCALE FOR GLOBAL WARMING POTENTIAL?

The historical method to account for the climate change impact of different greenhouse gases is GWP-100, or global warming potential over 100 years. This approach has emerged as the default when converting greenhouse gases like methane, nitrous oxide, and hydrofluorocarbons into a common base unit of carbon dioxide-equivalents (CO_2e). The selection of this equivalence factor is a policy choice. GWP-100 looks at the amount of heat absorbed by a given greenhouse gas in the atmosphere over 100 years, normalized to the effects of carbon dioxide. A similar method uses a 20-year time period instead (GWP-20). Gases that have atmospheric lifetimes of less than 100 years will see their GWP-100 values differ, sometimes significantly, from their GWP-20 values. The difference between the two is most prominent for methane, which has a GWP-100 value of 29.8 and a GWP-20 value of 82.5. This difference is due to methane's high radiative forcing but relatively short atmospheric lifetime.

To illustrate the effects of different timescales on life-cycle assessment results, we examined a selection of the results presented earlier using both GWP-100 and GWP-20 (both using the three main greenhouse gases). We also examined the results using the full list of greenhouse gases, but there was little difference from the results of just using the three main greenhouse gases. This is because those other gases are largely combustion products, and we did not include data on the combustion of our fuels in real engines, turbines, furnaces, etc. Figure 10 presents the results of the comparison. For wood pellets, biopropane, and biodiesel, the difference between the two methods is negligible. Using GWP-100, biogas and RNG appear to be much more climate-friendly than the other three fuels. Using GWP-20, on the other hand, the preference switches, and biogas and RNG become the least climate-friendly. This change is due to the outsized role that methane plays in biogas and RNG life-cycle emissions compared to the other fuels. Given the pressing need to reduce greenhouse gas emissions over the next 20 years to forestall the worst effects of climate change, this difference is significant. Shifting to the use of GWP-20 would more accurately reflect the warming effects methane is having now and over the next three decades while discounting future warming and broader impacts of CO_2 emissions such as ocean acidification.

Figure 10.
Life-cycle greenhouse gas emissions for sample bioenergy fuels using GWP-100 and GWP-20 equivalence factors for the three major greenhouse gases (CO_2, CH_4, and N_2O).



*Please note the differences between GWP, described here, and carbon storage loss and land-use changes, discussed on pages 21 and 22. That distinction is especially important for wood-based bioenergies.

Life-Cycle Accounting Can Be Manipulated to Greenwash Bioenergy

Biogas that is produced from animal manure is often credited as having very low or even negative life-cycle emissions. This claim comes from assumptions about what would have happened to the manure had it not been used to create biogas. The most greenhouse gas-intensive manure disposal method, "lagooning," stores manure in pits where the moisture level results in significant methane emissions. Biogas or RNG produced from manure is often assumed to avoid lagooning emissions, which shows up as a large negative emission of greenhouse gas in a life-cycle analysis model.

Many life-cycle analyses, including those using GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation), a widely utilized and freely available tool from the Argonne National Laboratory, assume by default that lagooning is the alternative fate of any manure that is manufactured into biogas or RNG. This is a particularly false assumption in New England, where less than 10% of cow and pig farms use lagooning.[75] Instead, New England farms most often use low-emission manure management methods like field spreading, composting, solid storage, and manure drying. But even nationally, where lagooning is more common, that baseline is changing via the EPA's AgStar program to encourage environmentally responsible practices.[75]

The fact that default assumptions overstate these avoided emissions has led to some unintended and undesirable consequences. The California Low Carbon Fuel Standard, which uses GREET data to assign carbon intensity values to different fuel types, assigns values "as low as −630 g CO_2e/MJ for dairy biomethane-based electricity, −530 g CO_2e/MJ for dairy manure biomethane-based compressed natural gas, and −360 g CO_2e/MJ for swine manure-based biomethane LNG."[76] Under the California Low Carbon Fuel Standard (LCFS), for example, these avoided emissions become extremely valuable, which results in several perverse outcomes:

1. It heavily subsidizes manure-generating facilities, their activity, and biomethane production.
2. It incentivizes manure-generating facilities away from other methane mitigation strategies that may have greater climate, ecological, and economic impacts.
3. It currently incentivizes production of the lowest-value renewable fuel.
4. The large subsidy creates a significant risk for these facilities if the subsidy is removed.

