Heating Sector Transformation in Rhode Island

Pathways to Decarbonization by 2050

PREPARED FOR

Rhode Island Division of
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NOTICE

- This report was prepared by The Brattle Group, with support from Buro Happold and Jens Ponikau of Buffalo Geothermal Heating, for the **Rhode Island Office of Energy Resources (OER)** and the **Rhode Island Department of Public Utilities and Carriers (DPUC)**. It is intended to be read and used as a whole and not in parts. The report reflects the analyses and opinions of the authors and does not necessarily reflect those of The Brattle Group's clients or other consultants.
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As part of Rhode Island's commitment to economy-wide decarbonization, this report examines solutions to transform the state's heating sector. Dominated by space heating for the residential and commercial sectors, but also including water heating and industrial heating, the heating sector represents approximately one-third of the state's overall greenhouse gas emissions.[1]

There are many solutions for decarbonizing the heating sector, but they fall into three broad categories:

1. Reducing energy needs by improving building energy efficiency
2. Replacing current fossil heating fuels with carbon-neutral renewable gas or oil
3. Replacing current fossil-fueled boilers and furnaces with electric ground source or air source heat pumps powered by carbon-free electricity

The industrial sector may need other types of solutions, which can be very application-specific.

To transition to decarbonized heating fast enough to meet mid-century decarbonization targets, Rhode Island will need substantial policy support. The reasons include low fossil fuel prices (particularly for natural gas), which also do not reflect the social costs of greenhouse gas emissions; switching to electrified heating solutions requires substantial initial costs for equipment and installation compared to replacing boilers or furnaces; and other more qualitative factors such as information deficits, immature supply chains, a natural reluctance by consumers to change what seems to work well.

Rhode Island must base its policy framework for heating sector transformation on an understanding of the relative economic attractiveness of various decarbonization solutions. **Figure ES 1** shows the projected range of average annual heating costs in 2050 for a representative existing single-family home in Rhode Island, using existing fossil fuels (on the left) or several alternative decarbonized heating solutions (on the right). This figure shows two key insights:

1. For natural gas customers, who represent the majority of heating customers in the state, all of the decarbonized heating solutions will likely result in some increase in overall heating costs. This is less clear for fuel oil and propane customers. However, customer adoption of no-to-low carbon heating solutions will not take place in isolation. Viewing heating transformation within the context of broader decarbonization efforts across the electric

1 Although not directly a part of the heating sector, cooling will also play a role in the heating sector transformation since some heating equipment (notably heat pumps) can also provide cooling.

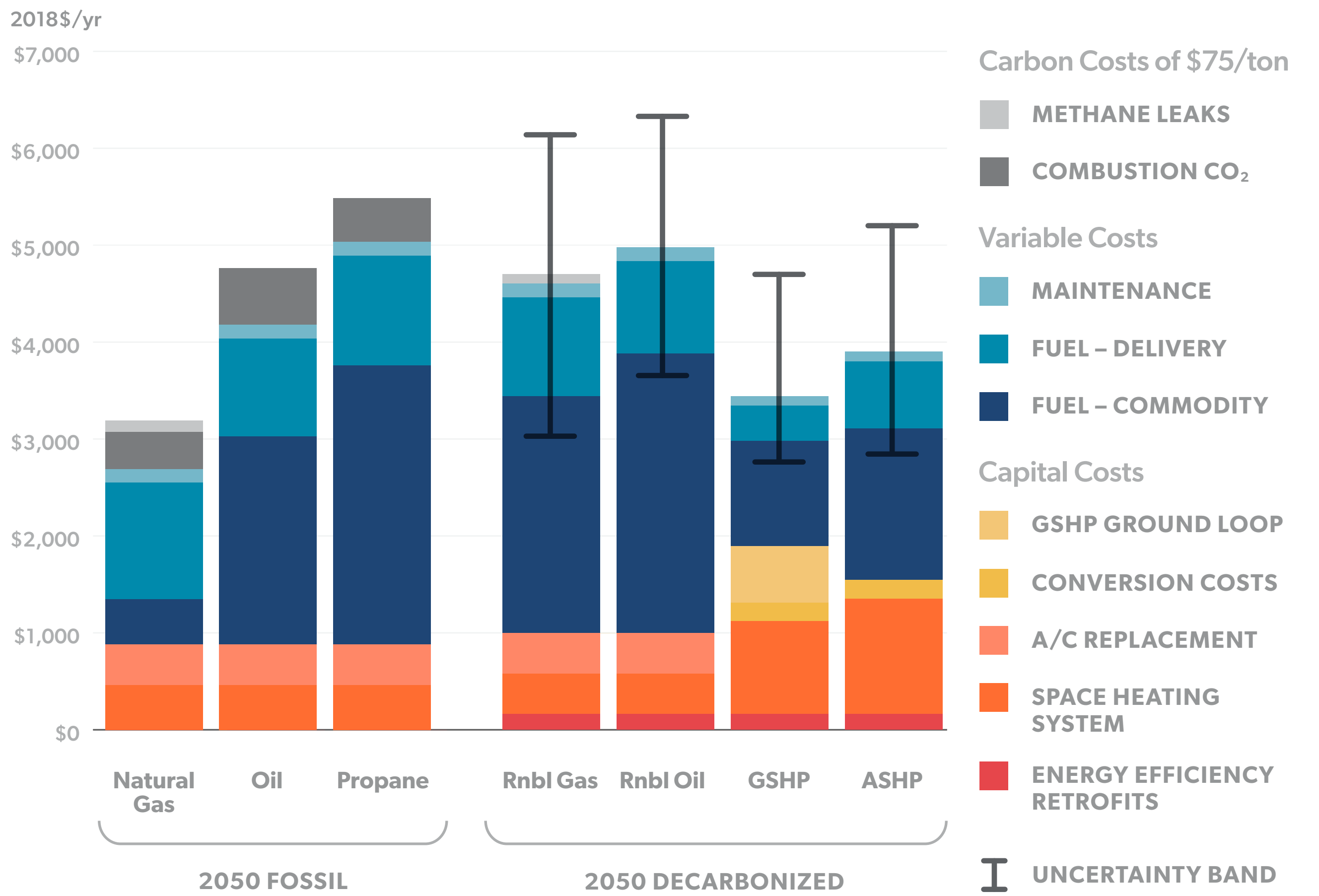


FIGURE ES 1: ANNUALIZED COST OF SPACE HEATING IN 2050, REPRESENTATIVE SINGLE-FAMILY HOME, BOOKEND SCENARIOS, 2018$

and transportation sectors, total consumer energy expenditures are likely to be similar to what is paid today in a fossil fuel-based system.

2. From today's perspective, no single solution is clearly more economically attractive than the others. This is due to the high uncertainty related to how the costs of all decarbonized heating solutions will evolve over the coming decades. The heights of the bars themselves are less important than the uncertainty bands around them (represented by black bands extending above and below the tops of the bars). These uncertainty bands are largely overlapping for the decarbonized technologies, indicating that it is not clear at this point which of these technologies will be most economical in the long run.

The analysis in **Figure ES 1** assumes that as part of decarbonizing the heating sector, cost-effective energy efficiency measures such as air sealing and attic insulation will be implemented in essentially all Rhode Island buildings. Doing so lowers the challenge to decarbonize heating and saves consumers money, which is relevant for all consumers and may be particularly important for disadvantaged communities.

This particular analysis is based on a set of "bookend" scenarios that assume for each decarbonized technology that this technology provides all heat across New England. It compares cases where fuels (gas and oil, in renewable forms) continue to primarily provide heat; or for electric heat pumps, assumes 100% adoption of either ground source heat pumps (GSHPs) or air source heat pumps (ASHPs). This captures the potential impacts of these technologies on the region's overall energy systems. For instance, the economic attractiveness of electric heat pumps

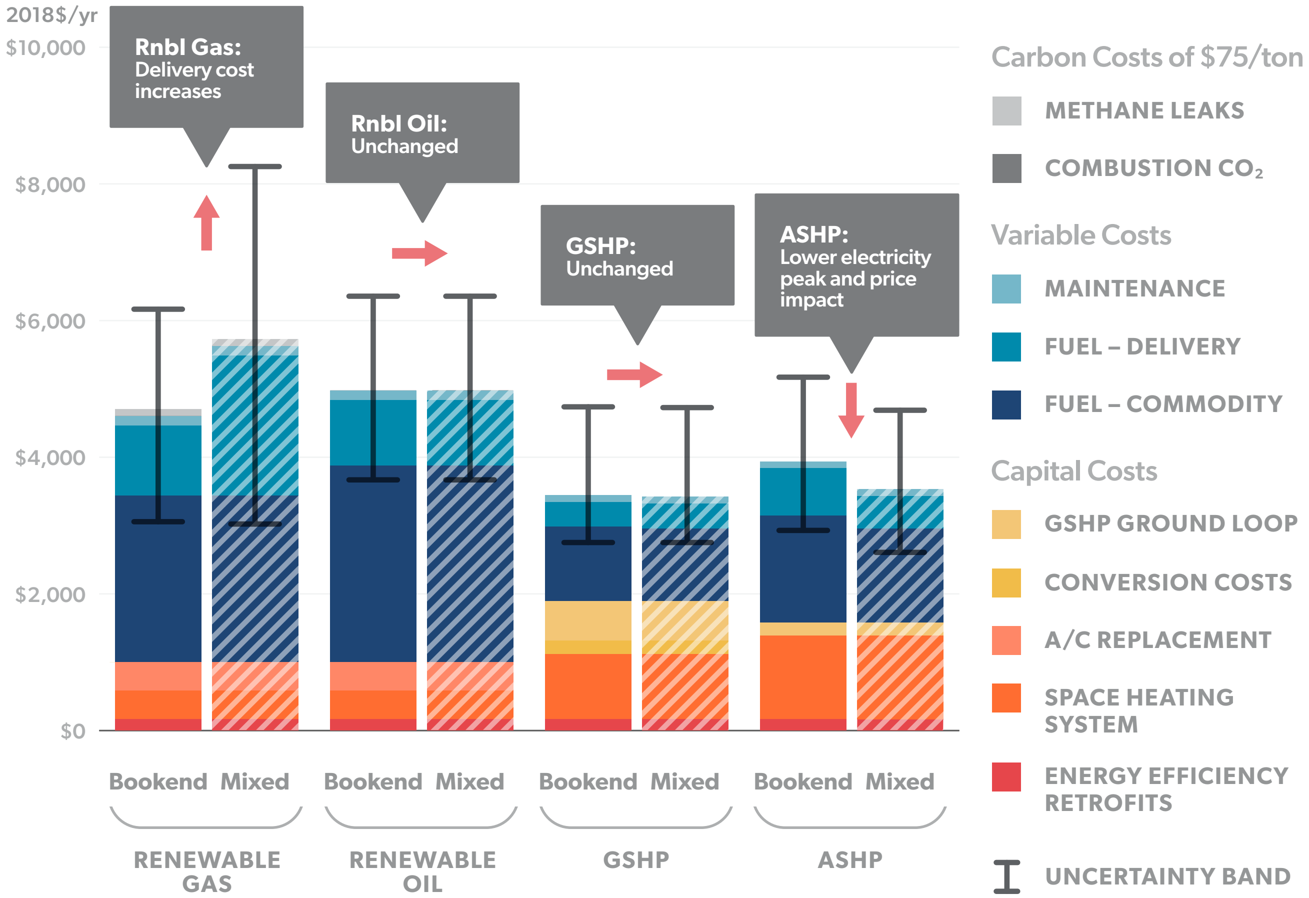


FIGURE ES 2: ANNUALIZED COST OF SPACE HEATING IN 2050, REPRESENTATIVE SINGLE-FAMILY HOME BOOKEND VERSUS MIXED SCENARIOS, 2018$

depends in part on the cost of (clean) electricity, which in turn depends on the impact that heat pumps will have on the electric system. Heat pumps themselves represent a substantial demand for electricity and can affect the price of power. Similarly, the attractiveness of renewable gas depends on its cost, which depends on the total gas volume demanded regionally and nationally, since low-cost supplies are limited.

One important lesson from these bookend scenarios is that widespread ASHP adoption could require substantial additional investments in the regional electric power system, and could create operational challenges. At very low outside temperatures, when the need for heat is greatest, ASHPs become significantly less efficient. If ASHPs are adopted widely, this could create extremely high peak electric demand during a few very cold days.

Since such bookend scenarios are unlikely to represent actual adoption of decarbonized heating solutions, Figure ES 2 shows how the results might change under one of many possible more-balanced adoption scenarios. This example shows a scenario that assumes that by 2050, electric heat pumps (one-third each by ASHPs and GSHPs) are providing two-thirds of heating; that (renewable) gas – which loses only 50% of volume relative to today – is providing most of the remaining heat; and that oil is providing the remaining amount.

This more mixed adoption of all the decarbonized heating solutions partially mitigates the extreme impact of 100% ASHP adoption on electric system peaks (and the resulting cost of electricity), making ASHPs relatively more attractive. On the other hand, reducing delivered gas volumes, due to increasing

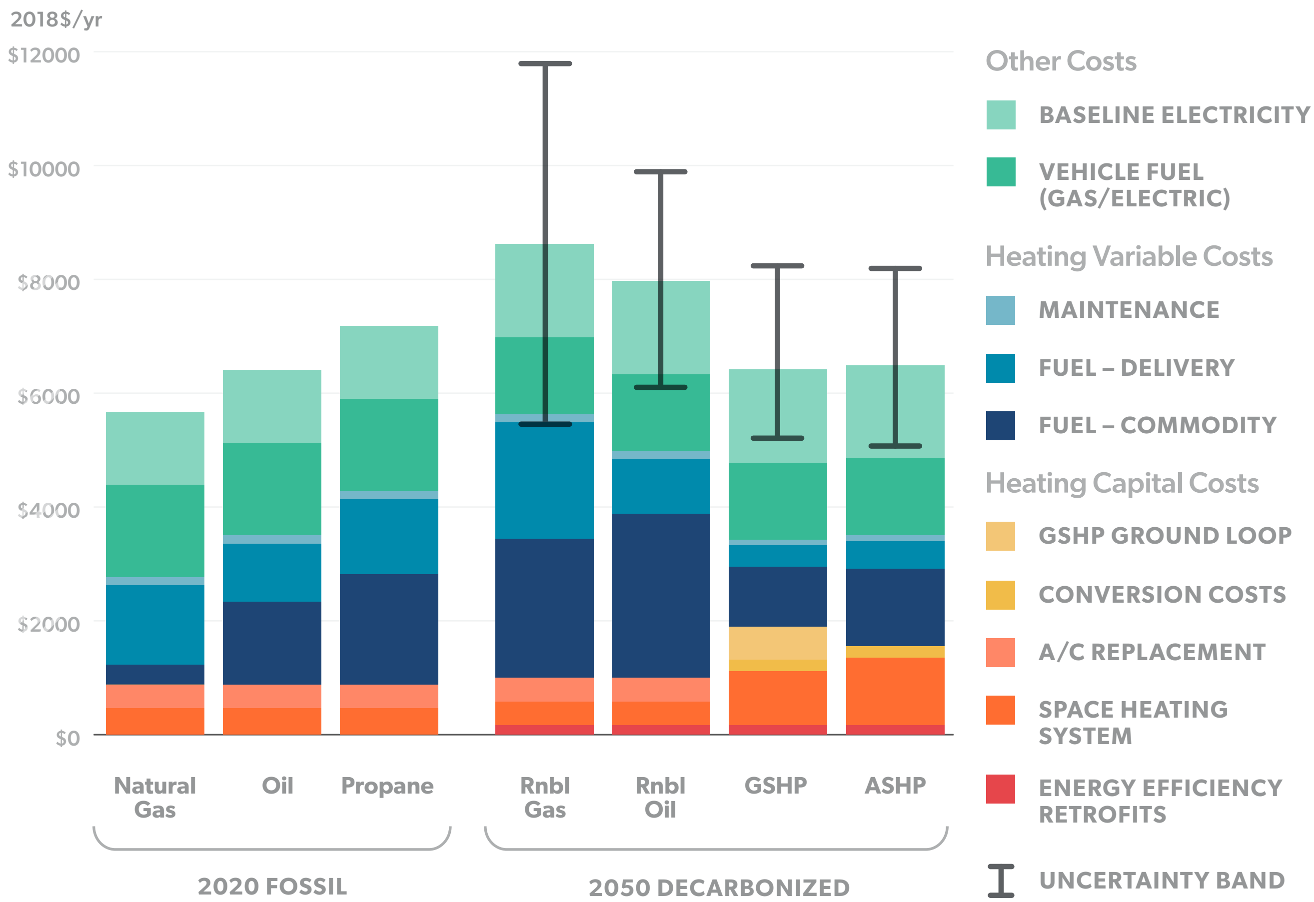


FIGURE ES 3: TOTAL ANNUAL ENERGY WALLET COMPARISON FOR REPRESENTATIVE CONSUMER: 2020 VS 2050 MIXED SCENARIO, 2018$

Note: Uncertainty band reflects uncertainty on heating costs as above, plus the effect of electricity price uncertainty on other end uses. Gasoline price excludes federal and state taxes. Water heating cost is not broken out explicitly, though to the extent electricity is currently used for water heating, this is included implicitly in Baseline Electricity Consumption.

energy efficiency or conversions to electrified heat, could increase the delivery cost of renewable gas, making it relatively less attractive. But, importantly, the more balanced adoption pattern of the Mixed Scenario does not alter the basic conclusion that no decarbonization solution is clearly preferred. The uncertainty ranges of the decarbonized technologies still largely overlap one another. Because the relative attractiveness of heating decarbonization solutions is sensitive to a) peak electric impacts and b) gas volume impacts, developing a better understanding of these effects, and opportunities to mitigate them, will be an important policy focus in the coming years.

Finally, the decarbonization of heating will not take place in isolation. Rather, it is embedded in broader economy-wide decarbonization efforts, including a likely shift toward electrified transportation. Heating decarbonization, and in particular the level of electric heat pump penetration, can affect electricity prices. This could have broader impacts on consumers' "energy wallet" – their total energy expenditures on baseline electricity consumption and electric vehicle (EV) charging, in addition to heating. However, changes in heating costs could be offset or exacerbated by impacts on other elements of the energy wallet, particularly transportation. EVs are expected – at least by 2050 – to have lower operating costs than current internal combustion engines.

Figure ES 3 compares a representative consumer's energy wallet spending today with what energy spending might look like by 2050, considering the various decarbonized heating solutions. The figure indicates that the attractiveness of ASHPs would not decrease substantially when considering the overall energy wallet. It also shows that, compared to 2020, any potential increase in heating cost could be at least partly offset by cost decreases elsewhere in the energy wallet, and by savings through energy efficiency. This does not mean that individual consumers or businesses will not see changes in their heating (and energy wallet) costs. Policy likely plays a key role in mitigating any potential cost increases, particularly where it may affect populations or industries that are vulnerable to increasing energy costs (and thus could be reflected in the state's economy).

The same broad conclusions apply to space heating uses in other settings, such as larger (multi-family) residential and commercial buildings, as well as to domestic water heating. Finally, various decarbonization solutions also exist for the remaining smaller uses of heat, such as electric cooking and clothes drying.

FIVE THEMES TO GUIDE RHODE ISLAND'S PATH FORWARD

The conclusion of this quantitative assessment of the relative attractiveness of various heating decarbonization solutions in Rhode Island is that, at present, there is no clear winning approach. Rather, the relative attractiveness of decarbonizing heating in the state depends on the evolution of the relevant costs – renewable gas, renewable oil, ASHPs, and GSHPs – which are highly uncertain today. Also, the attractiveness of the solutions in specific instances will depend on the particular context – the particular building, location, or application. In addition, each of the decarbonization solutions faces unique adoption and implementation challenges that Rhode Island will need to address to enable broad adoption over time.