An initial analysis of this feature of the LCFS conducted by an economist at UC Davis suggested that the subsidy to a participating dairy farmer could be as much as 50% of the total revenue of selling milk.[77] With these numbers, it becomes entirely possible that large farms will choose to expand their dairy or swine herds – and associated emissions - *because* of the subsidy. Environmental groups have petitioned the California Air Resources Board (which oversees the LCFS) to make changes to address these perverse incentives, but with little success so far.[76]

One lesson from the experience of the California LCFS is to be careful with the use of life-cycle factors and life-cycle assessment tools. Models are developed for specific purposes in specific contexts. When they are used outside of those contexts and for other purposes, some modeling decisions that may not have been originally significant could turn out to be destabilizing, as in the manure case. It is not a reason to discard the model but instead is a call to take care and potentially adjust the underlying modeling assumptions, ensuring that the data are representative of your new context. In New England, for instance, any attempts to claim large, avoided emissions from manure-based biogas run up against the reality of manure management in the region.

Conclusions

Examining representative life-cycle emissions intensities for different bioenergy pathways can be illuminating. It can reveal hidden sources of greenhouse gas emissions and clarify the erroneous claim that biogenic CO_2 emissions have no impact on the climate. It can also show how, in general, different bioenergy fuels stack up against each other and against fossil and renewable alternatives. However, there are real limitations in the use of quantitative life-cycle assessment results alone to guide policy at a high level. There is so much variability in the factors that go into a bioenergy life-cycle model that it is simply impossible to claim a definitive life-cycle emissions factor for each type of bioenergy. An attempt to do this in California's LCFS has led to unintended consequences. We have also learned that the land-based effects of bioenergy – land-use change and forest carbon storage loss – are some of the most powerful factors defining the life-cycle emissions of bioenergy, and yet we have huge gaps in knowledge about them.

This is not to say that life-cycle assessment has no role in guiding bioenergy and decarbonization decision-making. In situations that call for specific project analysis and technology alternatives assessment, it is a useful tool. Good analysts can look at the details of projects and locations, carefully and transparently craft life-cycle models, and work closely with project stakeholders to understand their positions. Results from the models can show tradeoffs, hidden impacts, and unintended consequences. This is the scale at which life-cycle assessment thrives because it is possible to input enough real data about projects to minimize uncertainty.

Life-cycle assessment should play an important role in guiding bioenergy and decarbonization policy, but such policy should not be decided through use of quantitative results alone. Instead, the logic that goes into constructing a life-cycle assessment model, sometimes known as "life-cycle thinking," can be sufficient to ensure that policymakers and the policies themselves take into account all of the various sources of both emissions and uncertainty. Policy competence in life-cycle thinking can also make it more difficult for representatives of polluting industries to use life-cycle assessment to manipulate perceptions of their technologies.

Land-use change and forest carbon storage loss are some of the most powerful factors defining the life-cycle emissions of bioenergy.

5. COST AND ECONOMIC CONSIDERATIONS

Production and Use Costs

Evaluating the cost of a bioenergy strategy faces similar challenges to assessing its impact on emissions. Costs are incurred throughout the fuel's life cycle.

The cost of energy production and market prices are useful indicators of whether a particular decarbonization strategy is economical. However, those indicators fail to account for the financial cost of the harms caused by use of fuels, such as human health impacts from worsened air quality and the financial costs of future generations because of greenhouse gases emitted today.

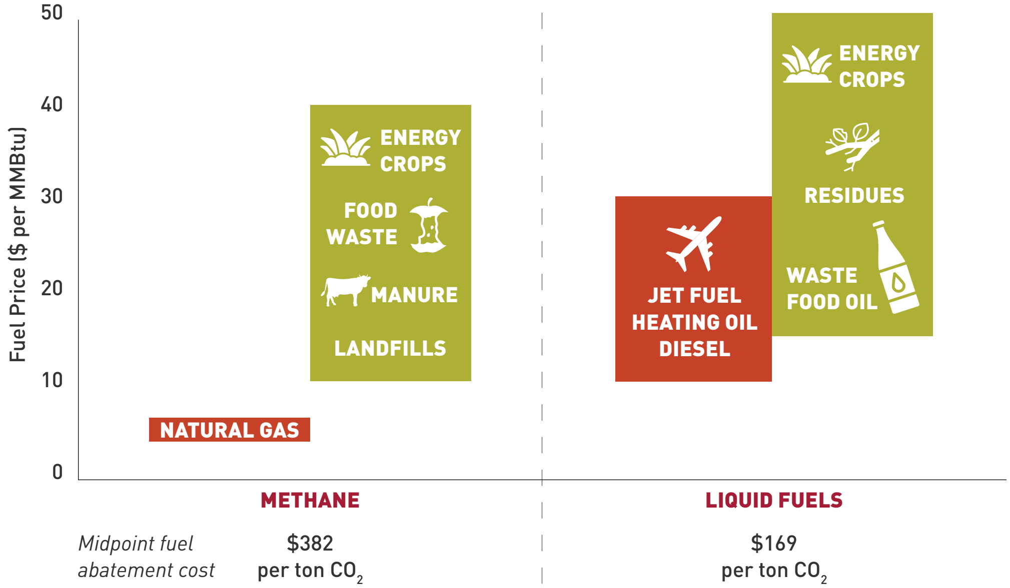
The cost of emissions is considerable. The EPA has recently estimated that the cost of emitting a ton of carbon dioxide creates a society-wide impact of nearly $200 (the social cost of carbon) and an impact of approximately $1,700 per ton of methane (2023 interpolation of EPA proposed social cost of carbon guidance[78]). Such costs will increase over time as the impacts of climate change are more acutely felt.

This section explores the drivers of bioenergy costs as well as some consequential costs and economic impacts.

Figure 11.

ABATEMENT COST OF BIOENERGY

Comparisons of production costs for fossil fuels (orange) and illustrative estimates for the production costs of each fuel's renewable counterpart (green). Abatement cost ranges are shown below each fuel. Fossil prices are obtained from Energy Information Administration wholesale or city gate prices for New England between 2019 and 2021.[35] Low prices for RNG are based on recent RNG cost[79] or cost proposals[41] in the region. The low price of liquid fuels is based on estimates of production from food waste.[80] High values are based on estimates of a study of Low Carbon Fuels in Net-Zero Energy Systems[81] and are in line with the range of estimates from other studies of RNG and renewable fuel prices.[8,18,39,82]



The differences between methane gas and liquid fuels shown in Figure 11 are notable. Bioenergy costs more than fossil energy because it requires substantial refinement of raw biomass, fossil fuels have greater economies of scale, and externalities created by agriculture are better reflected in crop prices whereas the externalities of fossil fuels are more broadly incurred by society. This cost differential is especially high in the case of methane. Fossil gas has to undergo relatively modest processing to separate methane, some valuable hydrocarbons (e.g., ethane, propane), and contaminants. RNG requires substantial refinement of biomass into a purified gas. The difference between liquid biofuels and fossil fuels is smaller as the resource demands of producing liquid biofuels are similar to refining crude oil into fossil liquids.[61]

As a result, the abatement cost – the cost to mitigate carbon dioxide combustion emissions – of methane (pipeline gas) is typically much higher than that of liquid fuels. This differential lies at the core of the imperative to prioritize the limited amount of bioenergy resources for the "highest and best uses." It is cheaper to defossilize a liquid fuel than pipeline gas. Ensuring that bioenergy resources are prioritized for hard-to-electrify sectors ensures more efficient, low-cost, and low-risk decarbonization. The low cost of fossil methane challenges the cost-effectiveness of electrifying buildings that use gas, but RNG poses *a greater* cost-effectiveness challenge, leaving its application dubious. The Massachusetts 2025/2030 Clean Energy and Climate Plan[83] showed that even if pipeline gas (methane) is still used in high demand, it should be the last fuel to be decarbonized. That is, it would be better to continue burning fossil methane for decades to come if burning gas is still necessary than to pay for alternative gases.

WHAT ABOUT HYDROGEN?

Adopting 100% green hydrogen as a heat source would incur considerable costs and disruption. Pure hydrogen is not compatible with the current pipeline gas distribution system. Hydrogen causes embrittlement of cast-iron pipes and also can affect the molecular structure of some plastic pipes.[84] A new pipeline distribution system, including new building distribution systems, would be needed. All appliances would at least need a change of burner tips, if not a full replacement, to be hydrogen compatible. Hydrogen has a global warming potential 11 times larger than CO_2 and, as a smaller molecule, is more susceptible to leakage.[85] Renewable energy resources deployed to create green hydrogen could be put to more efficient use in directly displacing fossil fuels in electricity generation or supporting electric heating. Given the limited potential benefits, efforts to incorporate hydrogen into the gas system would be a misallocation of resources.

The gradual blending of RNG and hydrogen into the pipeline system obscures an important price signal that should prompt customers to adopt more cost-effective carbon mitigation strategies. It obscures the fact that, long-term, such fuels will substantially increase consumer costs. Reliance on such fuels requires reliance on an expensive-to- maintain alternate energy distribution system, which further increases costs if such a system becomes redundant. Wealthier people will have more ability to leave the natural gas system by investing in cold climate heat pumps and weatherization projects, while lower-income people will likely become burdened with the resulting higher rates.

Broader Environmental and Socioeconomic Impacts

AIR QUALITY AND HEALTH

The combustion of fuels for energy releases various pollutants such as particulate matter, volatile organic compounds, and nitrogen oxides. The last two facilitate the production of ozone. High concentrations of these pollutants lead to adverse health outcomes: asthma, cardiac illness, cancer, and premature death.