This implies that, for policy to support Rhode Island's heating sector transformation, the next 10 years should not focus on advancing a single or limited set of solutions. Instead, Rhode Island should ensure that it is making progress, regardless of which solution (or mix of solutions) ultimately prevails. As illustrated in **Figure ES 4**, a policy framework for the next 10 years should involve five elements: **Ensure**, **Learn**, **Inform**, **Enable**, and **Plan**.

As an initial step to **ensure** decarbonization, improving the energy efficiency of buildings will provide several immediate benefits. By reducing heat needs, it will reduce greenhouse gas emissions, regardless of what heating technology is utilized (and to the extent heating is electrified, improved building efficiency will reduce heating's impact on electric loads). Importantly, cost-effective energy efficiency measures will reduce the total cost of heating, which will mitigate any potential increase in the cost of providing heat with decarbonized solutions. Finally, existing efficiency programs provide an effective program delivery network that can support the state's expanded heating-sector-related decarbonization efforts.

A second key policy element that will ensure progress towards decarbonizing the heating sector is enacting a set of technology-neutral measures that will reduce the carbon intensity of all energy sources used for heating – electricity, gas, oil, and propane – over time. Such measures may include renewable electricity requirements, carbon pricing or cap and trade policies, renewable fuel or heating standards, or other approaches. Complementary fuel-neutral policies include continued and increased efforts to improve the energy efficiency of Rhode Island's existing buildings, while also tightening the efficiency requirements for new construction.

Rhode Island must emphasize **learning** over the next decade, given the large uncertainties about

Ensure	Increase efficiency and reduce carbon content of all fuels to zero over time – ensures progress no matter which technologies are used
Learn	Data collection, R&D, pilot projects to understand technologies, infrastructure, and customers
Inform	Educate stakeholders – customers, installers, policymakers – about pros and cons of options, system interactions, etc.
Enable	Facilitate deployment with incentives; target natural investment opportunities; align regulations, rules, and codes; expand workforce
Plan	Expand planning horizon; develop long-term, high-level contingency plans now (do not commit yet) and use to guide near-term policy

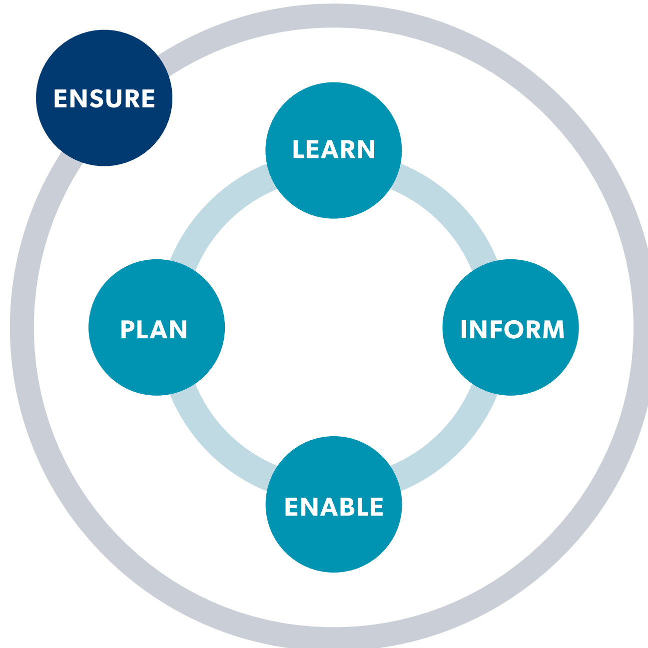


FIGURE ES 4: THEMES TO GUIDE EARLY POLICY RECOMMENDATIONS

both general and state-specific factors related to each of the decarbonized solutions and their implementation. Learning strategies should use pilot and demonstration projects, targeting state-specific issues or in collaboration for more general issues. At a minimum, learning policies should include:

- Information gathering to enable better incentive targeting (such as information on the type and age of heating-related equipment in the state)
- Proper research and development targeting Rhode Island-specific issues
- More general information in collaboration with other states or organizations

Rhode Island must **inform** key stakeholders, including consumers and the building trades, about the technical and economic issues related to decarbonized heat solutions that will require significant efforts to improve information level and flow. Potential policies in this area include broad information campaigns about the available solutions, including their pros and cons; publicly visible demonstration projects; developing training and certification programs for installers; and making information about qualified and experienced installers available to consumers.

Policymakers will need to enact several additional strategies to **enable** a heating sector transformation. These include policies that identify and address the implementation barriers, which may take the form of incentives to consumers and businesses designed to overcome both overall cost and especially first cost barriers, such as the high upfront cost of heat pumps. In addition, Rhode Island should realign its regulatory frameworks. Examples include removing existing incentives that favor gas system expansion, reconsidering rate structures for both electricity and gas, and exploring ways to integrate the regulatory treatment of National Grid's gas and electric businesses.

Another important enabling policy principle relates to identifying and capitalizing on "natural investment opportunities" where decarbonized solutions may be implemented at a lower cost and with less disruption by coordinating with other work being done on the infrastructure or building. Examples include instances where natural gas or electricity infrastructure is being upgraded or replaced, buildings undergoing deep renovations, or existing heating equipment that needs to be replaced as it approaches the end of its useful life. Policies that enable progress can also target existing codes, rules, etc. that may inadvertently create barriers to deploying decarbonized heating solutions that are otherwise attractive. Finally, enabling policies should identify and mitigate instances where heating decarbonization could impose undue burdens on vulnerable populations.

Planning will also be important. Changes to current planning approaches and some specific planning efforts will need to be part of the heating transformation strategy. In general, planning efforts should consider a long time horizon – 2050 or beyond – even if a typical planning exercise might only cover the next 10 years. This will allow Rhode Island to plan for the magnitude of changes needed to decarbonize the heating sector by mid-century, and account for the long lives of most heating-related infrastructure – buildings; pipelines; electric transmission and distribution equipment; GSHP ground loops; and even furnaces, boilers, and heat pumps themselves.

Also, some specific planning efforts will be necessary. An example is planning for the expansion of the electric distribution grid. Significant new electric loads are likely to come online over the next several decades, not just for heat but also for EV charging. This provides an opportunity to better understand the tradeoffs between "future-proofing" the grid by anticipating additional future demands, vs. planning only for near-term demands, which may lead to a series of smaller upgrades that could ultimately cost more. Similarly, even ahead of any clarity about the long-term role of the gas distribution system, developing plans for how the gas system might be altered to accommodate reduced gas use for heating, and whether there may be ways to do it more economically, will help inform the decisions that Rhode Island must undertake over the next few decades.

This report identifies several important technical issues that will affect the transformation of the heating sector. These include the potential impacts of electrified heat on the power sector, and the future role of the gas system and how reduced gas delivery volumes could affect it. These insights support an economic analysis of the different pathways to decarbonize heating – using renewable fuels with heating infrastructure similar to today's, or alternatively, electrifying heat with GSHP or ASHP.

That analysis showed that there is substantial overlapping uncertainty about the future economic attractiveness of the decarbonized solutions – regarding the long-run cost of renewable fuels (which is likely to be substantially above the current cost of fossil fuels), as well as the cost of heat pumps themselves and the clean electricity to power them. Because of these overlapping uncertainties, it is not possible to identify a clear winner among the technologies. However, it appears that decarbonized heat is likely to be somewhat more costly than natural gas heat is today, and potentially comparable with oil or propane. Still, overall consumer expenditures on energy in a fully decarbonized economy may be roughly comparable to today's costs.

This has several policy implications for driving a heating sector transformation over the next several decades. Policy approaches should support enabling early progress on decarbonization – by pursuing energy efficiency to reduce heat needs, and by decarbonizing all the energy sources used for heating – both fuels such as gas and oil, and also electricity to power new electrified heating systems. Beyond this, policies should support both the learning and informing stages, to begin to address the uncertainties, collect information that will be necessary for the transformation, and ensure a widespread understanding of the solutions and their implications. Regulatory changes can enable the transformation, addressing barriers and facilitating progress on any or all of the pathways. Policies that create structures to identify and capitalize on natural investment opportunities will also enable the transformation.

Broadening planning approaches for both the electric and gas systems will allow policymakers to consider longer time horizons consistent with the natural lives of heating infrastructure components and the timeframe and magnitude of the transformation. While it seems counterintuitive, Rhode Island must develop action plans knowing that it might not ultimately need them, since developing the plans will inform decisions about whether to implement them. The transformation of the heating sector over the next several decades will be a major undertaking, but it is achievable with early and sustained policy focus.

Introduction and Background

In line with well-established consensus in the scientific community and international commitments such as the Paris Accord, Rhode Island has committed to deep economy-wide decarbonization by 2050. Specifically, the Resilient Rhode Island Act establishes a goal of 80% economy-wide greenhouse gas ("GHG") emissions reductions relative to a 1990 baseline by 2050 with interim targets of 10% reductions by 2020 and 45% reductions by 2035.[1] Also, Executive Order 17-06 from June 12, 2017 reaffirms Rhode Island's commitment to the principles of the Paris Climate Agreement.[2]

As part of this commitment, Governor Gina M. Raimondo's Executive Order 19-06 requires the DPUC and OER to lead a Heating Sector Transformation and provide a corresponding report with recommendations to the Governor on or about April 22, 2020.[3] To fulfill this requirement, the DPUC and OER asked The Brattle Group to analyze options for decarbonizing Rhode Island's heating sector and the results of this analysis are presented in this report.

The report is the result of independent analysis conducted by The Brattle Group, supported by an extensive stakeholder effort involving interviews and meetings with over 20 individual stakeholder organizations, as well as three public workshops held to share information, present intermediate results, and collect feedback.[4] This report is accompanied by a **Technical Support Document**, which provides more detail on the modeling and assumptions underlying its findings. While this report addresses what would be needed to achieve the decarbonization goals of the heating sector, it is not intended to comprehensively address the aggregate costs of decarbonizing, how those costs would be funded, or the time period over which the transformation is achievable, given the practical challenges that will inevitably need to be addressed.

This initiative to evaluate heating sector transformation comes amid the COVID-19 pandemic,

1 Resilient Rhode Island Act of 2014 – Climate Coordinating Council, Chapter 42-6.2. http://webserver.rilin.state.ri.us/Statutes/TITLE42/42-6.2/INDEX.HTM

2 "Executive Order 17-06, Reaffirming Rhode Island's Commitment to the Principles of the Paris Climate Agreement," State of Rhode Island and Providence Plantations. June 12, 2017. http://www.governor.ri.gov/documents/orders/ExecOrder_17-06_06112017.pdf

3 "Executive Order 19-06, Heating Sector Transformation to Ensure Reliability and Protect Against Climate Change," State of Rhode Island and Providence Plantations. July 8, 2019. http://www.governor.ri.gov/documents/orders/Executive%20Order%2019-06.pdf

4 Three public workshops were held during the course of this project – two in-person meetings and one webinar-based presentation. Each workshop attracted more than 60 registered participants and included opportunities for stakeholder Q & A. Written public comments were also accepted via email.

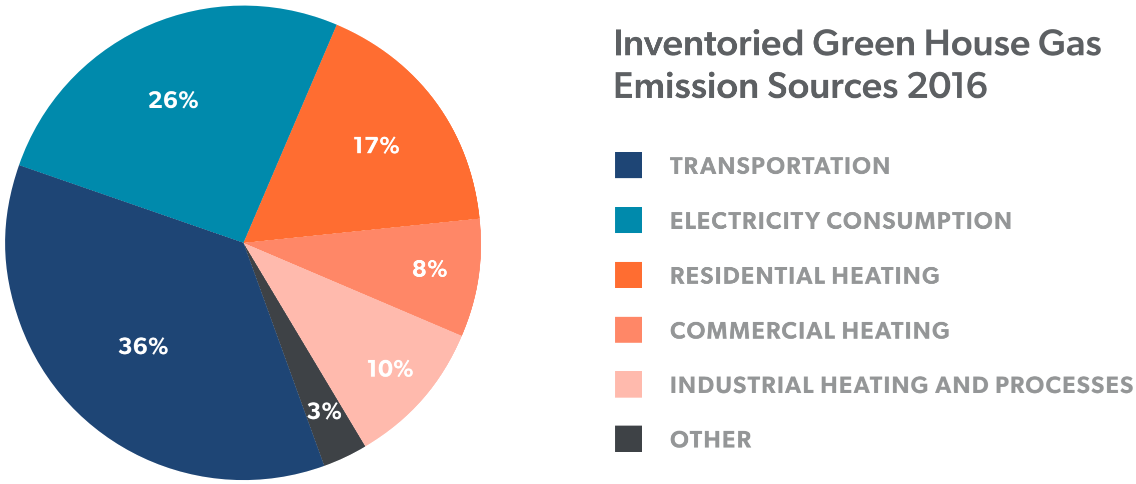


FIGURE 1: COMPOSITION OF RHODE ISLAND GHG EMISSIONS

Source: Rhode Island Department of Environmental Management, Rhode Island's 2016 Greenhouse Gas (GHG) Emissions Inventory Update, EC4 Meeting, September 12, 2019.

which has disrupted much of the state, national and international economy, including the energy sector. While this disruption will doubtless cause many short-term impacts throughout the economy, including the heating sector, we assume that these impacts will be relatively short-term in nature and will not fundamentally alter the long-term, multi-decade needs and goals for decarbonizing the economy. Indeed, climate change is a problem that will still exist and will need to be addressed long after the pandemic has been resolved.

This analysis also comes in the wake of the gas service outage that occurred on Aquidneck Island on January 21, 2019.[5] While this report addresses heating sector transformation in the context of climate change, it may also have implications for the future of heating service reliability. For most Rhode Island customers, heating currently depends strongly on the interstate and local gas distribution systems to provide natural gas on the coldest days, when gas demand is highest and the gas system is most constrained. Electrifying parts of the heating sector would reduce this reliance on the gas system, but would create a new reliance on the electric transmission and distribution infrastructure, which might become similarly constrained on those coldest winter days.

The effort to transform the Rhode Island heating sector occurs against the backdrop of concerns about climate change related risks and resulting state-level greenhouse gas reduction targets and efforts. **Figure 1** shows the composition of Rhode Island's GHG emissions as of 2016. As shown, heating related emissions (including industrial emissions) represent 35% of statewide emissions and are roughly equal to transportation emissions. Hence, even if all non-heating sectors were to become completely emissions-free by 2050, the heating sector would still need to be significantly decarbonized to meet the current GHG emissions reduction goals.

More likely, some emissions in the transportation sector, as well as industrial process (and likely some heating related) emissions will be very difficult to eliminate. Consequently, even if the State is successful

5 Summary Investigation into the Aquidneck Island Gas Service Interruption of January 21, 2019, October 30, 2019

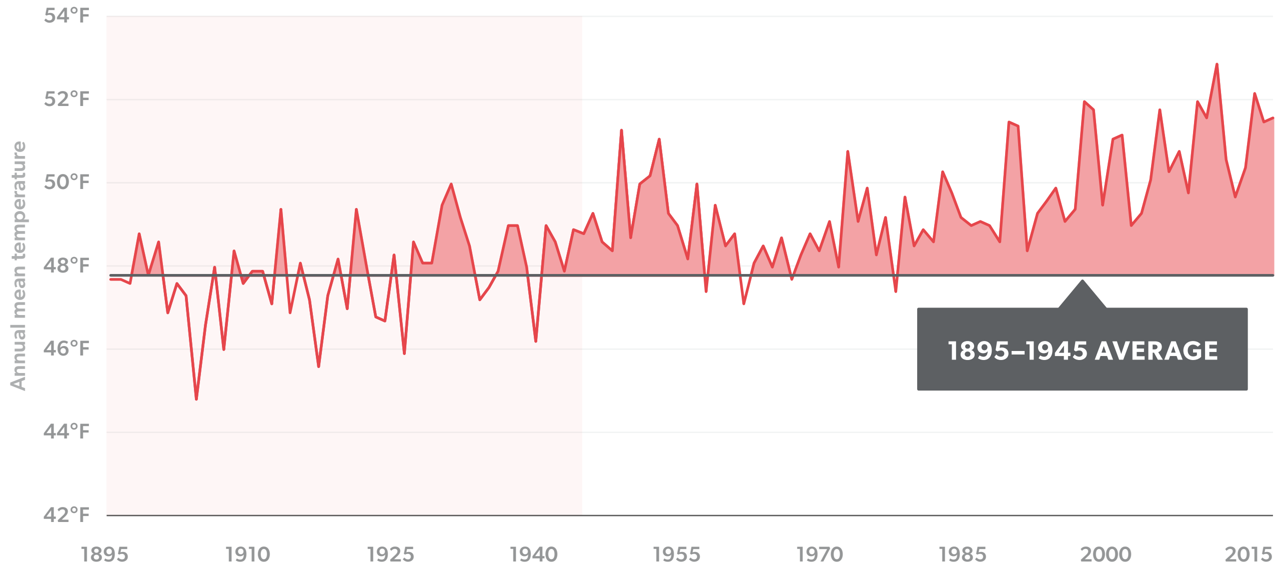


FIGURE 2: ANNUAL MEAN TEMPERATURES IN RHODE ISLAND (1895–2018)

Source: NOAA National Centers for Environmental Information, Climate at a Glance: Statewide Time Series, published January 2020, retrieved on February 2, 2020 from https://www.ncdc.noaa.gov/cag/

in fully decarbonizing the electricity sector, even full decarbonization of the heating sector would require very significant reductions in the remaining emitting sectors to achieve 80% GHG emissions reductions by 2050. This is not taking into account uncertainties about the contributions of emissions from methane leaks and/or non-energy emissions, such as land-use changes, which were not included in the State's most recent draft GHG emissions inventory.

Also, as recognized by Governor Raimondo's recent executive order to achieve a 100% renewable electricity supply in Rhode Island by 2030[6] and similar efforts to accelerate decarbonization goals relative to 80% reductions by 2050, evolving science and evidence related to climate change may require an acceleration of decarbonization relative to current policy goals.

For these reasons, this report identifies and evaluates various options and solutions for full decarbonization of the state's heating sector, recognizing that achieving full decarbonization may be very difficult for some heating applications and that deeper decarbonization in the other emitting sectors or the emergence of negative emissions technologies (including land-use measures that could increase GHG sequestration to offset some emissions) may create room for some remaining emissions in the heating sector.

However, recognizing the uncertainties described above, developing pathways for a transition to a fully decarbonized heating sector is both in line with existing policy goals and provides insurance value in case either non-heating emissions reductions are harder or more expensive to achieve or if GHG emissions reductions need to be deepened.

Finally, this report assumes that addressing heating sector emissions will remain vital even if climate change is expected to result in increases in average annual temperatures. As **Figure 2** shows, average Rhode Island temperatures have already increased by

6 Executive Order 20-01, Advancing a 100% Renewable Energy Future for Rhode Island by 2030, January 17, 2020

more than 3 degrees Fahrenheit since the beginning of the 20th century.

There is also some evidence that higher average temperatures result in warmer average winters in the Northeast,[7] which would have a tendency to lower the overall energy needed to heat Rhode Island homes and businesses. On the other hand, heating demand is greatest during the coldest days of the year and, somewhat counterintuitively, there is some evidence that suggests that climate change may increase temperature extremes in New England both in the summer and in the winter, leading to continued (and perhaps more intense) periods of extremely cold temperatures.[8] Since our energy systems are designed to ensure a reliable supply of energy during essentially all expected conditions, the possibility that winter temperature extremes will remain largely unchanged or worsen even as the state's average temperatures increase therefore needs to be considered when developing a heating sector transformation strategy for Rhode Island.

7 See for example USA Today, The Northeast warms ahead of rest of USA: 'Our winters now are not like our winters before (https://www.usatoday.com/story/news/nation/2019/12/25/climate-change-northeast-warming-faster-united-states/2743119001, accessed February 2, 2020)

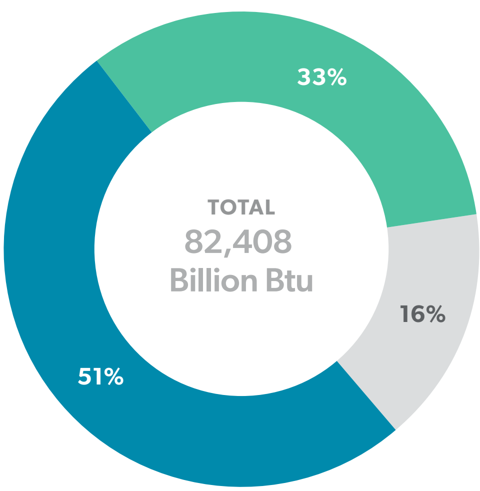
8 See for example Axios, The polar vortex splits, sending frigid air howling into the U.S., Europe, January 16, 2019 (https://www.axios.com/polar-vortex-means-winter-is-coming-to-east-coast-and-europe-5fb653fd-1664-41aa-9a99-549e2541d89a.html, accessed February 2, 2020)

Overview of the Rhode Island Heating Sector and Decarbonization Solutions

THE RHODE ISLAND HEATING SECTOR

Rhode Island's heating sector is comprised of a variety of uses and environments. Heat is primarily used for space heating and water heating in the residential and commercial sectors (with smaller amounts for cooking, clothes drying, etc.), and in various industrial applications, primarily as process heat. At the building level, heating occurs in single- and multi-family residential buildings, in a wide variety of commercial buildings and, finally, in a number of industrial applications. Industrial heating applications include a multitude of different process heat uses and therefore are significantly different from residential and commercial space and water heating. There is little detailed information available regarding the heating related energy use in Rhode Island's industrial sector.

Figure 3 shows the shares of total energy consumption in the residential, commercial, and industrial sector, respectively. Of total energy use in the state, the residential sector represents roughly 50% of total energy use, the commercial sector one-third, and the industrial sector the remainder. The share of energy



Total 2017 Rhode Island Energy Consumption by Sector

- **RESIDENTIAL** — 42,541 BBtu
- **COMMERCIAL** — 26,927 BBtu
- **INDUSTRIAL** — 12,940 BBtu

FIGURE 3: TOTAL 2017 RHODE ISLAND ENERGY CONSUMPTION BY SECTORS

Source: Buro Happold Analysis.

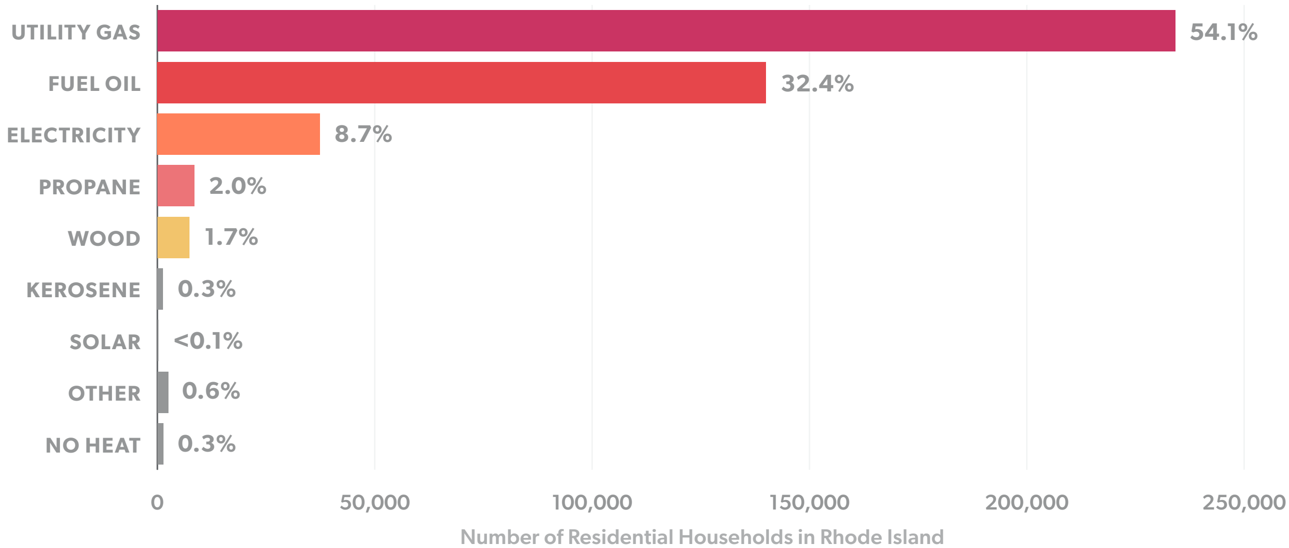


FIGURE 4: HEATING SOURCE FOR RHODE ISLAND RESIDENTIAL CUSTOMERS

Source: Meister Consultants Group, Rhode Island Renewable Thermal Market Development Strategy, prepared for the Rhode Island Office of Energy Resources, January 2017.

use by type (heating, cooling, other) likely differs significantly by sector, with the share of heating in total energy use likely the greatest for the residential sector, followed by the commercial sector. Overall, this implies that transforming the heating sector in Rhode Island will be impossible without a significant focus on the residential and commercial sectors. While decarbonizing the entire heating sector in Rhode Island will be impossible without also addressing industrial heat, which includes space and water heating as well as various types of process heat, decarbonizing process heat will require more tailored approaches.

Figure 4 provides an overview of the composition of heating in New England. Figure 5 provides additional insights into how total heating-related energy use is distributed across various types of residential and commercial buildings in the state. As shown, single family residential buildings represent close to 60% of all heating-related energy consumption in the state. Consequently, the analysis in this report focuses particularly on this building type. Larger buildings, such as multi-family and office buildings, are also important consumers of heating-related energy, and are considered separately.

Figure 6 illustrates that the large majority of residential buildings in Rhode Island were built before 1980 and, hence, are relatively old. With few new building permits issued each year,[9] it is clear that transforming the heating sector in Rhode Island must focus primarily on existing buildings. It also provides information on the heating fuel type by building age, confirming that natural gas is the dominant source of heating across buildings of all ages, followed by heating oil, which is a close second for buildings constructed between 1950 and 1980. The fact that the majority of the residential housing stock is old with existing heating systems designed for fossil fuels highlights the practical challenges Rhode Island may face in converting the heating systems in such a large number of buildings over the next few decades.

9 In 2019, 1,138 building permits for new residential housing were issued. (https://fred.stlouisfed.org/series/RIBPPRIV). In 2018, the number was 1,192. At this rate, less than 40,000 new housing units will be added by 2050, i.e., less than 10% of the current number of housing units.

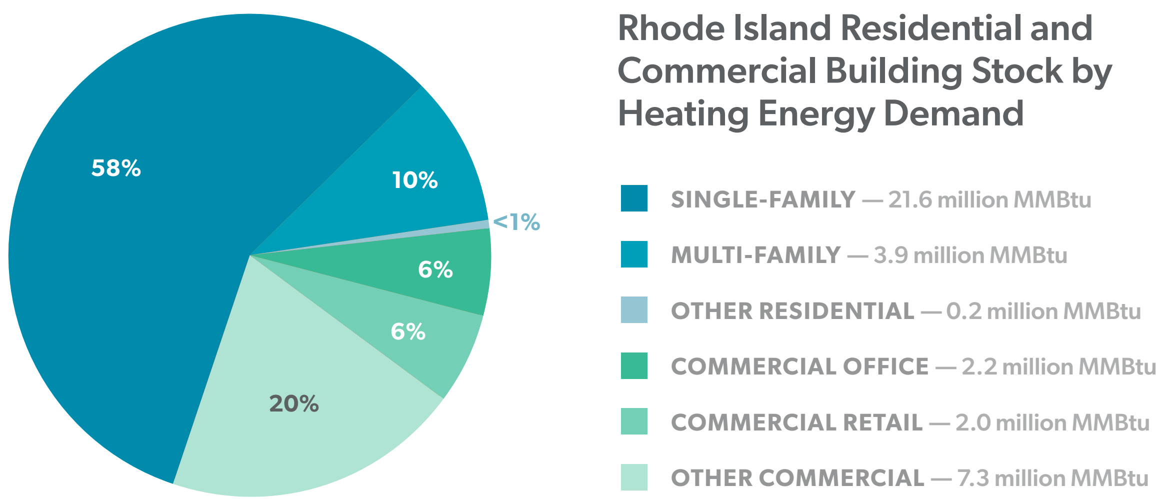


FIGURE 5: RESIDENTIAL AND COMMERCIAL BUILDING STOCK BY HEATING ENERGY DEMAND

Source: Buro Happold Analysis.

Figure 7 shows similar summary descriptions of Rhode Island's commercial building stock, by building type and square footage. This is the backdrop against which the rest of this report assesses decarbonization solutions for the Rhode Island heating sector.

PRIMARY HEATING APPLICATIONS IN RHODE ISLAND

Heating is used for three broadly defined purposes: space heating, water heating and process heating. Secondary applications include cooking, clothes drying, etc. Within the residential and commercial sectors, which together represent 84% of total heating energy demand in the state, space and domestic water heating represent the largest share of total heating related fuel demand.

Figure 8 indicates that among fuel-based heating, space heating in New England represents more than three-fourths of total energy use and that all uses other than space or water heating represent only four percent of total energy demand.[10]

Figure 9 provides the same summary for the commercial sector and indicates that while other heating uses are more prevalent in the commercial sector (notably cooking), the share of space and water heating in the commercial sector also exceeds 80%.

Because of the dominance of space heating in total heating demand, transforming the Rhode Island heating sector must focus on space and, to a lesser extent, domestic water heating.

For smaller buildings in Rhode Island, such as single family homes, small multi-family buildings, and some small commercial buildings, primary heat is typically provided in one of a few ways. Fuel can be burned in a furnace to heat air, which is then distributed through the building by a forced hot air system consisting of a blower fan and ductwork. Alternatively, fuel is burned in a boiler to heat water in a hydronic system, which pumps the hot water through pipes to distribute the heat to radiators (sometimes boilers produce steam

10 These figures exclude households using electricity for space and domestic water heating, but it is likely that the respective shares of each heating type are similar. Also, these figures represent New England averages, which are likely close approximations of the relevant shares in Rhode Island.

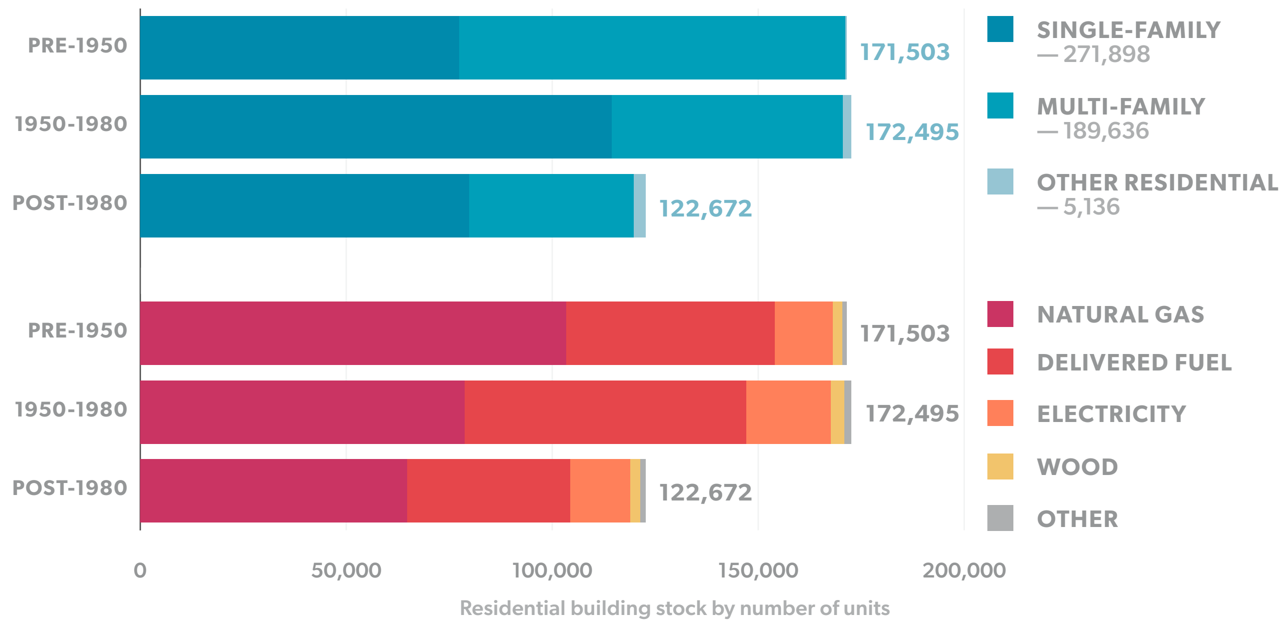


FIGURE 6: RHODE ISLAND RESIDENTIAL BUILDING STOCK BY AGE, HOME TYPE AND FUEL

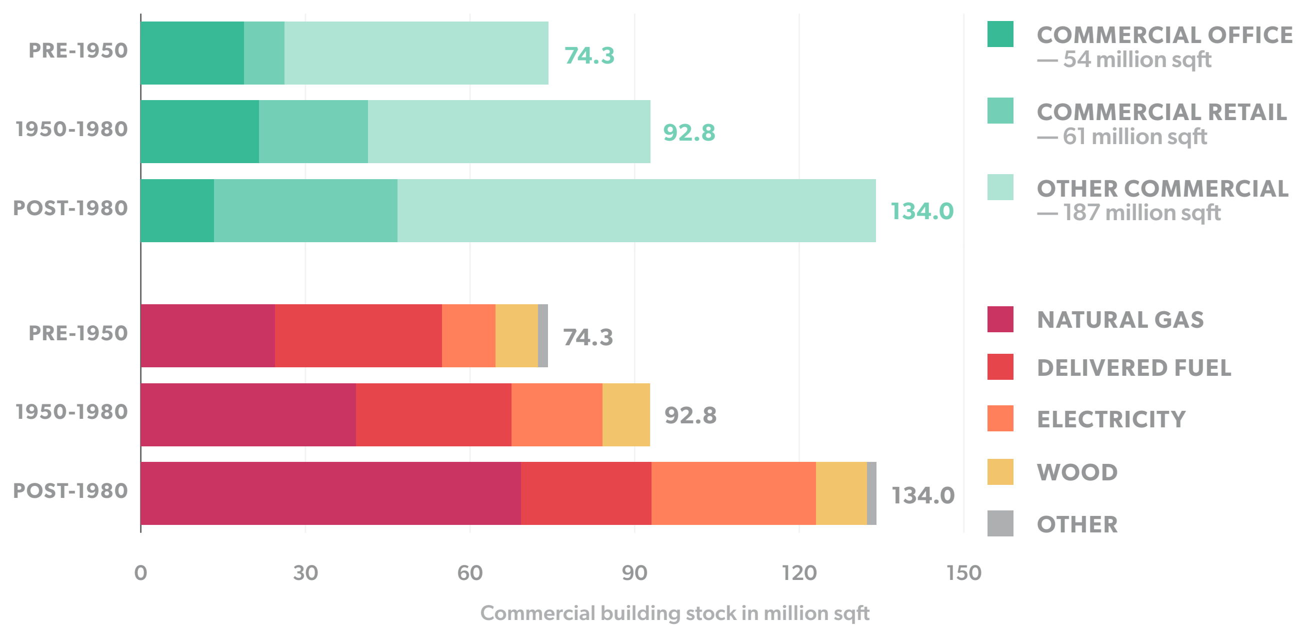


FIGURE 7: RHODE ISLAND COMMERCIAL BUILDING STOCK BY BUILDING TYPE, SQUARE FOOTAGE AND FUEL

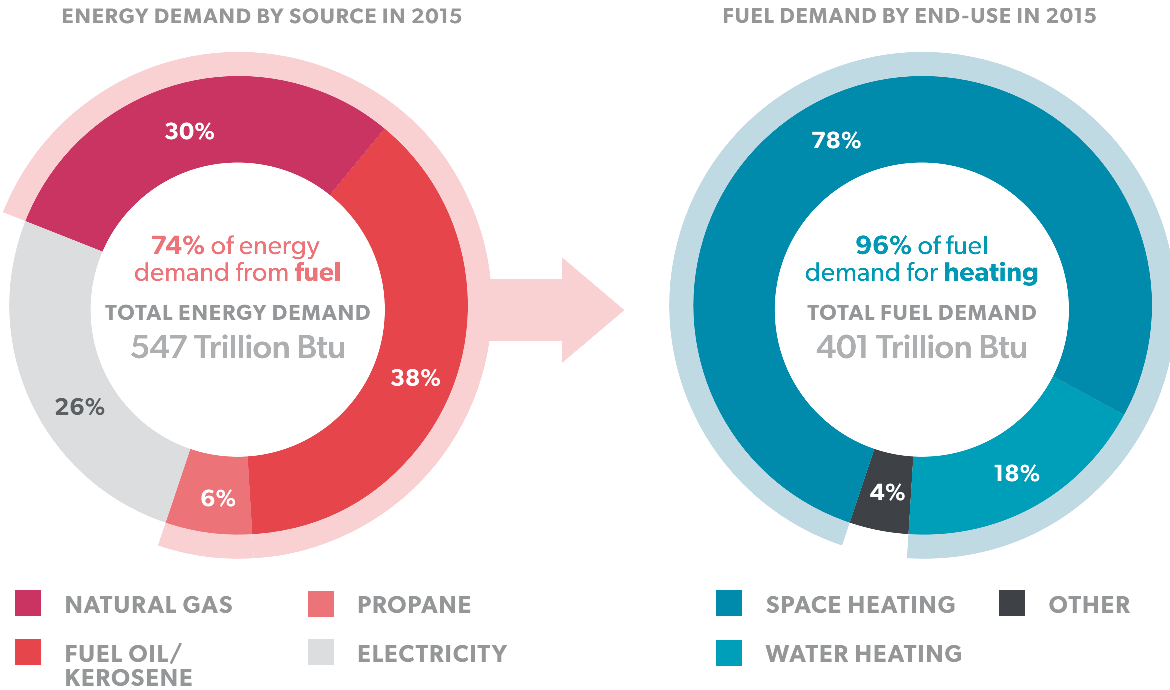


FIGURE 8: ENERGY DEMAND IN NEW ENGLAND FROM HEATING FUELS OTHER THAN ELECTRICITY (RESIDENTIAL SECTOR, 2015)

Source: EIA 2015 RECS Survey Data.