The transition from coal to gas has resulted in a remarkable reduction in air pollution nationally and a concomitant reduction in mortality from air pollution arising from stationary sources.[13] During this time, renewable energy policies around the country reinforced wood biomass consumption across several sectors. Displacement of coal for wood biomass in industrial boilers and maintaining wood and pellet home heating position woody biomass as the most significant contributor to mortality – despite incidences of mortality being down nationally.[13] In all New England states, wood is the largest generator of such point source air pollution, largely from home heating.

The coming years may see an additional reduction in point source air pollution as the economy decarbonizes.[6,86] These improvements will be driven by a number of factors:

- Growth in wind, solar, and storage reduces reliance on combustion-based generation.
- Proliferation of electric heating technology dramatically reduces combustion for heat – possibly eliminating such combustion in some locations.
- Building retrofits are associated with improved indoor air quality stemming from electrification of cooking and improved ventilation.[87]

For sectors still reliant on combustion, replacing fossil fuels with bioenergy maintains the production of harmful pollutants.[88,89] Using RNG for cooking will likely result in the accumulation of indoor air pollution similar to that observed with fossil gas, but may involve different contaminants.[90] Burning bioenergy fuels in vehicles, kitchens, and building heating equipment means limited potential to apply pollution controls because these are decentralized facilities. For example, combustion of methane for cooking and methane leaks in the home have been associated with higher levels of indoor air pollution.[90,91]

Bioenergy production, from cultivation to management to delivery, will likely also involve the generation of adverse air pollution. The scope and the scale depend greatly on the process and any mitigation steps: for example, electrification of trucks transporting feedstock and fuels. Conversion facilities may be a source of potential pollutants if not properly regulated. Siting of facilities should consider such impacts.

ECONOMIC AND OTHER IMPACTS

Decarbonization shifts spending from out-of-region energy purchases to in-region capital energy infrastructure assets (Figure 12).[8,83] Increasing energy production from wind, solar, ambient heat, and modest local bioenergy resources not only leads to a reduction in the reliance on imported fuels but also results in periods where the region is a net exporter of energy – likely via an increased electric transmission with neighboring states and Canadian provinces.[91]

This brings incredible economic opportunities. Investment in local low-carbon assets can bring significant co-benefits ranging from the increased comfort associated with building electrification and efficiency retrofits to more sustainable waste management to a net increase in jobs.[4,83,92,93]

Overreliance on fossil or bioenergy imports can hinder such opportunities from being realized. As noted earlier, regional bioenergy resources can only amount to a small fraction of the region's energy demand. As a result, job creation from the development of regional bioenergy resources is limited compared to the job creation associated with renewable electricity, building retrofits, and the upgrade of transmission and distribution infrastructure.

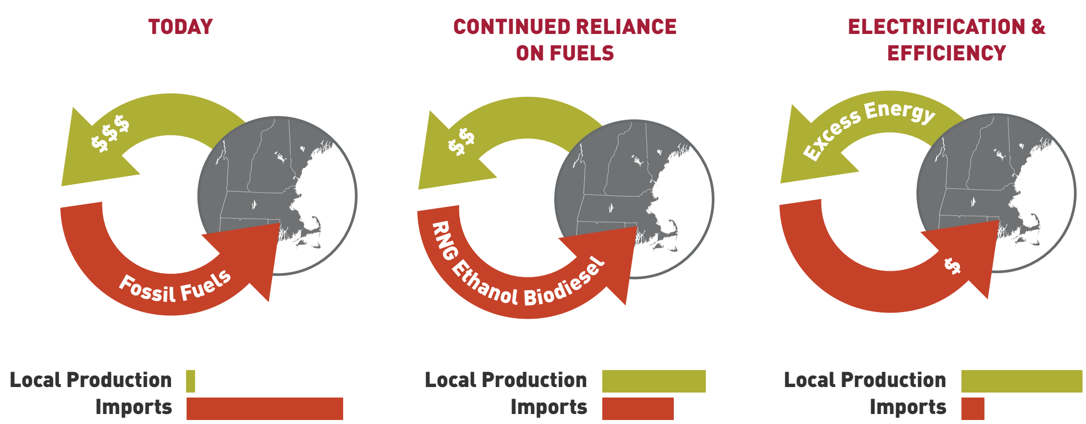


Figure 12. Energy spending today, a future that continues to rely on fuels, and an electrified and efficient future. The findings of the Massachusetts Decarbonization Roadmap[8,83,94] inspire the diagram.