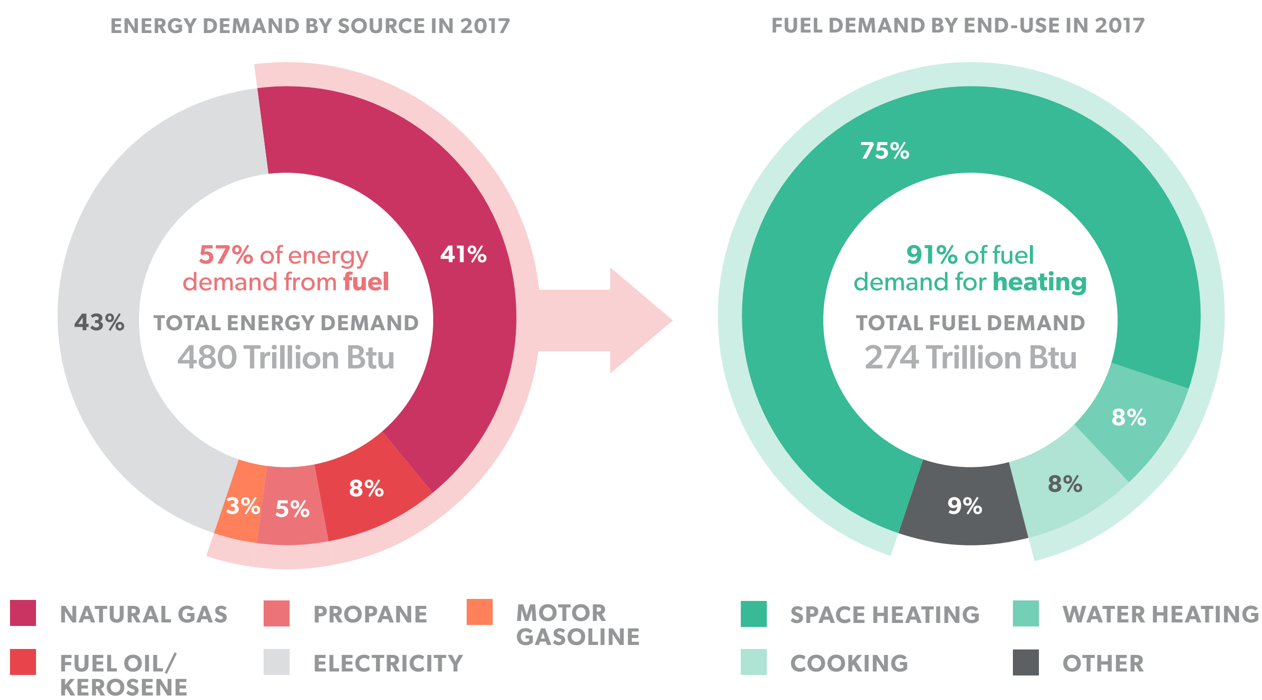


FIGURE 9: ENERGY DEMAND IN NEW ENGLAND FROM HEATING FUELS OTHER THAN ELECTRICITY (COMMERCIAL SECTOR, 2017)

Source: AEO 2019 and EIA 2012 CBECS Survey Data.

Note: "Other" includes office equipment, cooling, refrigeration, manufacturing, and electricity generation.

that circulates through steam pipes to radiators). With both furnaces and boilers, the fuel can be natural gas, heating oil or propane. Less frequently, heat is provided by electricity, usually with electric resistance (baseboard) heat, and rarely, for now, using a heat pump, which works much like an air conditioner (and can be used either in heating or cooling mode). A few buildings are heated by other means, such as wood stoves and solar.

Figure 10 shows an indicative comparison of the costs of the predominant fossil heating options, for a representative single-family home in Rhode Island with average energy use for heating.[11] This type of comparison will be used again later in this report to illustrate the relative costs of decarbonized heat solutions as well. The shades of orange at the bottom of each bar depict the annualized cost of the capital equipment required – furnace or boiler that must be replaced periodically in the case of fossil heat; as shown below, the equipment needs for some of the decarbonized heat solutions are different and more involved. The shades of blue above represent the operating costs of the heating systems – primarily the cost of the input energy which is fuel for most current systems, or electricity. Currently, natural gas is the least costly option for heating in Rhode Island with an overall cost of about $2,700 per year for a representative existing detached single-family home, because the fuel cost of natural gas is much less than oil ($3,500) or propane ($4,300). Heating with electric resistance heating is the most expensive current heating solution ($5,500 per year). Projections for 2050 costs are also provided, with future fuel costs based on the AEO fuel price projections,[12] and including assumed improvements in furnace and boiler efficiencies, particularly for natural gas-fired heating.[13] The gray area at the top of each bar represents the cost of carbon emissions at $75/metric ton CO_2 (based on the current implicit carbon value used to evaluate efficiency investments) for both 2020 and 2050, though by 2050, the relevant carbon price may be higher, and may in fact become part of the fuel prices paid by consumers. (no carbon cost is associated with electric heating in 2050 since it is assumed that electricity will be carbon-free by then, in line with Rhode Island and regional policy goals).[14] The relative ranking of the standard heating technologies remains unchanged, with natural gas heating still being the least costly and electric resistance heating still the most costly.

The demand for heating in larger buildings (e.g., multi-family apartment buildings and large commercial buildings such as office towers) of course tends to be higher in total, though the heat need usually grows less quickly than the building's square footage (i.e., as building size increases, the outer surface area of the building through which heat is lost grows less quickly than the square footage). These larger

11 The economic analyses here are expressed in real (i.e., inflation-adjusted) 2018 dollars.

12 U.S. Energy Information Administration, Annual Energy Outlook 2019, Table 3: Energy Prices by Sector and Source.

13 Caution should be used in interpreting the 2050 projections, since the fuel price projections by the AEO underlying these values are probably not consistent with the decarbonized future considered by Rhode Island and other New England states.

14 Estimates of the "social cost of carbon," measure of the value to society of avoiding one ton of CO_2 emissions, tend to increase over time since the value is equivalent to the value of avoided future damages caused by GHG emissions and as the time when more serious damages due to GHG emissions are expected is closer to the present in 2050 than today. For example, until 2017, the U.S. estimated the social cost of carbon to be $42/ton in 2020 (expressed in constant 2007 dollars and using a 3% discount rate), rising to $69/ton by 2050. Using a 2.5% discount rate, the value increases from $62/ton in 2020 (which represents approximately $75/ton in 2017 dollars) to $95/ton (or $115/ton in 2017 dollars) in 2050. See Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866; Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, August 2016. Electricity prices for 2050 reflect the projected cost of a decarbonized electricity supply.

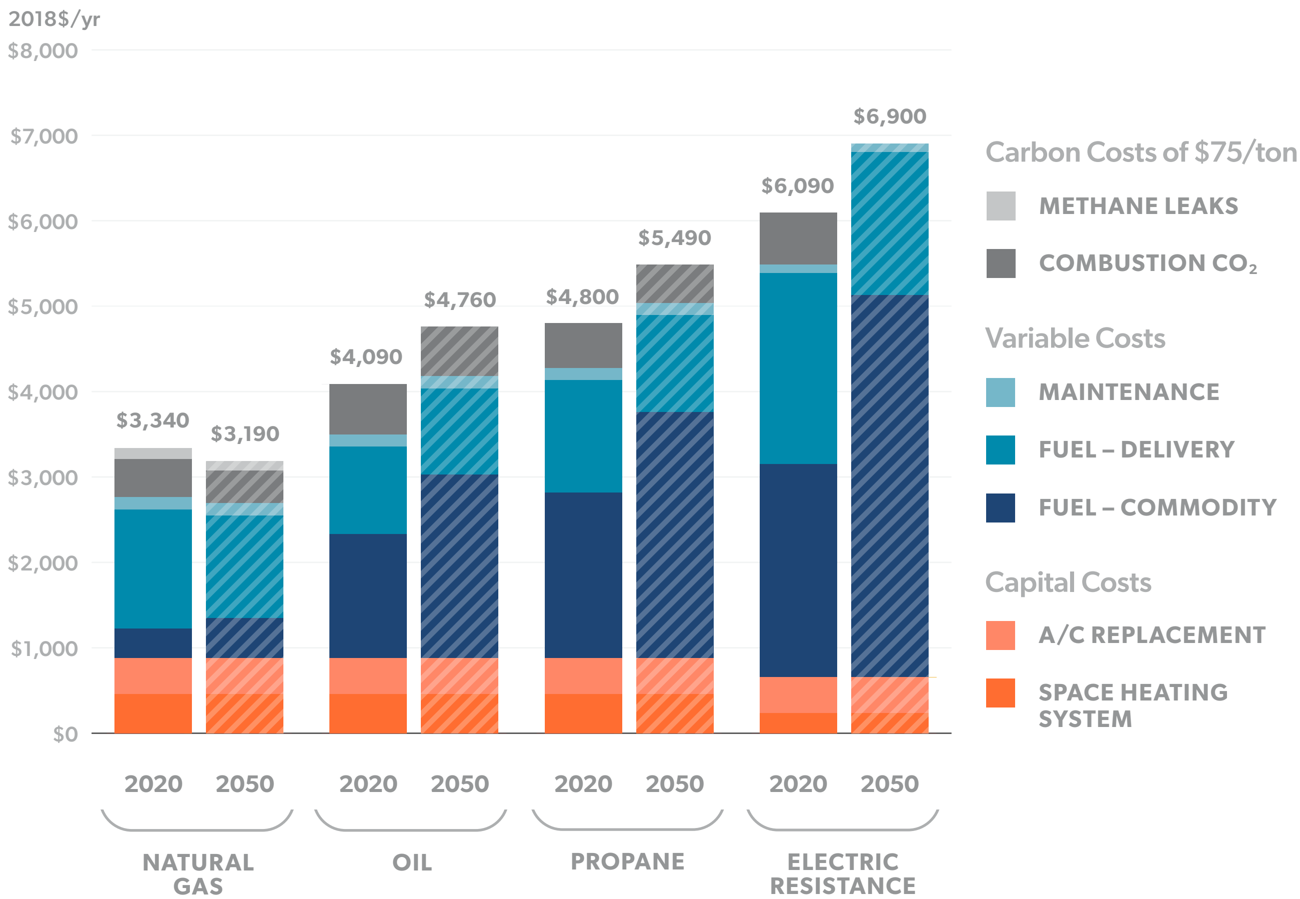


FIGURE 10: ANNUALIZED COST OF CURRENT HEATING TECHNOLOGIES, SINGLE-FAMILY HOME 2020 AND PROJECTED 2050 (2018$)

Notes: Fossil fuel prices for 2050 are based on Annual Energy Outlook projections. Electricity price for 2050 is based on the cost of an assumed carbon-free electricity supply for New England that would be able to supply traditional electricity uses plus electrification of light-duty vehicles.

buildings can have different types of heating/cooling systems, particularly regarding the internal distribution systems within the building. In addition to needing less heat per square foot, larger buildings typically need some cooling even in the heating season. But larger buildings are highly idiosyncratic in terms of their heating systems, perhaps even more so than small buildings. They typically combine large boilers that provide heat with chillers and cooling towers for cooling, and use hydronic (water-based) distribution systems within the building to move the heat and cool to where it is needed. Fans or forced air systems are used to move the heat or cool from the hydronic system into the various building spaces that require space conditioning. Still, despite the differences in their heating systems, the relative economics of heat in large buildings is similar to that for small buildings, since both are driven by the relative costs of the different available fuels and the heating equipment

DECARBONIZATION SOLUTIONS FOR RHODE ISLAND

Depending on the heating application and building type, there are several options to decarbonize heating, some of which are substitutes while others can be used in combination. This section discusses the various solutions at a high level. The 2017 Rhode Island

Space and water heat Several primary solutions are feasible across many applications/buildings	**Decarbonized Fuel** Supply may be limited from less-costly sources	**Renewable gas/power-to-gas (P2G) for gas customers** • Landfill gas, anaerobic digesters, gasification, synthetic gas
		Biofuel or power-to-liquids (P2L) for most other customers • Biodiesel, ethanol, synthetic fuels
	Heat Pumps	**Air source heat pump (ASHP)**
		Ground source heat pump (GSHP) • Including GeoMicroDistric
Industrial heat	• May be more specialized (e.g., high-temp) • May require (decarbonized) fuel, including hydrogen	

TABLE 1: DECARBONIZATION SOLUTIONS

Renewable Thermal Market Development Strategy report ("Meister Report")[15] provides a more detailed technical description of many of these technologies. Further information is provided in the **Technical Support Document** accompanying this report. Very broadly, apart from energy efficiency measures, which must play an important role independent of what heat solution is chosen, the decarbonization solutions fall into the categories outlined in **Table 1**.

As the table shows, the two primary pathways include decarbonizing fuels and electrifying heat via heat pumps. The relative attractiveness of these paths has been studied in a variety of contexts and geographies.[16] These and similar studies provide an important background for the analyses in this report as a basis for developing a heating transformation strategy for Rhode Island.

1. The Role of Energy Efficiency

One of the most obvious approaches to decarbonizing the heating sector is to lower the overall need for heat, which can be achieved through increasing the efficiency of buildings – primarily via weatherization and/or more efficient heating equipment for existing buildings, and via building codes requiring better energy performance for new buildings.[17] Cost-effective energy efficiency measures will reduce GHG emissions, and will reduce the total cost to customers, mitigating the potentially higher cost of decarbonized heat. Of course, energy efficiency efforts targeting

15 Meister Consultants Group, Rhode Island Renewable Thermal Market Development Strategy, prepared for the Rhode Island Office of Energy Resources, January 2017

16 See for example KPMG, 2050 Energy Scenarios, July 2016; DNV-GL, The Potential Role of Power-to-Gas in the e-Highway 2050 study, 2017; E3, The Challenge of Retail Gas in California's Low-Carbon Future, Final Project Report, California Energy Commission, CEC-500-2019-055-F, December 2019; E3, Deep Decarbonization in a High Renewables Future, California Energy Commission, CEC-500-2018-012, June 2018

17 Switching to heat pumps has also been supported under existing energy efficiency programs, but these are discussed below as a separate decarbonization pathway.

heating demand and electricity demand already play an important role in Rhode Island through the energy efficiency programs implemented by state utilities.[18] Existing efficiency programs provide an effective program delivery network that can be accelerated to further reduce the energy needs for heating (and cooling) in existing and new buildings, and can also be expanded to support providing decarbonized heating systems. Heating related energy efficiency measures can be very cost-effective in new buildings. By designing a building to be energy efficient from the earliest stages, its need for heat (as well as other forms of energy) can be reduced dramatically for very modest initial cost, often just a few percent of the initial cost.[19] Specifically, very tight building envelopes, insulation, efficient windows, and efficient heating and cooling systems are often very cost-effective since they tend to require little or no incremental labor and only modest materials cost, and often pay back in two to three years.[20] However, even such easy and cost-effective measures are not always undertaken in new buildings, in part because they are not an integral part of traditional design approaches, complicated by the fact that the designer/developer does not typically pay the building's energy costs and thus has little direct incentive to reduce them. For these reasons, new building codes and standards, as well as energy disclosure requirements, are an important way to ensure that new buildings comport with the goals of decarbonizing the heating sector, causing the state's buildings to become more efficient as the building stock grows renewed and grows over longer time horizons. the fact that new construction will account for a small share of the buildings in Rhode Island by 2050, an effective heating transformation strategy must ensure that cost-effective efficiency measures for new buildings – likely primarily in the form of building codes – are also part of Rhode Island's heating transformation strategy. Cost-effective efficiency measures save money for customers, and even though the building stock turns over slowly (perhaps especially because it turns over slowly), ensuring that new buildings are efficient will protect Rhode Island customers in the long run.

However, since most of the existing Rhode Island building stock is quite old – almost 75% of residential buildings are over 40 years old – it is very likely that most of the buildings that will exist in 2050 have already been built. Therefore, transforming the heating sector will require a substantial effort to retrofit existing buildings, unless there is a substitute decarbonized fuel that can be used with the existing heating systems and appliances that utilize existing fossil fuels.[21]

Efficiency measures for existing buildings such as weather stripping, air sealing and attic insulation tend to be relatively low cost since they do not require intrusive interventions in the building. They have been shown to be cost-effective and are at the heart of Rhode Island's energy efficiency programs. Such measures have represented the bulk of "building envelope" related energy efficiency measures to date. For example, in the 2018 program year, National Grid's EnergyWise program resulted in over 3,700 weatherization measures implemented, carved out from over 10,000 customers that received an energy audit as part of the program. Counting the overall program expenses for the EnergyWise program, average costs per weatherization were just short

18 Rhode Island is home to three electric distribution utilities (National Grid, Block Island Utility District, and Pascoag Utility District, with National Grid serving the large majority of customers) and one gas distribution utility (National Grid).

19 See for example EPA, Rules of Thumb – Energy Efficiency in Buildings, p.2, which suggests an increase in building costs of 2-7% for green high-performance buildings relative to "normal" buildings.

20 See for example EPA, Rules of Thumb – Energy Efficiency in Buildings, p.2, which suggests a payback period for high performance buildings of 2 years, 2.1 years for libraries and 2.6 years for schools.

21 This report does not address how comprehensive retrofits of existing buildings would be funded.

of $4,200, with average participating customers contributing approximately $575.[22] However, these measures typically achieve only a moderate reduction of overall heating demand; in aggregate, they tend to reduce heating energy needs by 10-15%. Further reductions in heating energy needs require additional measures that have a higher cost and are more intrusive to the occupant of the existing structure.[23]

Heat energy savings of 40% or more are possible in existing buildings, but require "deep" retrofits with measures such as window replacement and adding insulation not only to attics, but also to exterior walls and floors. Such activities tend to be more disruptive and entail significant cost when retrofitting an existing building. The necessary interventions in an existing building also tend to be highly building-specific and, therefore, difficult to standardize.[24] Their cost can exceed $50,000 or even $100,000 for a residential home, with comparably high costs for most commercial buildings. Such deep retrofit measures have so far not been deemed to be cost-effective in existing buildings and face significant initial cost and implementation barriers.[25]

Looking forward, energy efficiency measures in existing buildings that are cost-effective today are even more likely to be so in the future. Implementing cost-effective efficiency measures reduces customer expenses for heating (and electricity) – particularly relevant at a time like the present when the COVID-19 pandemic is affecting the incomes of many local residents and businesses, but important in normal times as well. Energy efficiency will also need to play an important role in transforming the heating sector in the longer term. At present, National Grid is on pace to complete energy audits of essentially all residential buildings in the state by 2050. However, even though such measures are generally cost effective, only about one-third of residential customers who receive an energy audit also opt for these weatherization measures. Going forward it will be important to develop policies and incentives to improve this conversion rate so that cost-effective weatherization efforts reduce the need to provide decarbonized heat to the greatest extent possible. Energy efficiency programs may also be useful delivery mechanisms for heating transformation solutions such as deploying heat pumps where cost effective. In that case, future policy likely needs to focus on increasing conversion rates (the rate of adoption once cost effectiveness has been established, for example via an energy audit), since the extent of deployment of such solutions across the more than 400,000 buildings will depend critically on what fraction of customers adopt such solutions.

Beyond weatherization, there are also newer, technology-enabled energy efficiency measures that can provide additional heat energy savings. They include behavioral programs to encourage conservation, including those made possible through smart thermostats. At present it seems unclear what the net effect of simple weatherization

22 Calculated based on National Grid, 2018 Energy Efficiency Year-End Report, May 15, 2019, p.8 and Table E-3.

23 When evaluated in a bundle with insulation, an evaluation of Maine weatherization programs found an average reduction of 17.9 MMBtu or 17% relative to pre-measure energy consumption in homes heated with natural gas. A comparison with other air sealing and insulation programs suggests a typical range of savings between 9% and 17%. West Hill Energy and Computing, Efficiency Maine Trust Home Energy Savings Program Impact Evaluation, Program Years 2014-2016, August 23, 2019, p.23, Table 3-5.

24 There are efforts to develop standardized deep retrofit approaches to existing residential buildings. NYSERDA is currently in a phase of pilot project through the RetrofitNY program, leveraging efforts to develop standardized retrofits in the Netherland pioneered by EnergieSprong. (See https://energiesprong.org/country/new-york/ and https://www.greenbuildingadvisor.com/article/u-s-looks-to-europe-for-energy-retrofit-model)

25 Home Energy Services Impact Evaluation (Res 34), Produced in collaboration with Navigant and Cadeo, prepared for the Electric and Gas Program Administrators of Massachusetts, August 2018, page 26.

and such behavioral programs might be. Since smart thermostat penetration will likely increase over time, it is likely that more customers will at least have access to such programs. Beyond conservation, these programs also contribute to reducing demand peaks, which will help lower the cost of electricity in a fully clean power grid of the future.

Two other points need to be emphasized. First, cost-effective energy efficiency measures not affecting heating demand, but electricity demand instead, will likely be critical in enabling a successful heating sector decarbonization. By reducing the demand for electricity relative to what it would otherwise be, they will reduce the challenge of building a portfolio of electricity generating resources capable of supplying the state (and region) with 100% clean electricity. Second, by having been in place for many decades and having steadily improved over time, existing energy efficiency programs and their administration and delivery are likely a key delivery vehicle for implementing other heating related policies. The fact that current state incentives for heat pumps are delivered through existing energy efficiency programs is likely only the beginning of using and improving an existing delivery channel for many of the policies needed to transform the sector.

Recognizing the contribution of cost-effective weatherization on the costs of various decarbonization solutions for customers by 2050, the analysis below assumes that the combination of cost effective energy efficiency measures will lower the total heating requirements of a representative Rhode Island building by 15% and that the remaining (very significant) sources of heat must be decarbonized to achieve the state's decarbonization targets. The two primary pathways for decarbonizing heat in Rhode Island are discussed next – electrifying via heat pumps (with a decarbonized electric sector) and decarbonizing the heating fuel.

2. Decarbonized Electrification with Heat Pumps

Using electricity to heat homes is not new. In fact, it is the primary heat source for about 9% of Rhode Island's residential customers and 13% of commercial square footage.[26] Currently, most of the electric heat in Rhode Island is electric resistance, but an increasing share is using electric heat pumps, particularly in the commercial sector. Heat pumps are based on a technology that is well understood and widely deployed – it is the same approach used in refrigerators and air conditioners. In contrast with furnaces and boilers which generate heat, a heat pump moves heat – from outside the building to the inside (or the reverse in cooling mode). With this approach, heat pumps take advantage of energy available in the environment (even cold outdoor air in the winter contains significant heat energy) and consequently can achieve efficiencies well above 100%. That is, for each unit of electric energy consumed, they provide more than one unit of heat to the building.

There are many types of heat pump applications, but they can be grouped into two broad categories: Air Source Heat Pumps (ASHP) and Ground Source Heat Pumps (GSHP), with the primary distinction being the outside heat source used (or heat sink in cooling mode). ASHPs use outside air as a source for heat, with a fan to move the air across a heat exchanger. The heating efficiency of ASHPs declines with outdoor temperatures, and thus ASHPs consume more electricity, particularly in colder weather. For this reason, despite recent performance improvements, ASHPs are generally installed with a back-up heating system that can substitute or supplement the ASHP

26 Meister Report, Figure 1, Table 5, Table 7.

during very low outdoor temperatures.[27] GSHPs, on the other hand, use groundwater or the ground itself, which maintains a stable year-round temperature of about 50 degrees Fahrenheit a few feet below the surface. To access this reservoir of heat, GSHPs require a "ground loop," piping that circulates a refrigerant that absorbs heat from the ground or water, or injects heat in cooling mode. A ground loop can be installed horizontally as a "slinky" coil of flexible pipe buried a few feet underground, or vertically by drilling one or more boreholes several hundred feet deep. The ground loop typically makes GSHPs more costly to install, but since the ground temperature is constant throughout the year, they can operate at very high efficiency regardless of outdoor temperature.

An advantage of heat pumps over burning decarbonized fuels (e.g., renewable oil or gas) is that they provide cooling as well as heating, whereas furnaces and boilers burning fuels can only provide heat.[28] In a warming Rhode Island, air conditioning is likely to become more important and by being able to provide both heating and air conditioning, heat pumps can replace not just a furnace or boiler, but also the need for a separate air conditioning system.

A potential disadvantage of heat pumps is the demand they put on the electric system, particularly in a scenario of wide scale deployment. Heat pumps have the potential to create a strong winter peak in electricity demand in the coldest weather. This peak impact is particularly acute for ASHPs, as discussed below in Section III.C. While the analysis below finds that decarbonizing the grid and scaling it up to meet such higher peak demand would only lead to moderately higher electricity costs in the long run, projecting the impact of this dual challenge (decarbonization and scaling up) on prices remains a source of significant uncertainty. It also increases the challenge of building out a regional carbon-free electricity supply in time to meet potentially much higher peak demand.

There is also a question about whether ASHPs should be sized to cover all reasonably expected outdoor temperatures. While ASHPs can be sized to meet all reasonably expected heating needs, this analysis assumes that it is likely more cost-effective to use inexpensive electric resistance heating capacity to cover the small number of hours when temperatures are so cold that ASHPs are not much more efficient than traditional resistance heat.

Another practical disadvantage of heat pumps relative to decarbonized fuels is that converting to heat pumps would require that most of the existing buildings throughout the state would need to have their heating systems replaced, abandoning, altering or removing parts of the existing systems. This would require

27 Even though ASHPs can be sized to provide sufficient heat during very low outdoor temperatures, the required "oversizing" of the heat pump tends to be uneconomical. Where heat pumps replace (or complement) an existing heating system, the existing heating system can be retained to provide backup heat, at least until that system requires significant investment (such as replacing a furnace). Electric resistance heating likely provides the most cost-effective back-up heating in the long run, since at temperatures below -5˚F the efficiency of an ASHP drops to the efficiency of electric resistance heat. Wood stoves are another potential carbon-neutral back-up heating source. This analysis has not attempted to project the interim use of non-electric backup heat, instead focusing on all-electric Bookend Scenarios to understand the potential magnitude of the electric system impact. However, the analysis below does consider a Mixed Scenario where decarbonized heat is provided from a variety of sources; this scenario offers a good proxy for the interim use of non-electric backup heat sources.

28 A heat pump can also be designed to run on natural gas, and could provide cooling as well as heating, though gas-fired heat pumps are not currently commercially available. Although it would be less efficient than an electric heat pump, a gas-fired heat pump would provide a significant efficiency improvement over gas-fired furnaces or boilers. The COP of a gas-fired heat pump in heating mode is about 1.3 (and 0.6 in cooling mode), relative to efficiencies in the range of 0.80-0.9 for a gas-fired furnace or boiler. (See Baig and Fung, Impact of Carbon Pricing on Energy Cost Savings Resulting from Installation of Gas-Fired Absorption Heat Pump at A Library Building in Ontario, MDPI Proceedings, August 16, 2019). There is currently little information about the likely installed cost of such heat pumps, and so they were not analyzed as a separate option for fully decarbonized heating in this analysis. However, future developments could potentially make them an attractive option. They would likely have relatively high initial costs, potentially similar to electric heat pumps, and would likely require similar modifications to existing buildings, but their fuel costs would be lower than for furnaces or boilers fired by renewable gas.

disruptive construction activity in the homes of most Rhode Islanders, and an initial cost that is much more costly than simply replacing an existing boiler or furnace with a new, more efficient one that is otherwise similar.

3. Decarbonizing Fuels

Rather than installing electric heat pumps to replace the boilers and furnaces that burn fossil fuels, it is also possible to keep the same or similar heating equipment, but to decarbonize the fuels themselves. That is, the fossil natural gas, oil and propane fuels currently in use can be replaced with carbon-neutral "drop-in" substitute fuels, i.e., fuels whose carbon emissions during combustion are essentially releasing carbon that was recently absorbed from the atmosphere to synthesize the fuel. Two examples explained in more detail below are biomass-based fuels, where carbon absorbed through photosynthesis by plants is converted into biofuel and re-released into the atmosphere when burnt, and "Power2Fuels" approaches, which use renewable energy to convert water into hydrogen and add carbon dioxide captured from the atmosphere to make renewable gas, oil, or other fuels. Deploying such drop-in substitute fuels has the advantage that little or no change is necessary inside the building, since for the most part, existing heating equipment and distribution systems can continue to be utilized.

Heating Oil ⇢ Renewable Oil

Currently, about a third of Rhode Island customers use heating oil and another 2% heat with propane.[29] Many of these customers reside outside of Rhode Island's urban core communities. A decarbonized liquid fuel such as biodiesel can be used as a drop-in replacement for heating oil. There are several potential sources for decarbonized heating oil, including those derived from waste oils (used cooking oil), various oil crops (rapeseed, soy, palm) and potentially synthetic liquid fuels produced from water electrolysis and subsequent steps to synthesize carbon-neutral fuels.

In fact, Rhode Island's Biodiesel Heating Oil Act of 2013 currently requires a 5% biodiesel blend (B5) in heating oil.[30] In theory, this blend requirement could be ratcheted up significantly over time. In line with this possibility, the Northeast's heating oil industry has recently committed to achieving net-zero CO_2 emissions by 2050, with interim targets of a 20% biodiesel blend (15% reduction in carbon intensity) by 2023, and a 50% blend (40% carbon reduction) by 2040.[31] At higher blending levels, there may be some "blend-wall" issues for biodiesel.[32] However, there do appear to be solutions to overcome some of these issues[33] and the opportunity exists for Rhode Island to begin increasing its blending requirements along the lines committed to by the delivered fuel industry.

While there are likely some limits on the quantities available from the relatively less costly sources,[34] a synthetic version of biodiesel could be produced in unlimited quantities, at least in theory. The "Power2Liquids" (P2L) pathway, illustrated in **Figure 11**, could use carbon-free electricity, water electrolysis and further refining to provide decarbonized liquid fuel in quantities constrained only by the availability

29 See Meister Report, p.24.

30 State of Rhode Island, Biodiesel Heating Oil Act of 2013, § 23-23.7-4.

31 See https://nefi.com/news-publications/recent-news/heating-oil-industry-commits-net-zero-emissions-2050/ and nbb.org.

32 Today, biodiesel content over 20% may cause several issues with existing equipment – for example, a biodiesel tank must be in a conditioned space since B100 congeals at temperatures below 42˚F.

33 Ibid.; also see a series of modest steps proposed for a conversion to B100 (https://www.netzeromontpelier.org/blog/2018/10/8/biodiesel-for-home-heating, accessed February 2, 2020). See also https://www.hpac.com/heating/article/20925981/b100-makes-the-grade (accessed February 2, 2020), which discusses a Brookhaven National Laboratory test of a hydronic condensing boiler using B100.

34 See RIEC4, Rhode Island Greenhouse Gas Reduction Plan, December 2016 , p.73

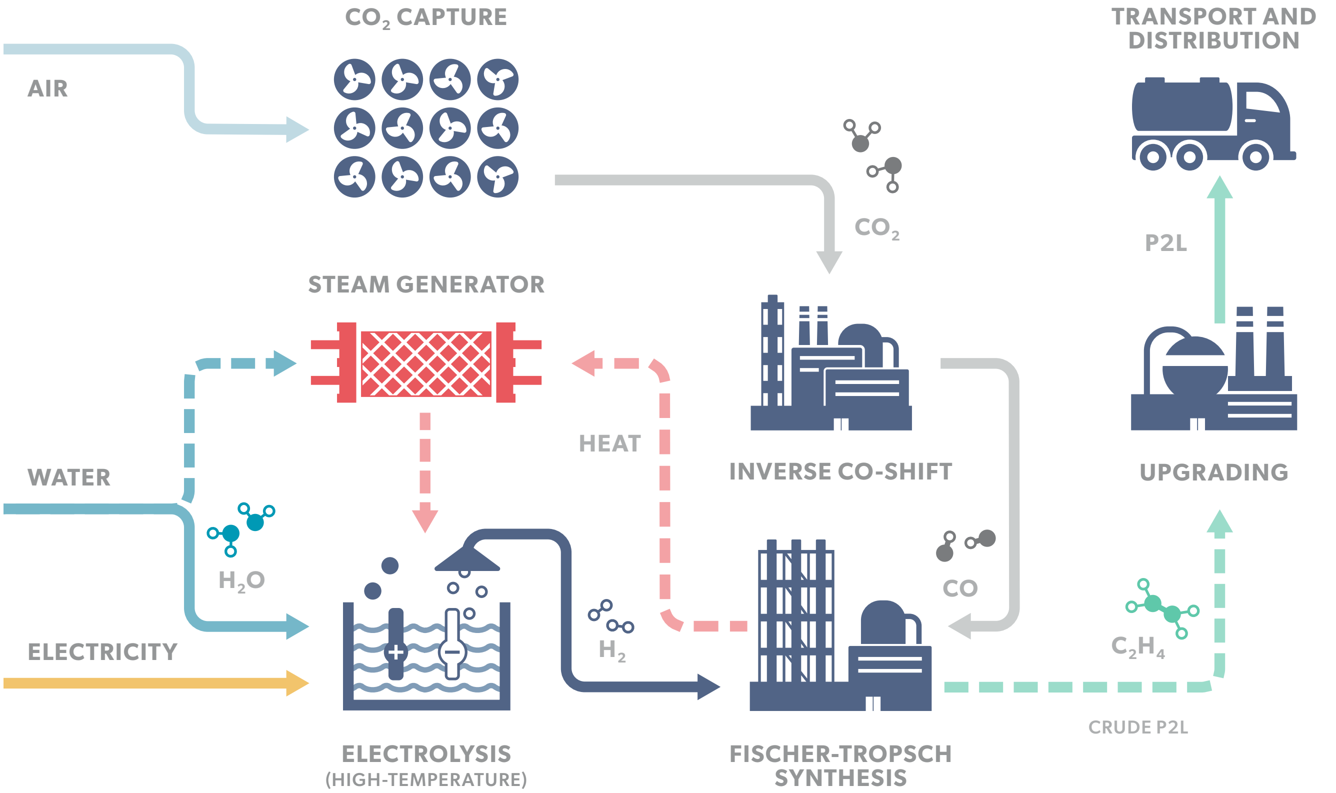


FIGURE 11: POWER2LIQUIDS (P2L) PROCESS

Source: Reproduced from Figure 3, Power-to-Liquids Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel, Umweltbundesamt, September 2016

of renewable electricity and the ability to develop the infrastructure and equipment to produce it. The primary concern with the P2L approach may be the cost of producing fuel in this way. This suggests that even if the supply of relatively low-cost biodiesel from waste products may be limited, the potential for P2L means there is likely no hard limit to the availability of renewable oil.

The remainder of this report will use the term “Renewable Oil” to refer to both biodiesel and synthetic P2L fuels, since the latter is not biologically based.

Finally, while the EPA considers biodiesel to be carbon neutral,[35] some other assessments of the lifecycle emissions of biodiesel conclude that biodiesel production does emit some GHGs. Some estimates suggest that switching to biodiesel could lower GHG emissions by as much as 80%, but not 100%.[36] Similarly, a case study of Fulcrum Sierra BioFuels for the California Low Carbon Fuel Standard estimated a potential GHG reduction of 62.1% with biodiesel.[37] Hence, the decarbonizing potential of B100 for the RI heating sector would likely depend on the assessed lifecycle emissions of B100, which in turn depends on how (and from what) the B100 is produced.

Propane is also used as a delivered fuel for heat

35 See https://www.eia.gov/energyexplained/biofuels/biodiesel-and-the-environment.php

36 See $(S\&T)^2$ Consultants, BIODIESEL GHG EMISSIONS, PAST, PRESENT, AND FUTURE, A report to IEA Bioenergy Task 39, January 2011, Table ES-2

37 See Life Cycle Associates, Life Cycle GHG Emissions for Fulcrum Sierra Biofuels LLC’s MSW-to-Fischer Tropsch Fuel Production Process, LCA.6060.120.2015, December 2015, Table 6, page 12.

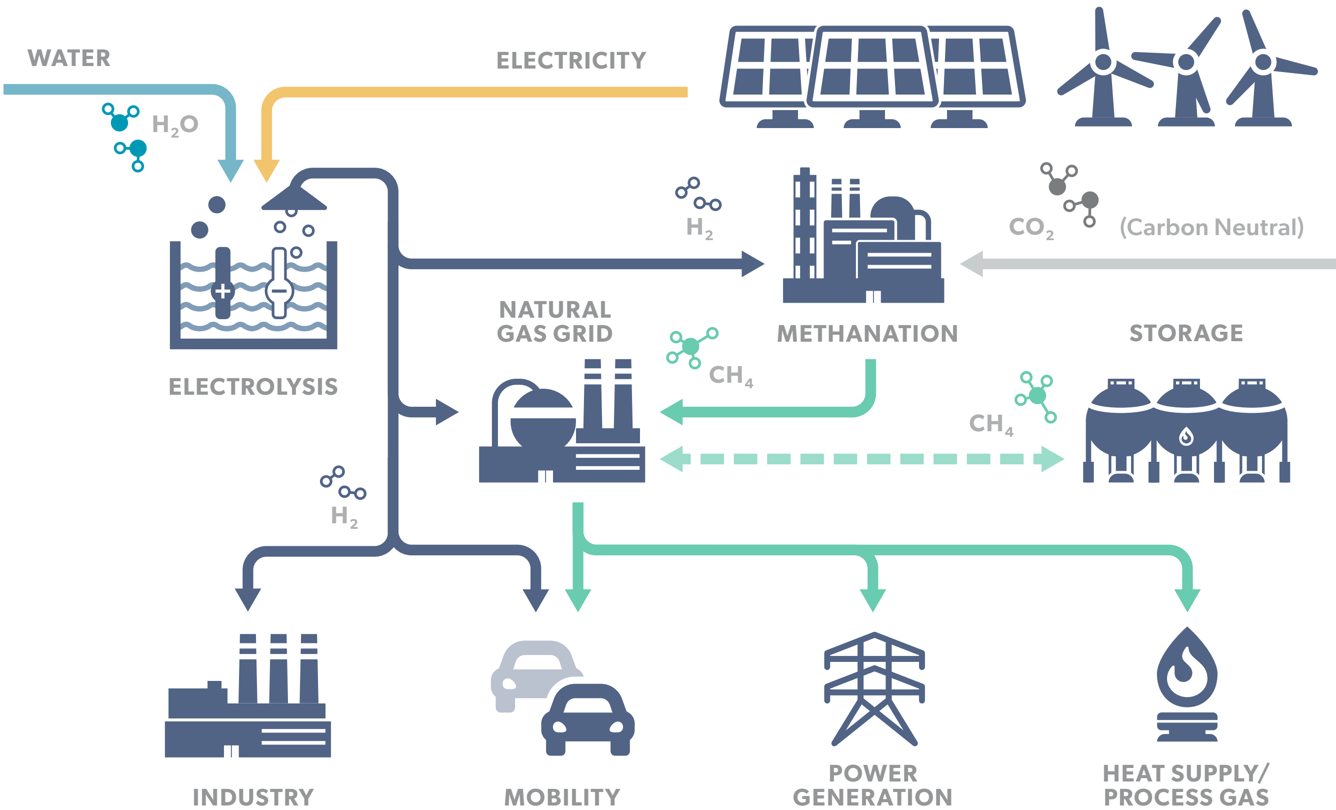


FIGURE 12: POWER2GAS (P2G) PROCESS

Source: Muhammad Akif, Analysis of Gas Power Systems, Today & Tomorrow, 2015, Figure 17, p.21

in Rhode Island, though rarely.[38] Conceptually, renewable propane could be produced by similar processes as renewable gas and renewable oil, including P2Fuel pathways, and so the same types of issues discussed for those fuels are likely to apply to renewable propane.