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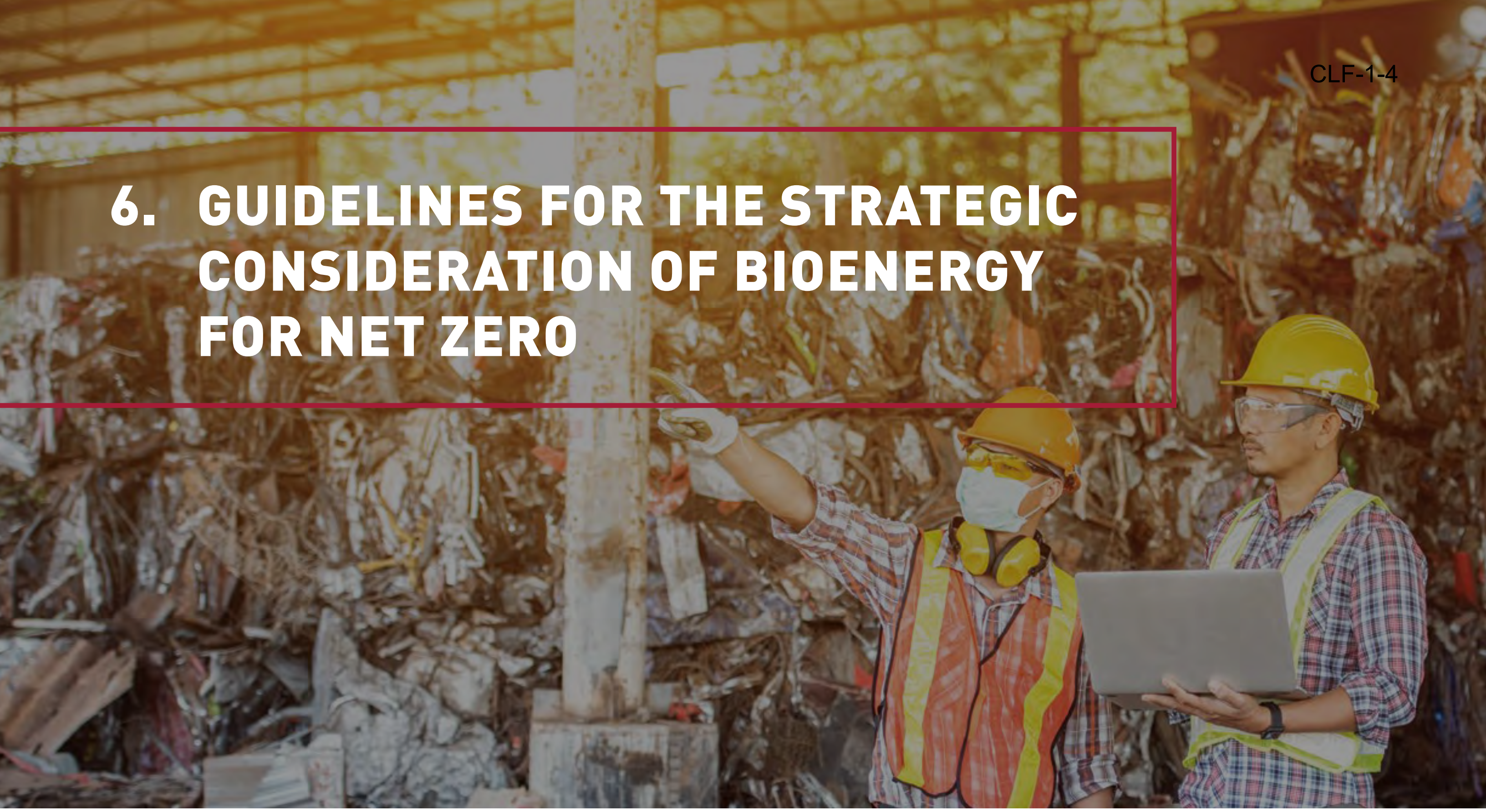

6. GUIDELINES FOR THE STRATEGIC CONSIDERATION OF BIOENERGY FOR NET ZERO

Aligning the energy system and society's bioresources with climate goals involves complex tradeoffs and dynamics. In addition to the goal of eliminating emissions, many New England states have sought to integrate other criteria into evaluating climate strategies: costs, health, equity, employment, reliability, resiliency, and safety, among others.

Even if climate impact is the sole evaluation criterion for a given strategy, life-cycle greenhouse gas accounting, especially for bioenergy, is limited because **(1)** use of bioenergy can create sprawling, higher-order impacts that are difficult to measure and attribute with certainty; **(2)** bioenergy use creates impacts that evolve due to the growth cycles of potential bioresources; and **(3)** bioenergy strategies can involve biomethane or displaced fossil methane, which are potent greenhouse gases that undergo time-dependent atmospheric evolution.

A *systems perspective* is essential to evaluating the efficacy of a bioenergy strategy – a policy or a project – in supporting the region's climate goals. Many regional,[3,8,95] national,[6] and global[96,97,98] studies of ambitious climate transitions have identified common actions (often referred to as properties, pillars, features, or characteristics) needed to drive forward these goals. Table 5 adapts these actions within a bioenergy context to evaluation criteria for bioenergy strategies.