Fossil Natural Gas ⇢ Renewable Gas

Natural gas (methane) is the dominant heating fuel in Rhode Island, serving 54% of the state's residential customers.[39] Almost all natural gas used today is produced from fossil sources and transported via pipelines to the point of use. Small amounts of methane are available from landfill gas and anaerobic digesters (using animal waste, food and agricultural waste, waste water, etc.), and can be blended into pipeline gas. Two potential gaseous replacement fuels for natural gas are being widely discussed: hydrogen and bio-methane, and a growing number of reports discuss the potential role of decarbonized gas in a decarbonized energy system.[40] In addition, methane can be synthesized via "Power2Gas" (P2G) pathways, which begin by producing hydrogen. As with oil, this report will use the term "Renewable Gas" to refer to both bio-gas and synthetic P2G fuels, and will use "Renewable Fuels" to refer to renewable gas and renewable oil collectively. Figure 12 illustrates the P2G pathway.

Hydrogen can be blended with methane in the gas system, or can be used in pure form as a fuel itself. Most hydrogen is currently produced by splitting

38 See Meister Report, p. 24.

39 Ibid.

40 See for example Black & Veatch, The Role of Natural Gas in the Transition to a Lower-Carbon Economy, May 2019; Navigant, Gas for Climate, March 2019

natural gas into hydrogen and CO_2 via a process called steam methane reforming ("SMR"), which releases the CO_2 into the atmosphere. If the CO_2 were to be captured and permanently sequestered, the hydrogen would be carbon-neutral; this is referred to as "blue hydrogen."[41] Alternatively, "green hydrogen" can be produced from carbon-free electricity by using electrolysis to split water into hydrogen and oxygen. Either of these forms of carbon-neutral hydrogen can be used to replace natural gas as a heating fuel, and potentially in industrial high-temperature process heat applications. However, hydrogen is not a true "drop-in" fuel since it differs from methane in ways that may require significant upgrades and investments to the existing gas infrastructure. This would likely involve equipment both in front of the meter (transportation and distribution pipes, and associated infrastructure) and behind it (internal gas lines, gas appliances).[42] Thus hydrogen sacrifices the ability to continue using existing infrastructure, as well as the accompanying convenience and cost advantages. For these reasons, we do not focus on hydrogen as a primary candidate for a gaseous heating fuel, but believe that renewable methane is likely to be more suitable.[43] Nonetheless, if hydrogen does overcome these disadvantages to be the more attractive version of renewable gas, or if hydrogen and renewable methane are both viable, the conclusions we reach below about renewable methane are also applicable to renewable hydrogen.

The alternative to hydrogen is to create renewable gas that is the chemical equivalent of natural gas. Methane can be produced from various biological sources – landfill gas, anaerobic digestion or the gasification of biological feedstocks such as wood, food waste, municipal solid waste, etc.[44] Renewable gas can also be produced synthetically via a P2G pathway by combining hydrogen from water electrolysis with CO_2 from a carbon-neutral source, in a chemical process is called "methanation." Renewable gas has the advantage of being fully compatible with existing natural gas heating equipment, and with a very large existing gas infrastructure, including pipelines, gas distribution systems and large gas storage fields, where it can be stored for long periods of time (particularly useful for dealing with seasonal storage needs).

One concern with renewable gas is its potential cost, which may be considerably higher than current fossil natural gas prices, particularly for P2G pathways. Another factor is that gas pipeline and local distribution systems leak some of the gas that is transported. Methane is a particularly strong GHG itself, 30 to about

41 Since natural gas is currently very inexpensive in the U.S., hydrogen produced in this way could be relatively low cost if the cost of carbon sequestration were reasonably low, though sequestration has so far remained disappointingly costly.

42 It may be possible to blend hydrogen with natural gas at low concentrations (up to about 10%) without significant infrastructure upgrades. This can achieve near-term GHG reductions, but since such blending is limited to low concentrations, it does not offer a pathway to full decarbonization. The hydrogen "blend wall" beyond which significant infrastructure upgrades may be required depends on the composition of the particular gas distribution system in question, and determining it would require detailed study. For a more detailed assessment of various issues related to hydrogen blending, see for example Melaina et al., Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues, NREL, March 2013.

43 Hydrogen may offer advantages in some particular applications, particularly for high-volume uses where dedicated infrastructure might be used, avoiding the need for broader upgrades. This could include large industrial applications, and also power generation, where hydrogen could offer an attractive way to store energy for use in thermal generators, to facilitate matching intermittent generation to load and providing ancillary services. The opportunities for hydrogen to address some of these industrial and power generation needs warrants further study. For one discussion of some of the opportunities for hydrogen, see "Hydrogen in a low-carbon economy," UK Committee on Climate Change, November 2018, at https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf.

44 For an in-depth discussion of both biological feed stocks, see American Gas Foundation, Renewable Sources of Natural Gas: Supply and Emissions Reductions Assessment, December 2019

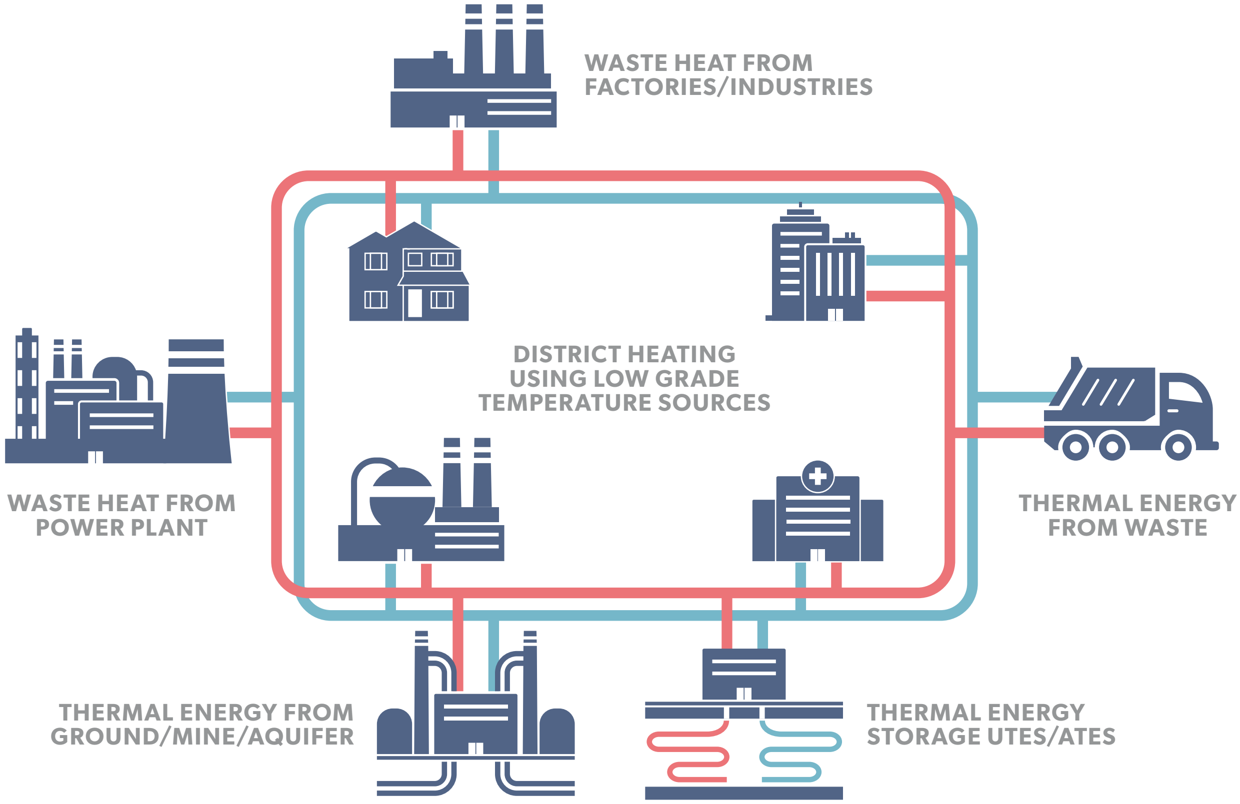


FIGURE 13: ILLUSTRATIVE SCHEMATIC OF DISTRICT HEATING SYSTEMS

Source: https://www.flexis.wales/research-item/wp9-smart-thermal-energy-grid-prof-hr-thomas/low-grade-district-heating-network/

85 times stronger than CO_2,[45] so even if the renewable gas itself is entirely decarbonized, any leaks would partially offset the emissions reductions of replacing fossil natural gas with renewable gas. At the current leak rate, methane leaks can add roughly 30%-85% to the GHG of the CO_2 in the combustion products. While there are ongoing efforts to reduce leaks, it is unlikely that they can be eliminated entirely. Finally, renewable gas, like natural gas, presents safety risks from indoor gas leaks, and health risks related to indoor air quality).

4. Decarbonized District Heating

All of the decarbonization solutions discussed so far concern the "fuel" or "technology" used to decarbonize heating. Any of these approaches can be applied in a distributed system, with every individual building unit having its own fuel conversion system such as a boiler, a furnace or a heat pump. However, heating can also be provided through more centralized systems where, rather than distributing fuel (oil, gas, electricity) to individual buildings, the heat itself is produced centrally and distributed to individual buildings for use. The latter is often referred to as "district heating", which is prominent in several northern European and Asian countries and, on a smaller scale, on university and office campuses, etc. Figure 13 illustrates how a district heating system works.

45 Natural gas leak rates are estimated at 2.7% by Deeper Decarbonization in the Ocean State: The 2019 Rhode Island Greenhouse Gas Reduction Study, September 2019, Stockholm Environment Institute, et al. The 100-year global warming potential for methane is 30, and the 20-year GWP is 85, based on U.S. EPA ranges (U.S. EPA, "Understanding Global Warming Potentials", available at: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials). This is consistent with IPCC estimates (IPCC, Fifth Assessment Report, Chapter 8: Anthropogenic and Natural Radiative Forcing, p.714, Table 8.7).

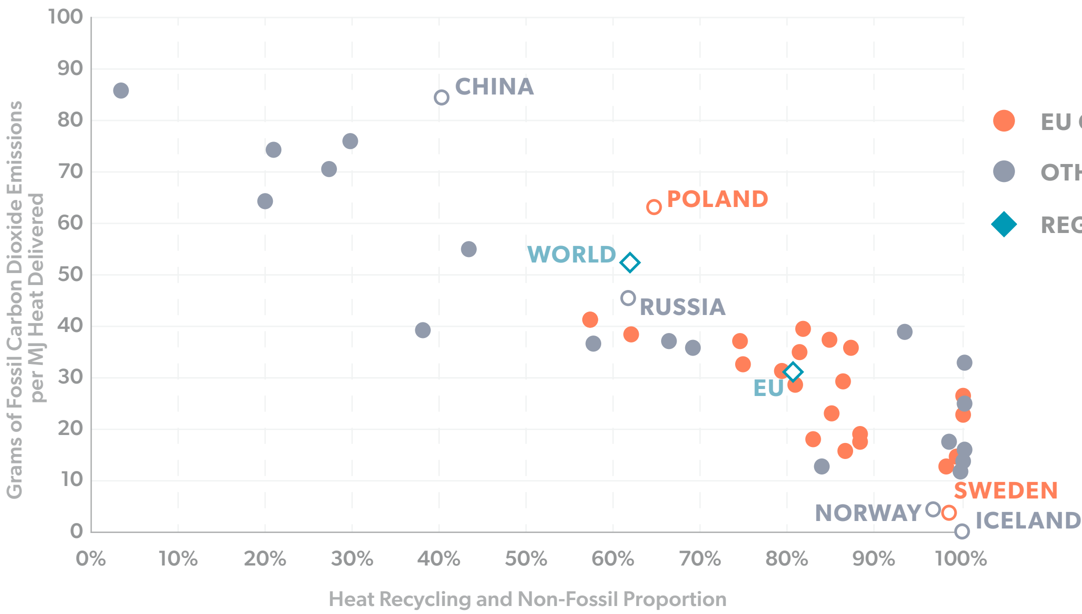


FIGURE 14: CARBON INTENSITY OF SELECT DISTRICT HEATING SYSTEMS

Source: Sven Werner, International review of district heating and cooling, Energy 137 (2017), pp. 617-631

Using district heating as a substitute for the typical distributed heating system provides additional opportunities to decarbonize heating by potentially improving the economics, feasibility or speed of transforming the heating sector.

District heating systems have been around since the 19th century and were initially introduced for a variety of reasons, including to reduce local air pollution (by centrally creating heat through the combustion of coal, oil or gas) and to take advantage of waste energy and heat (by using combined heat and power plants, waste incineration or by directly using waste heat from industrial processes). As a primary source of space and water heating, district heating systems are particularly prominent in the former Soviet Union, China and several northern European countries (Denmark, Sweden, Finland, Germany). In particular, as shown in **Figure 14**, Scandinavian countries have achieved district heating systems with very low carbon emissions.

In most district heating systems, heat is generated centrally – for example in a large combined heat and power plant (a power plant, where the heat that is generated as a byproduct is used rather than wasted) – and then distributed through a network of pipes to end users. The transfer medium can be either steam – such as the district heating system still in place in parts of New York City – or via warm water, which is then used to heat buildings. More recently, "mini district heating" has emerged as a possible alternative to large centralized systems. One particular application that has received recent media attention is the development of so-called GeoMicroDistricts[46] that create neighborhood ground source heat loops that can deliver heat to multiple buildings in a particular neighborhood.

Two of the major advantages of district heating are that it takes advantage of large economies of scale by producing heat centrally and thus avoiding the need for furnaces and boilers at the end user site and

46 See http://www.hydrogenfuelnews.com/massachusetts-might-replace-natural-gas-with-geothermal-heating/8538985/

also that they allow effective use of waste heat. As a consequence, district heating systems have been shown to be very cost effective heating options, especially in new developments such as university campuses or new housing developments, i.e., where the district heating system does not replace an already existing system. Similarly, community-systems using a common ground loop have the potential to significantly lower the cost of the ground loop.[47] Larger (community) scale systems likely also create opportunities for operational efficiencies by taking advantage of diversity of heating and cooling demands from the various buildings connected to the system. For example, if such systems are installed in neighborhoods with both commercial and residential (and perhaps even industrial) customers, simultaneous demand for both heating and cooling – for example for refrigeration or warm water production – can result in such a system operating at higher average efficiencies (and potentially lower overall costs by requiring a smaller size when compared to systems serving single buildings.[48]

The most significant technical challenges for district heating systems are their proper sizing – once in the ground, it can be costly to change the overall capacity to deliver heat, for example in response to growing demand via population density in a given area, as well as the fact that the cost effectiveness depends on the level of participation. Put differently, district heating systems can be very cost effective[49] if everybody participates (by spreading the high fixed costs of such a system over many customers), but less so if participation is low. In areas without preexisting district heating systems, this makes adoption of district heating via switching from existing heating potentially challenging.

Finally, decarbonized district heating solutions face some of the same practical barriers as heat pumps. The buildings to be served by a proposed district heating system would need to have their heating systems replaced, abandoning, altering or removing parts of the existing systems, and requiring disruptive activity in those buildings and in the neighborhood. In addition, converting to a district heating solution requires high participation to obtain the potential efficiencies, which requires the agreement of many individual homeowners and building owners in the affected area.[50]

5. Other Considerations

Several other considerations influence the cost and feasibility of heating decarbonization solutions and should be considered when developing a Rhode Island heating sector transformation strategy.

First, the attractiveness of various decarbonization alternatives for space and water heat may be influenced by building size (up to a point), even though the basic solution pathways are similar. While smaller commercial buildings are often similar to larger residential buildings, most large commercial buildings (and often large multifamily residential buildings) differ. They tend to use

47 See Justin Mahlmann and Albert Escobedo, Geothermal Heat Pump Systems for Strategic Planning on the Community Scale, ACEEE Summer Study on Energy Efficiency in Buildings, 2012, which claims that for single family residential applications (typically less than 10 tons of heating capacity) the cost of the ground loop is $50-$100 per foot of ground loop. For systems with 100 tons or more of heating capacity, the costs decline to $15-25 per foot. As one example, a system for Ball State University with over 1,000 tons of heating demand requiring 680 boreholes of 500 feet of depth each (the equivalent of 680 single family systems), the costs decline to $11 per foot. (p.6).

48 Ibid, p.6.

49 A feasibility study commissioned by HEET concludes that GeoMicroDistricts can result in significant installation cost savings relative to individual GSHPs. Buro Happold, GeoMicroDistrict Feasibility Study.

50 While the district heating solution also presents a similar up-front cost barrier to other GSHP solutions, this might be mitigated to the extent the distribution utility is authorized to finance, build and operate the system as a part of its business model, including it in rate base. In Massachusetts, the state regulator is considering some pending utility-sponsored geothermal proposals. See https://www.wbur.org/earthwhile/2020/01/13/heat-eversource-geothermal-energy-climate-change.

boilers for heating and a combination of chillers and cooling towers for cooling. In these larger buildings, heating is relatively less important and cooling more important than in smaller buildings because of the lower surface area to volume ratio, and the often large density of incidental heat sources within the building (lights, computers, people). Internal heat (and cooling) distribution systems are mostly hydronic, in contrast with the large share of air-based (forced hot air, central A/C) systems in typical residential settings. Although this report does not explore this in great detail, the decarbonized solutions described above can work in buildings that have very different heating loads, different uses and different building-level heat distribution systems, though the particular details of how they are applied will differ from building to building.

Second, different buildings are likely to require different solutions in part because of the considerable diversity of existing buildings. The idiosyncratic features of a given building or site can affect which decarbonization solutions may be feasible or reasonable. Such features can include whether and how well they are insulated, and the ability to add insulation, interior ductwork or hydronic distribution; whether a given building has access to the gas distribution network; or whether the geology is appropriate for a ground loop for a GSHP – indeed even whether there is enough space in an urban area to install a ground loop.

Third, while it seems likely that electricity will play an increasing role in any decarbonized future (for transportation as well as heat), the same is less clear for gas and the gas distribution system. If many existing gas customers adopt electric alternatives for part or all of their heat needs, the throughput on existing gas distribution systems will decline, perhaps significantly. Even if the carbon intensity of the gas flowing through these pipes can be reduced – e.g., by blending with increasing shares of renewable gas – the reduced throughput will concentrate the (essentially fixed) costs of the gas distribution system more heavily onto each remaining unit of gas. Increasing distribution rates, particularly if combined with higher costs for the decarbonized gas itself, could cause a substantial increase in delivered gas prices for local utility customers. This raises some important issues. For example, low- and moderate-income customers may have limited ability to switch from gas, due to the high initial cost of electrified heat pumps, and because they are more likely to be renters unable to control the heat source in their homes. Absent some way to counteract this, they could bear the brunt of gas cost increases. More generally, it raises questions about whether and how the gas system may need to be reconfigured. This might include reducing or eliminating service in residential areas where heating electrification is widespread, raising the question of how to "unwind" part of the network in an orderly way, and particularly how to protect vulnerable populations in the process, all while maintaining the economic health of the gas utility, so that it can ensure safe and reliable service to those customers who continue to rely on gas. And it could include maintaining or even expanding the gas system in areas like industrial zones where there are few viable alternatives to burning fuel. The potential future of the gas distribution system has thus become an increasingly important topic for a decarbonized future.[51] In Rhode Island, however, one utility provides both electric and gas distribution services. It may be possible to address or mitigate this effect by regulating the utility as an "energy delivery company," instead of treating the entity as separate gas and electricity businesses for ratemaking purposes.

Finally, the attractiveness of any of the above solutions

51 For example the California Public Utility Commission (CPUC) has initiated a regulatory proceeding that requires advance planning to explore various potential future paths for natural gas infrastructure. (CPUC, Order Instituting Rulemaking to Establish Policies, Processes, and Rules to Ensure Safe and Reliable Gas Systems in California and perform Long-Term Gas System Planning, Proceeding R2001007, issued January 27, 2020)

may depend on "systemic" effects. As an example, the price of electricity may depend on how widespread ASHPs are adopted. ASHPs increase the "peakiness" of electricity demand, which increases the cost of electricity and in turn impacts the economic attractiveness of ASHPs (as well as affecting the cost of other electricity uses). The best strategy may also depend on a number of practical implementation issues: How much cost-effective weatherization can actually be achieved by 2050? How many homes can realistically be converted to heat pumps by 2050, given the need for specialized labor to perform the installations and the current tightness of this labor force? How do geological and other local conditions affect the feasibility and cost of GSHP? How much renewable oil supply is available, and how does this compare with potential demand, accounting for the fact that Rhode Island may not be the only state relying on renewable fuels as a part of their decarbonization strategy? For these reasons, a wide range of cost and implementation issues must be considered when developing a heating transformation strategy for Rhode Island.

Methodology

This section describes the methodology used to analyze various heating decarbonization pathways for Rhode Island at a summary level. A more detailed description of the methodology, including modeling and assumptions, is included in the **Technical Support Document**.

Research Questions

1. **Understand the relative economic attractiveness of the decarbonized heat solutions identified, as applied to the primary heating applications in Rhode Island.**
2. **Understand how decarbonizing may affect related energy sectors that provide the energy for heating (i.e., renewable fuel and clean electricity), and how these feedback effects impact the costs to consumers, for heating and for overall energy consumption.**
3. **Identify the implications of these analyses that can be used to guide policies for heating sector transformation.**

HEATING NEEDS AND DECARBONIZATION SOLUTIONS

To understand the attractiveness and feasibility of various decarbonization pathways various heating situations were mapped to decarbonization solutions, as illustrated stylistically in **Figure 15**.

Figure 15 does not explicitly represent all building types, current fuels, applications or decarbonization solutions, though it does cover the vast majority of heating situations and decarbonization solutions for Rhode Island. Additional options such as the use of solar hot water heating or the use of wood heating may exist, though they will likely play only a relatively small and complementary role in transforming the Rhode Island heating sector.

Two sets of arrows (in different colors) in **Figure 15** provide two examples of "representative" heating situations, for which decarbonization solutions were identified as "applicable" and therefore analyzed for a specific building type/current fuel/application.

Preliminary analysis showed that a significantly smaller subset of "representative" heating situations can be used to analyze the attractiveness of heating decarbonization solutions across the full span of heating applications. This is because, ultimately, the feasibility and attractiveness of heating decarbonization depends heavily on a small number

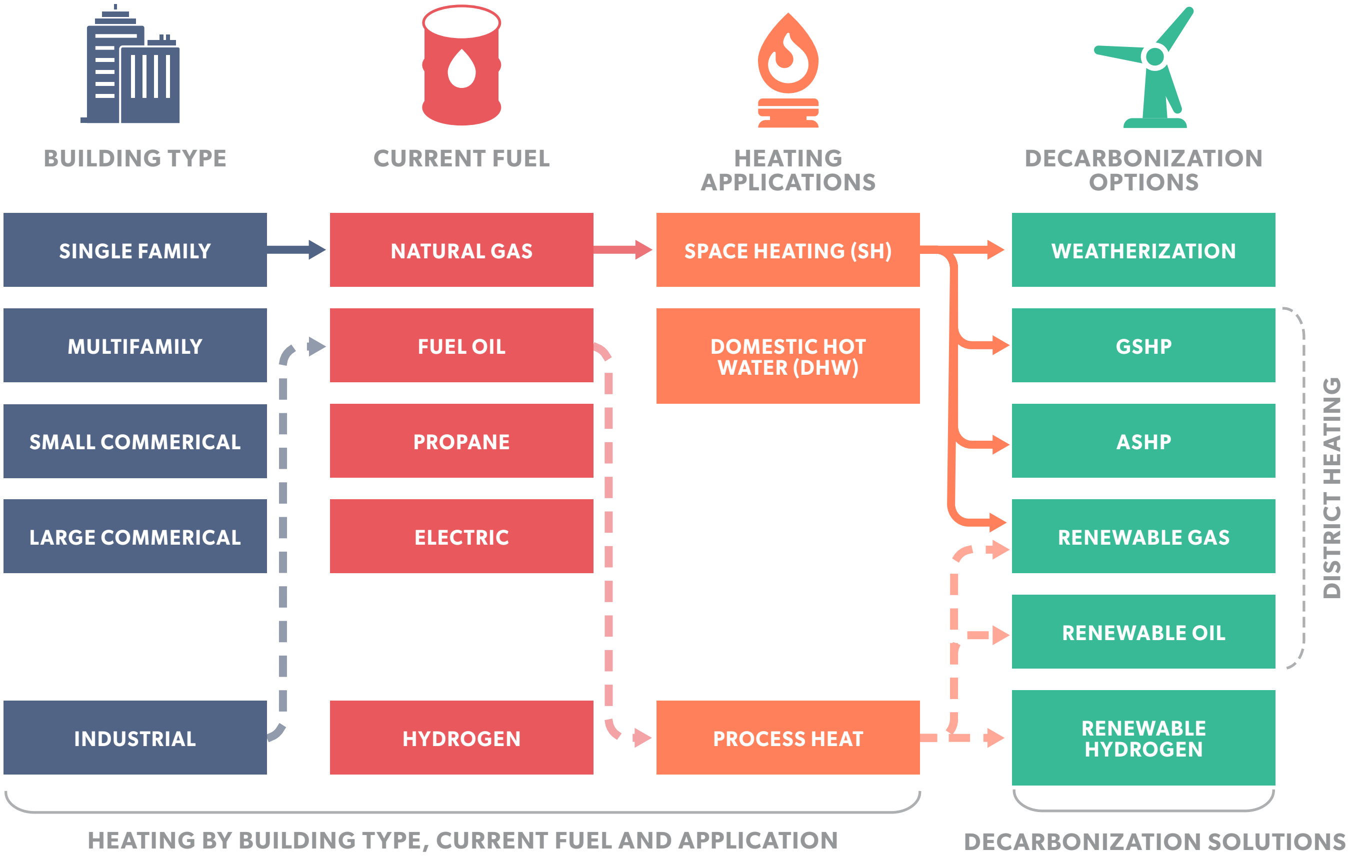


FIGURE 15: STRUCTURE OF HEATING TRANSFORMATION ANALYSIS

Note: Arrows indicate two situations. 1) A single-family home currently using natural gas for space heat could decarbonize using efficiency in combination with a heat pump or renewable gas (solid arrows). 2) An industrial facility currently using oil for process heat could decarbonize by substituting renewable oil, renewable gas, or renewable hydrogen (dashed arrows).

of factors. For space heating, the economics (and in some instances the feasibility) of various decarbonization solutions are primarily driven by the total heating demand for a given building, and the current heating system. Up to a certain size, residential (single- and multi-family) and commercial buildings tend to utilize the same types of fossil heating technologies, and can be transformed using similar decarbonization solutions. Current heating technologies in larger buildings differ from those used for smaller buildings; while this does not fundamentally alter the decarbonization solutions for such buildings, it may affect the cost tradeoffs among the decarbonized solutions. Similar relationships hold true for domestic water heating. Industrial heating represents a small share of the overall Rhode Island heating demand and is highly specific to particular industrial applications, for which little detailed information is available. For this reason, industrial heating applications were treated separately and more qualitatively.

ECONOMIC MODEL OF DECARBONIZED HEAT

To explore the economics of heating decarbonization for "representative" residential/commercial heating situations, this study uses an economic model to estimate annualized heating costs. This model can be applied to both current fossil and future decarbonized alternatives. Annualized costs include both "fuel" costs (natural gas, oil, electricity) and equipment costs (furnace or boiler, heat pump, etc.), amortized over the expected life of each major equipment component. Doing this requires the use of a discount rate to enable comparing the initial up-front cost of equipment installation or replacement with a stream of future costs and benefits. When different heating options involve a very different split between upfront costs and ongoing operating costs, the discount rate can matter: a higher discount rate means that the up-front installation costs are more important relative to the costs and benefits that occur in the future; a lower discount rate means the opposite – that upfront costs matter less. Since the available heating decarbonization solutions do differ substantially in that regard – GSHPs, for example, have significantly higher installation costs than ASHPs, which are in turn more costly than traditional furnaces and boilers – this may be an important issue. The quantitative analysis uses a 3% (real) discount rate, reflecting a commonly used "social discount rate", such as is often used to determine the value of avoided greenhouse gas emissions.[52] However, there is evidence that individuals, when facing decisions about investments like energy efficiency that trade off upfront costs vs energy cost savings over time, choose as if they have a discount rate substantially higher than 3%. To reflect this, we also show "payback periods" for the tradeoffs between alternatives, to illustrate how various decarbonization solutions might be viewed by consumers and how adoption rates might be influenced by a longer or shorter payback period.

Given that the two primary pathways are the decarbonized electrification of heating and the decarbonization of "fuels," it is necessary to consider the impacts of electrifying heating on the electricity sector, which in turn impacts the cost of electricity, and the potential cost of renewable fuels.[53] Both will be major factors in the attractiveness of the respective pathways, particularly since widespread adoption of some of these technologies could impact the pricing of the respective fuel. To explore the issue of feedback between decarbonizing heat and the availability and costs of electricity and/or decarbonized fuels, several "Bookend Scenarios", in which each technology option is evaluated in a context where essentially all the heat in the region being provided by that technology are developed.[54] These investigations generate several important insights in their own right, which are discussed below in Sections III.C and III.D. **Figure 16** illustrates the analytical modeling structure used to develop quantitative comparisons between various heating decarbonization solutions, incorporating interactions with the electricity sector, and considering the availability and cost of renewable fuels. The primary focus of these analyses is space heating, which represents about 60% of total residential energy demand in Rhode Island; we also examined options to decarbonize domestic water heating (the second largest energy need, at 16%). In addition to these quantitative analyses, we performed a more qualitative analysis of considerations related to decarbonizing industrial heating.

Because projecting the costs of heating three decades into the future necessarily involves significant uncertainties, the model considers a range of potential future costs. There are also a number of non-quantifiable factors related to

52 There is no "correct" discount rate per se. There is a large literature discussing the use of a "social discount rate" to evaluate policy that takes into account various societal issues rather than just reflecting private decision making. In general, social discount rates are in the range of 2.5-7%, and some argue for a 0% discount rate (in real terms). For example, U.S. estimates of the social cost of carbon use discount rates of 2.5%, 3% and 5% (See Resources for the Future, Social Cost of Carbon 101, August 1, 2019). See also OMB Circular A-4, September 17, 2003, which includes an in-depth discussion of the rationale for using various discount rates.

53 We do not separately model the cost and availability of renewable oil, but instead rely on existing modeled prices of renewable oil.

54 The Bookend Scenarios are: all GSHP, all ASHP, and all Renewable Fuel (where customers retain the fuel type they currently use, but the fuel itself is replaced with a renewable version – fossil heating oil is replaced with Renewable Oil (B100) and fossil natural gas is replaced with Renewable Gas).

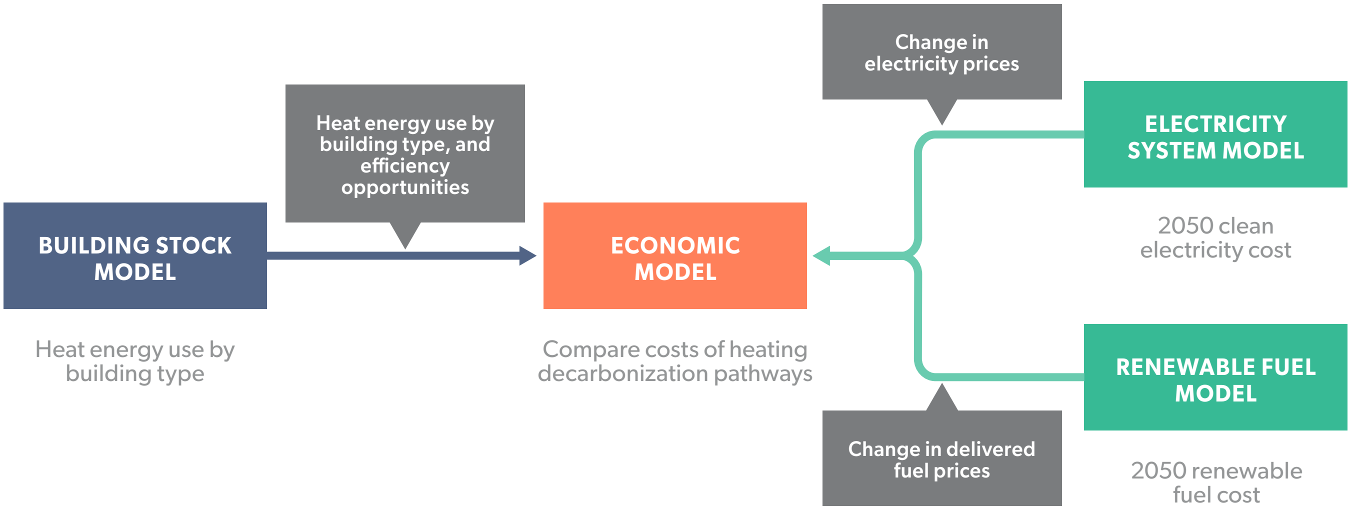


FIGURE 16: ANALYTICAL MODEL OVERVIEW

the heating decarbonization solutions, such as implementation barriers and other not easily quantified benefits and costs. These more qualitative factors are also considered as part of the overall assessment of the attractiveness of a given solution for a given building type. Before describing the financial model itself, the electricity and renewable fuels models are described next.

ELECTRICITY SYSTEM MODEL AND IMPACTS OF DECARBONIZED HEAT

Because heating in northern climates requires a large amount of energy, widespread decarbonized electrification of heating via heat pumps would have a substantial impact on the demand for electricity. The impact on the shape of electricity demand may even be greater, since heat needs are highly correlated across the region, peaking in the coldest weather. These impacts are evaluated using the Bookend Scenarios introduced above, in the context of a decarbonized electricity sector. Electrifying all heating in New England with either GSHP or ASHP would turn the current summer-peaking New England electric system into a strongly winter-peaking system, affecting supply needs and electricity prices. Although electric heating and cooling use essentially the same technology, the electricity needed to heat a building with a heat pump is much greater than the power required to cool it with an air conditioner, because the temperature differentials that must be maintained between outside and inside are much larger in winter (50-70˚F) than they are in summer (20-30˚F).

However, there is a distinct difference between air source and ground source heat pumps. Either technology must accommodate the fact that the demand for heat is much greater when outside temperature falls very low. But it is easier for a GSHP to provide the necessary amount of heat than it is for an ASHP. GSHPs draw heat from the ground, which is always about 50˚F, whereas the ASHPs draw heat from the outside air, which contains less heat energy at just those times when the demand for heat is greatest. This means that when it is very cold, ASHPs must use considerably more electricity to deliver the same amount of heat as GSHPs. That is, at very low temperatures, its efficiency is much lower.

The efficiency of a heat pump is measured by its "coefficient of performance" or CoP – the ratio of output heat energy to the amount of electric energy consumed. For a GSHP, this CoP is constant at about 3.6 regardless of outside temperature – i.e., for each kWh of electricity consumed, the GSHP delivers about 3.6 kWh of heat. But for ASHP, the CoP depends on the outside air temperature. At an outside temperature of 50˚F, an ASHP has a CoP very similar to a GSHP. But the CoP for an ASHP falls to about 1.0 when air temperature is around 0˚F. This means that when it is 0˚F outside, an ASHP will require about 3.6 times as much electricity as a GSHP to deliver the same amount of heat. Thus in the ASHP Bookend Scenario, the peak electricity demand from heating would be about 3.6 times what it is in the GSHP scenario. (Of course the overall system peak differs by less than 3.6x because of the other electric load that is similar in either case).

Figure 17 illustrates the projected impact of electrifying all New England heating via all ASHPs vs all GSHPs in 2050, when it is also assumed that transportation will be mostly electrified. As can be seen, the impact of electrifying heating on total energy consumption is modest: Demand increases 12%-15% relative to demand without heating electrification (but with transport electrification). With all GSHPs, peak demand increases by 17%, slightly more than the energy increase. But with all ASHPs, the increase in peak demand would be dramatic at 94%, almost twice the peak demand without electrified heating via ASHPs. As can be seen in the bottom panel of the figure, which ranks hourly demand from highest to lowest, this increase in peak is caused by a very small number of hours, precisely those when outside temperatures decline to levels, where the efficiency of ASHPs approaches 100% (and hence is equal to the efficiency of electric resistance heat; in fact, we assume that electric resistance will be used to supplement ASHPs to meet peak). The almost doubling of peak demand with an all ASHP system could result in materially higher electricity prices.[55] Because ASHPs require more electricity, and their disproportionate peak impact would increase electricity prices, widespread ASHP adoption could substantially raise the cost of electric heating.

Figure 18 displays estimates of the delivered electricity price in these future scenarios based on the projected cost of building a renewable power system that would serve each of these load profiles.[56] The current average delivered price for power in Rhode Island is 18¢/kWh. In a decarbonized 2050 system without electrified heat, electricity costs would be somewhat higher than today, at 22¢/kWh (in $2018). With all heating electrified via GSHP, the electricity price would essentially remain unchanged (21.8¢/kWh), but with ASHP, it would be considerably higher, at 24.6¢/kWh. This accounts for the higher cost of generation, since more peaking capacity would be necessary (in a decarbonized system, this would be a combination of storage such as batteries, and possibly conventional generators using renewable fuel). It also considers the additional costs for the transmission and distribution system, which must be sized to meet the system peak and is thus heavily affected by a higher system peak.

The estimated increase in retail costs for a fully decarbonized power supply able to meet electricity demand in each of the scenarios is relatively moderate, in the range of 10-35%. These estimates are of course uncertain, since the costs of many of the resources to supply 100% clean electricity are evolving rapidly, and the generation component of clean energy is projected to increase more sharply. But some of this increase will likely be offset by lower per-kWh transmission and distribution costs. Even though a considerable amount of new transmission

55 The modeling of electricity prices assumes some mitigating factors such as the use of batteries to shift demand away from the highest demand hours. Other mitigating options not modeled include the use of thermal storage, which is just emerging as a potential technology option for ASHPs. For more detail on electric sector modeling underlying these calculations, see the Technical Support Document.

56 A higher peak demand would affect the cost of both the generation of renewable electricity and the cost of the transmission and distribution system needed to reliably deliver electricity to consumers.