Generally, good strategies use waste and residual biomass feedstocks in hard-to-decarbonize sectors. Poor bioenergy strategies rely on dedicated crops, unsustainable harvesting of woody biomass, and easy-to-electrify applications that are poorly suited for carbon capture (e.g., building heating and transportation).

For example, Princeton University's Net Zero America Study demonstrated scenarios where the country could achieve zero emissions without increasing land use for bioenergy production.[6] In these scenarios, bioenergy was exclusively dedicated for use in hard-to-electrify sectors or to support carbon capture and storage. An increase in overall bioenergy use was simulated, with limited expansion of energy crops, through increased collection of wastes and residues and the shifting of corn ethanol to more productive perennial crops, which have the added benefit of increasing soil carbon and improving other ecosystems.

Given the urgency of climate change, the Table 5 criteria are essential for guiding the climate-optimal use of bioenergy. However, consideration of bioenergy strategies should also incorporate criteria that reflect social, economic, and other environmental values.

Table 5.

STRATEGIC EVALUATION CRITERIA FOR THE USE OF BIOENERGY RESOURCES

NET-ZERO ACTION	EVALUATION QUESTIONS	EXAMPLE BEST ALIGNED WITH NET-ZERO TARGETS	EXAMPLE INCONSISTENT WITH NET-ZERO TARGETS
CLEAN ELECTRICITY	• Does the bioenergy use support or hinder the scaling of low-cost wind and solar resources? • Is bioenergy being used in a way that generates low-to-negative emission electricity when factoring in reasonable life-cycle assumptions?	• Electricity generation from unavoidable biogas or landfill gas. • Potentially, electricity generation from waste and residues using carbon capture and sequestration.	• Unsustainable management of forest cutting for biomass combustion. • Legacy or existing inflexible biomass power plants.
EFFICIENCY IN ENERGY AND MATERIAL USE	• Are energy inputs for feedstock production, conversion, and distribution low relative to the usable energy produced? • Does the process result in fugitive greenhouse gas emissions?	• Utilization of wastes with low energy demands for collection and production. • Energy-efficient and high-energy-yielding conversion processes. • Use of bioenergy in certain combined heat and power situations.	• Energy-intensive crops or conversion processes (e.g., corn ethanol). • Conventional biomass combustion for electricity with high unrecovered waste heat. • Electricity-demanding purification of biogas to RNG when direct electricity generation from biogas is viable, and RNG has a high potential for leakage.
ELECTRIFICATION AND SMART USE OF FUELS	• Is the fuel being used in a difficult-to-electrify sector or end-use? • Would a fossil fuel (coupled with CO_2 removal) be better than a renewable fuel, based on cost and life-cycle impacts, and allow for better use of a bioenergy resource? • Is bioenergy being positioned as a complement or an alternative to electrification?	• Renewable fuels used for aviation, shipping, and industry. • Some situations may benefit from a hybrid strategy depending on the availability of a waste resource (e.g., a modest number of oil- or gas-heated homes may benefit from a heat pump supplemented by a pellet stove heating system).	• RNG used for building heating. • Credit systems that treat electrification and renewable fuels as fungible decarbonization strategies risk deferring necessary electrification.
APPROPRIATE USE OF WASTE RESOURCES	• Does the bioenergy strategy help reduce the waste's climate and other environmental impacts? • Does the production of bioenergy overincentivize the generation of waste?	• Waste bioenergy strategies are implemented with waste source reduction, reuse, and recycling policies to reduce upstream emissions, enhance food security, and minimize other unsustainable practices.	• Valorized waste can disincentivize efforts to reduce production of waste and unnecessary production and consumption. This is a lost opportunity to avoid reducing upstream greenhouse gas emissions.
SUPPORTS CARBON DIOXIDE REMOVAL	• Does the use of bioenergy feedstocks result in long-term distribution to natural carbon stocks and the ability of such stocks to remove carbon from the atmosphere? • Is the carbon released from the use of bioenergy captured and permanently sequestrated?	• Waste and residues that would otherwise quickly decompose are used as feedstock in various bioenergy with carbon capture and storage technologies. • Production of feedstock that enhances the ability of natural lands to sequester and store carbon.	• Indiscriminate use of bioenergy in applications without carbon capture and storage. • Use of bioenergy at scales that reduce the ability of natural systems to sequester carbon.

Example Application of Guidelines to Pending Bioenergy Strategies in New England

The following sections apply the guidelines above to pending policy frameworks and projects relevant to New England.

RNG AND HYDROGEN BLENDING ARE UNSUITED FOR BUILDING HEAT

New England's natural gas utilities have proposed blending RNG and hydrogen into their distributed gas.[26,27,41] The utilities' prime motivation is maintaining the gas system's size, as they earn returns on the size and ability to reinvest in the system. But alternative approaches would provide significant cost benefits while maintaining flexibility.

Electrification of most heat demand and other end-uses is much more cost-effective than RNG and will likely become cost-competitive with fossil gas given long-term forecasts in the costs of pipeline gas delivery in the Northeast.[20] Building upgrades will provide customers with increased value (e.g., improved health and more comfortable homes). Partial electrification, if chosen by a customer, can be achieved with non-pipeline fuels. Those who prefer cooking over a flame can utilize propane if pipeline gas service becomes unavailable or uneconomical, though propane combustion will continue to emit harmful indoor air pollution and greenhouse gas emissions. Studies[8,83] and assessments of gas system investment needs[23] indicate that downsizing the gas system can generate substantial cost savings relative to electrification costs.

The question then becomes: as gas demand declines, should RNG substitute fossil methane? With the urgent need to reduce emissions, the answer may seem obvious. A direct life-cycle comparison of RNG to fossil gas shows that it may provide modest reduction of greenhouse gases relative to fossil methane – with a lot depending on leaks and avoided feedstock emissions. However, comprehensively evaluating this strategy (Table 6) shows significant deficiencies in its utility as a decarbonization strategy. The qualitative assessment aligns with the analysis conducted by the Massachusetts Executive Office of Energy and Environmental Affairs, which demonstrated that decarbonization of pipeline gas is the most expensive emissions abatement action.[8,83] This aligns with other research[81] exploring the optimal use of fuels. Using RNG for building heat would be an expensive misallocation of bioenergy resources that are better suited for decarbonizing other sectors.

Another way of understanding this dynamic is that if some emissions are still allowed from the energy system in 2050, those residual emissions should emanate from the most expensive-to-abate sectors. The decarbonization of pipeline gas is the most expensive-to-abate fuel (Figure 11). Even if the policy required the elimination of energy sector emissions – but some high-quality offset mechanism was allowed – the high abatement cost of RNG and green hydrogen would compete with the use of fossil methane offset by a removal. The need to mitigate leaks would further disadvantage any use of gas in such a scenario.

In summary, policy should avoid frameworks that consider renewable gas as a viable building's decarbonization strategy. Achieving building sector emissions reduction requires robust and direct policies that maximize the promulgation of electrification and efficiency while winding down the gas system to align with the region's climate targets.

Table 6.

RNG FROM VARIOUS SOURCES FOR USE IN BUILDING HEAT

NET-ZERO ACTION	EVALUATION QUESTIONS	ASSESSMENT
CLEAN ELECTRICITY	• Does the bioenergy use support or hinder the scaling of low-cost wind and solar resources? • Is bioenergy being used in a way that generates low-to-negative emission electricity when factoring in reasonable life-cycle assumptions?	**Not consistent with net-zero action:** Landfill gas or biogas (from digestors) used to produce RNG could otherwise be directly burned to generate low-carbon electricity. Biogas can be stored in short timescales and be used as a firm electricity resource that can complement wind and solar generation.
EFFICIENCY IN ENERGY AND MATERIAL USE	• Are energy inputs for feedstock production, conversion, and distribution low relative to the usable energy produced? • Does the process result in fugitive greenhouse gas emissions?	**Not consistent with net-zero action:** RNG requires significant energy inputs for purification, upgrading, and compression for pipeline injection. These result in significant losses, and while fossil gas remains the marginal fuel on the grid, it limits life-cycle emissions reductions of RNG. These energy losses are particularly remarkable compared to electrification using heat pumps and renewable electricity. Like fossil methane, RNG has a high global warming potential. Even a modest amount of RNG leakage can obviate any emissions savings relative to fossil methane.
ELECTRIFICATION AND SMART USE OF FUELS	• Is the fuel being used in a difficult-to-electrify sector or end-use? • Would a fossil fuel (coupled with removal) be better than a renewable fuel, based on cost and life-cycle impacts, and allow for better use of a bioenergy resource? • Is bioenergy being positioned as a complement or an alternative to electrification?	**Not consistent with net-zero action:** Injection of RNG into the pipeline is intended to decarbonize aggregate pipeline gas consumption for heat. Electrification is a more suitable, efficient, and cost-effective strategy for decarbonizing building heat. Application of RNG seeks to prevent rather than complement building electrification. Allocation of bioenergy feedstocks for RNG is better suited to liquid fuels and harder-to-electrify sectors.
APPROPRIATE USE OF WASTE RESOURCES	• Does the bioenergy strategy help reduce the waste's climate and other environmental impacts? • Does the production of bioenergy overincentivize the generation of waste?	**Consistent with net-zero action, but not unique to RNG. Policy design can potentially overincentivize waste:** RNG can help to manage waste; however, so can other waste energy recovery and non-energy waste management strategies that may be more aligned with other climate goals. Appropriate design of incentives is needed to ensure that waste production does not get overincentivized and that resources aren't shifted away from sectors that would better use them.
SUPPORTS CARBON DIOXIDE REMOVAL	• Does the use of bioenergy feedstocks result in long-term distribution to natural carbon stocks and the ability of such stocks to remove carbon from the atmosphere? • Is the carbon released from the use of bioenergy captured and permanently sequestrated?	**Not consistent with net-zero goals:** The demand for RNG to displace fossil gas consumption at current scales will cause land-use change due to the need to use dedicated crops and competition with other sectors that require renewable fuels. Feedstocks allocation to RNG eschews opportunities for carbon capture and storage.

INDICATOR CATEGORY/ NAME	EVALUATION CRITERIA	ASSESSMENT
ENVIRONMENTAL		
AIR QUALITY	What are the types and quantities of non-greenhouse gas emissions (particulates, NOx, SO_2, VOCs [volatile organic compounds], dioxins, and other toxic emissions) that result from producing and consuming a bioenergy resource?	**Adverse impact:** Continued reliance on fuel combustion for building heat maintains indoor and outdoor air quality impacts.
WATER QUANTITY AND QUALITY	What are the effects of the use of this bioenergy resource on water quality?	**Indirect potential beneficial impact from modest use, but not exclusive to RNG:** Collection of animal wastes for energy recovery may reduce nutrient loading from untreated waste. **Excessive use leads to adverse indirect land-use change driven by expanding energy crops:** Growing dedicated bioenergy crops can lead to land-use change, impacting watersheds.
SOIL QUALITY	What are the effects of this bioenergy resource on soil quality?	**Indirect potential beneficial impact from modest use, but not exclusive to RNG:** Anaerobic digestion yields a nutrient-rich soil amendment that can enhance soil quality but that may contain contaminants, such as PFAS, if contained in the feedstock. **Adverse impact from excessive use:** Growing dedicated bioenergy crops for RNG can lead to land-use change, impacting soil quality.
BIODIVERSITY	What are the effects of the use of this bioenergy resource on biodiversity?	**Adverse impact from excessive use:** Growing dedicated bioenergy crops for RNG can lead to land-use change, reducing biodiversity.
SOCIAL		
FOOD AVAILABILITY	Does this bioenergy resource reduce food availability or increase food costs?	**Adverse impact from excessive use:** Growing dedicated bioenergy crops for RNG can lead to land-use change, leading to competition with food production. **Adverse impact from improper waste management:** The availability of a food waste energy recovery pathway could reduce incentives to rescue usable food.
LAND USE	What are the effects of this bioenergy resource on land use?	**Adverse impact from excessive use:** Growing dedicated bioenergy crops for RNG can lead to land-use change.
JOBS	Does the use of this bioenergy resource shift jobs out of the region?	**Adverse impact from excessive use:** Strategies that are overreliant on fuels require importing fuels from outside the region. This shifts out-of-state spending relative to electrification and efficiency strategies that create local jobs through local investment.
ENVIRON-MENTAL JUSTICE	Does the use of this bioenergy resource reproduce historical patterns of environmental injustice?	**Adverse impact:** Strategies that maintain the gas distribution system do not rectify the ongoing impact of methane leaks and air pollution on burdened communities. Decarbonizing heat using RNG is generally a higher-cost strategy relative to electrification that will exacerbate energy cost burdens.
PUBLIC HEALTH	What are the effects of this bioenergy resource on public health?	**Adverse impact:** Strategies that maintain the gas distribution system at current scales do not rectify the ongoing health impact of methane leaks and air pollution.
ECONOMIC		
COST	How does incorporating a bioenergy strategy affect systems costs and how would consumers realize these costs?	**Adverse impact:** RNG is more expensive than electrification for most heating needs. Decarbonizing peak heating demands through renewable non-pipeline fuels or offsets will likely be cheaper than using RNG.
LONG-TERM RISK	Does the application of bioenergy reduce or increase or mitigate risks associated with energy systems?	**Adverse impact:** RNG production will need to scale as gas consumption declines. RNG strategies require developing and maintaining expensive production and distribution infrastructure. Ratepayers are typically responsible for the risks of such infrastructure.
LOCAL SPENDING VS. ENERGY IMPORTS	Is the use of bioenergy creating local economic benefits or is it continuing the practice of spending money on fuel imports that accrue wealth outside the region?	**Adverse impact from excessive use:** Strategies that are overreliant on fuels require importing fuels from outside the region. This shifts out-of-state spending relative to electrification and efficiency strategies that create local jobs through local investment.

CLF-1-4

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CLF-1-4

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