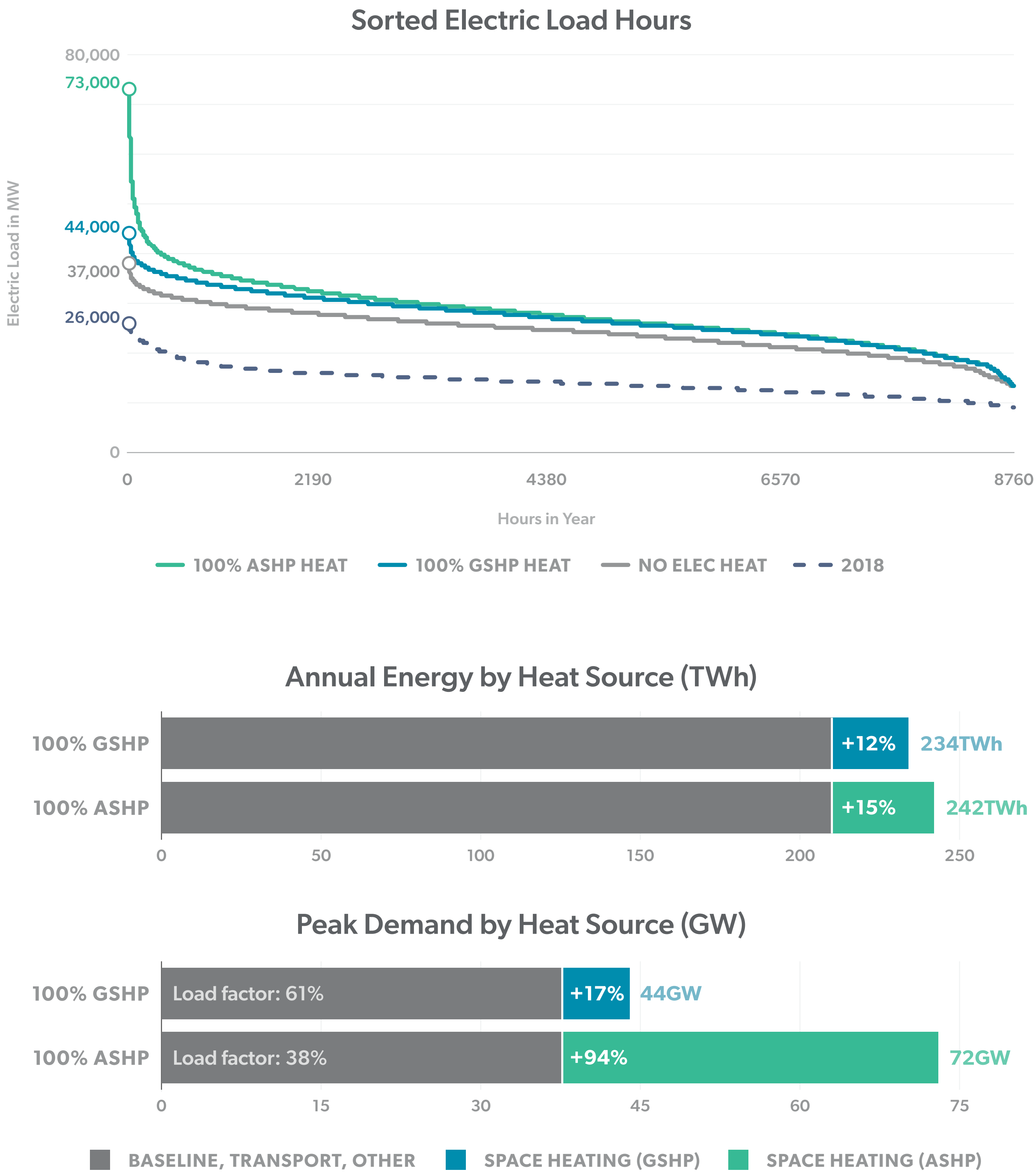


FIGURE 17: IMPACT OF ELECTRIFYING HEAT VIA ASHP VS GSHP – 2050

Note: The 2050 load characterization assumes that the transportation sector is mostly electrified, and also assumes continuing efficiency improvements in baseline uses of electricity (current uses).

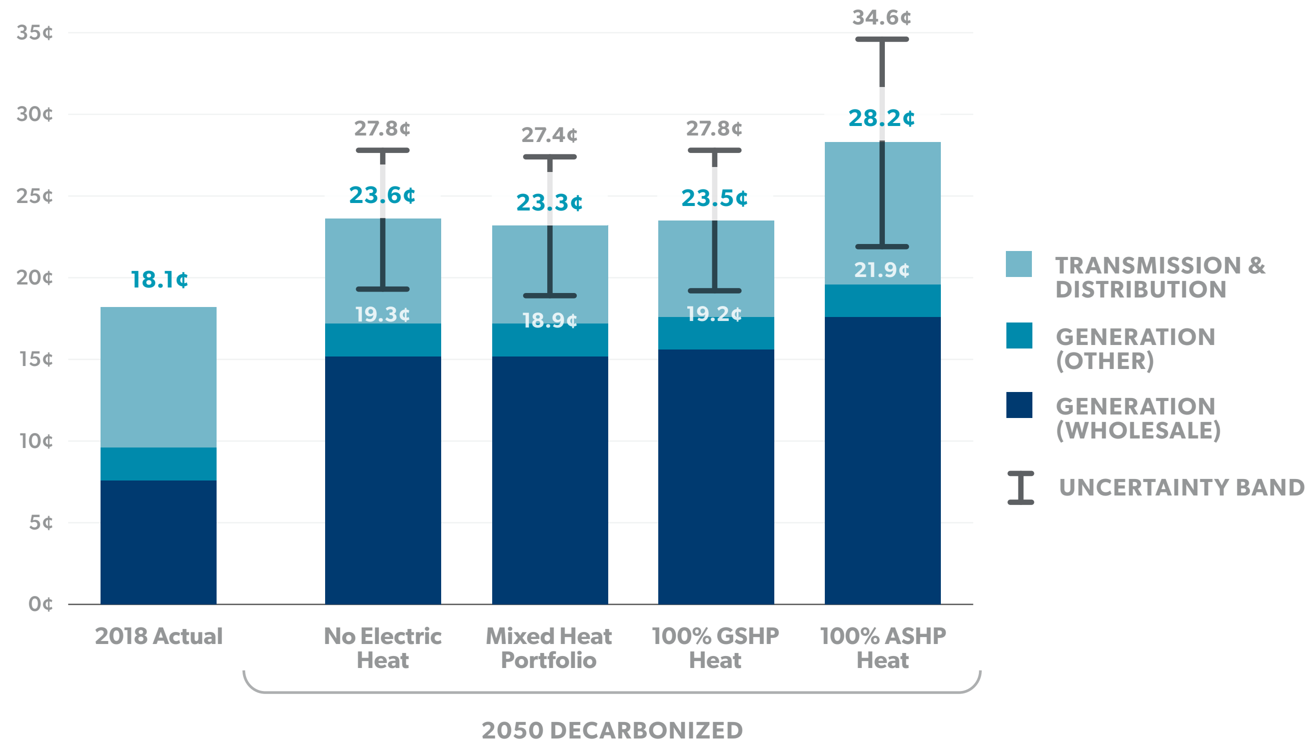


FIGURE 18: **RHODE ISLAND ELECTRICITY PRICE BY SCENARIO (cents/kWh, IN 2018$)**

Note: The 2050 Decarbonized estimates assume that transportation is largely electrified. Generation (Wholesale) represents the cost of an emissions-free electricity generation system, based on the electric sector model described in Technical Support Document. Generation (Other) reflects costs related to electricity supply beyond the supply resources themselves (administrative costs of the ISO and utility to manage electricity purchasing, etc.). The high and low electricity price estimates reflect a +20% (high) to -20% (low) change in the generation component. T&D costs reflect the cost of the transmission and distribution system, with required T&D expansions to meet increased load evaluated at National Grid's approximate embedded T&D cost of $291/kW-year (high case), at National Grid's Avoided Energy Supply Components value of $83.26/kW-year (low case), and at the mid-point of the two ($187/kW-year) for the nominal estimate.

and distribution infrastructure will be needed in a decarbonized and largely electrified future, and total T&D costs will be higher (especially in the 100% ASHP Heat Scenario), the total volumes of power delivered, including for EV charging as well as electrified heat, are likely to increase by even more, lowering the unit T&D cost. Much of this effect is due to EV charging, which provides significant year-round demand with a somewhat complementary daily load shape relative to other electricity demands, thus increasing the utilization of the existing T&D infrastructure. In addition, the T&D system can accommodate 20-25% more power in winter than in summer, meaning that the winter peak caused by electrified heat will require substantially less T&D expansion than would a summer peak.

RENEWABLE FUELS MODEL

The second basic pathway for decarbonizing heating is to substitute renewable fuels, such as renewable oil or renewable gas, for the current fossil oil and natural gas used in the vast majority of cases. A major advantage of this pathway is that renewable fuels generally require little or no changes to existing infrastructure and equipment, either at the customer site or in the delivery system.[57] As discussed above, there are a number of

57 As discussed above, renewable hydrogen, if used beyond low concentrations, would likely require upgrades to many components of the gas infrastructure.

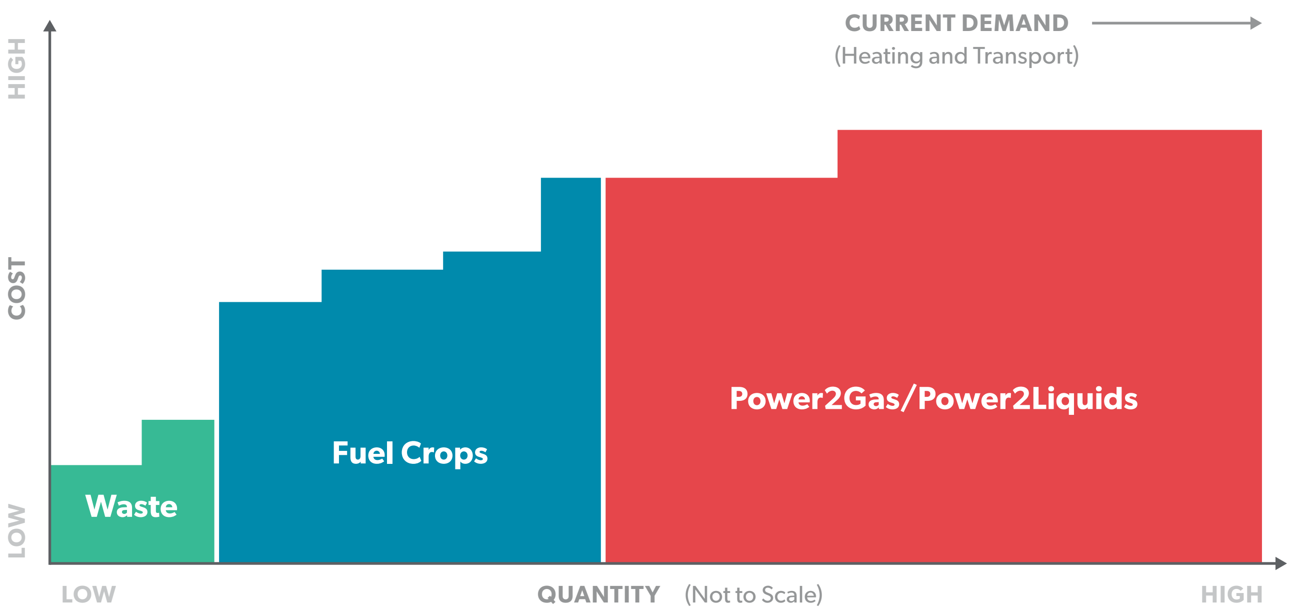


FIGURE 19: SOURCES OF RENEWABLE FUELS

potential sources for both renewable oil and renewable gas, though one of the challenges may be the limited quantities available from less costly sources.

1. Taxonomy of Renewable Fuels

The sources for renewable fuels can be thought of in three categories: waste biofuels, fuel crops, and power-to-fuel technologies, as illustrated in Figure 19.[58] Potential waste sources include used cooking oil for biodiesel, and landfill gas or waste biomass (e.g., food waste, animal manure or wastewater via anaerobic digesters) for natural gas. Some woody biomass may be available as byproducts of agriculture or forestry processes, which can be gasified or perhaps converted to methanol. These are often among the least costly sources for renewable fuels, but because their source is the waste or byproduct of some other process, the quantities available are limited, and in fact are small compared to current demand for natural gas and heating oil.

The second category is fuel crops – biomass that is grown and harvested specifically for fuel. This includes oil crops (rapeseed, soy, palm), other crops such as switchgrass or sugarcane that can be used to produce ethanol or methanol, and many types of biomass which can be gasified. These types of sources are already in use on a relatively small scale, but if they were to be scaled up to produce the quantities necessary for widespread use as heating fuel, the amount of land and resources they would require could put major stresses on agriculture and the environment. In part because of this, the cost of renewable fuels produced from fuel crops will generally be higher than those produced from waste biomass. Also, both the available quantity and the net greenhouse gas emissions impact of fuel crops remain uncertain.[59]

58 There may be some hybrids among these categories, such as combining waste or agricultural feed stocks with P2Fuel technology as a way to facilitate the production of other fuel types.

59 There is a very active debate about the impact of fuel crops on land use and greenhouse gas emissions. Apart from the question of land availability to meet high levels of renewable fuel demand from fuel crops, net greenhouse gas emission reductions are also uncertain, given that fuel crops would likely result in direct or indirect land use changes involving conversion of land areas that are carbon sinks into fuel crop land that would at best be carbon neutral. For a discussion of the literature on this issue see https://farm-energy.extension.org/indirect-land-use-impacts-of-biofuels/.

The third category includes the Power2Fuels technologies introduced above, in which fuels are synthesized using renewable electricity to create hydrogen, are further converted via what is called methanation to methane, and possibly using additional chemical processes to turn methane into liquid fuels. In principle, P2Fuels processes (illustrated in Figures 11 and 12 above), should be scalable to very high volumes, limited only by the availability of renewable electricity and the capital equipment required. There have even been suggestions that P2Fuels pathways might complement a high-renewable power system, taking advantage of cheap or free renewable electricity at times it would otherwise be curtailed; this might lead to relatively inexpensive renewable fuels since the cost of input electricity is a substantial component of their cost.[60] It is unlikely, however, that sufficient surplus renewable electricity would be available if P2Fuels production were implemented at a large scale. Demand for renewable electricity for P2Fuels production would consume otherwise curtailed renewable power in most hours, raising the price until it is consistent with the prevailing power price at other times or the economics of P2Fuels production at higher prices are no longer attractive. Also, the equipment needed to produce P2Fuels – electrolyzers, methanizers and, potentially, CO_2 air capture devices - is costly, so it would not be cost-effective to operate only in the relatively infrequent times when electricity remains very cheap or free. In addition, operational constraints may prevent the kind of flexible operation that may be required to take advantage of periods of excess renewable power generation. Therefore, if deployed at large scale, the electricity used as an input to P2Fuels production will likely be priced at or near the average cost of producing renewable power (which includes their capital costs).

Finally, depending on where P2Fuels processes take place – in theory, electrolysis, methanation and CO_2 capture could occur in different places, but there are also likely synergies for co-location – the manufacturers of renewable fuels would incur delivery charges for the electricity used in the process.

2. Markets for Renewable Fuels

Since renewable fuels that can be used for heating can also be used in other sectors, including transportation and industry, and are easily transportable, the market for renewable heating fuels, like current markets for fossil fuels, will not be local or limited to the heating sector. This will cause prices to tend to equilibrate across sectors and regions.[61] This means that the prices of renewable fuels will be set by market forces working across a geographic region much larger than Rhode Island and economic sectors well beyond heating fuel. It also means that, as with all goods, competitive economic forces will ensure that the least costly production sources will be utilized first and that the last, most costly source needed to meet a given level of demand – across sectors and geographies – will set the price at that level of demand.

Thus, the market for renewable fuels will likely be national or international in scope. Sources of waste biofuels are widespread across the country, but not concentrated in the Northeast and, in aggregate, can supply only a small share of current fuel uses.

3. Supply Curve for Renewable Fuels

For all of these reasons, and because P2Fuels processes are still in their infancy, the availability and the costs of renewable fuels – both liquids and gas

60 For a discussion of the use of surplus renewable energy to make hydrogen or renewable gas to use in power generation, see for example https://physicsworld.com/a/oversizing-renewables-to-avoid-shortfalls/ or https://www.windpowermonthly.com/article/1578773/green-hydrogen-economically-viable-2035-researchers-claim.

61 Fossil prices differ across regions in the United States, in part because of how close fuel production is to fuel consumption, but also due to different fuel standards resulting in different production processes. One would expect some price differences for renewable fuels to occur as well, even though price differences would be limited by the opportunity to sell such fuels into higher priced destination markets.

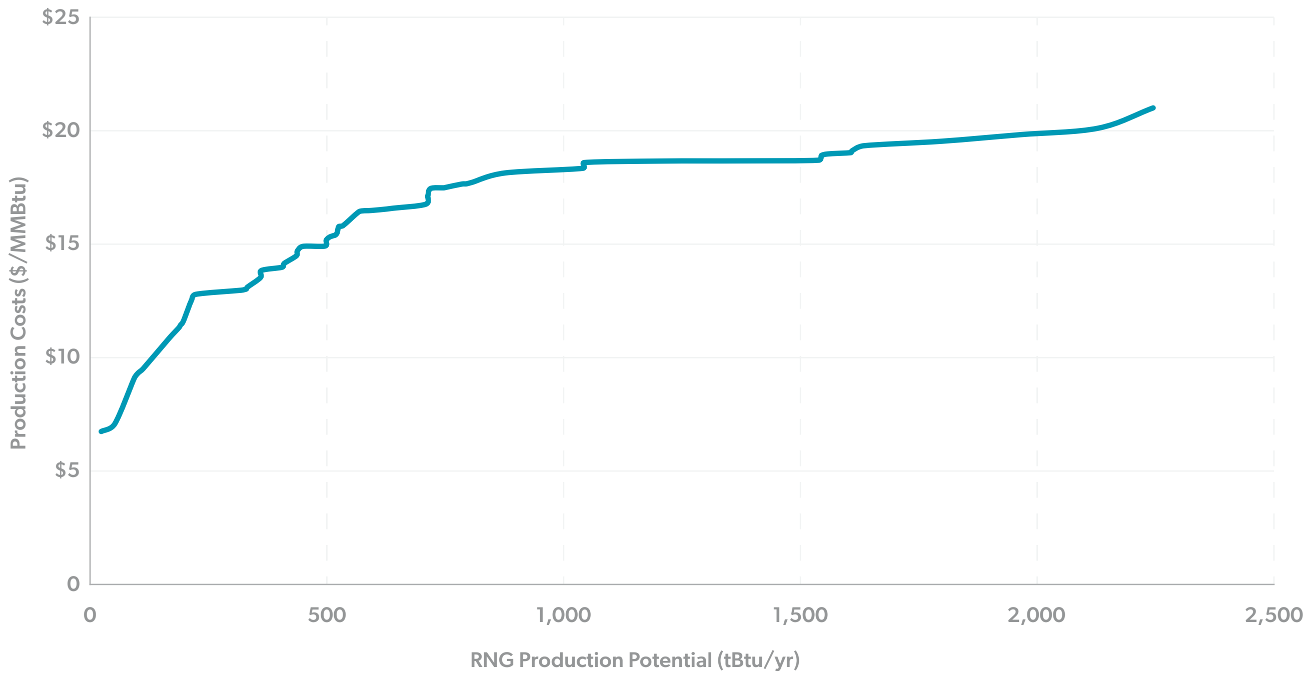


FIGURE 20: AMERICAN GAS FOUNDATION U.S. SUPPLY CURVE FOR RENEWABLE GAS (HIGH RESOURCE POTENTIAL SCENARIO)

Source: Reproduction of Figure 34, Combined RNG Supply-Cost Curve (based on high resource potential scenario), less than $20/MMBtu in 2040, American Gas Foundation, Renewable Sources of Natural Gas: Supply and Emissions Reductions Assessment, December 2019.

– in the near term and through 2050 remain highly uncertain. It is likely that only limited quantities will be available at relatively low costs.

For renewable gas, a recent report by the American Gas Foundation estimated the supply of renewable gas available at a cost below $20/MMBtu – which is roughly eight times the current price of natural gas. **Figure 20** reproduces this modeled supply, which reflects the AGF's High Resource Potential Scenario.

As **Figure 20** shows, the analysis by the American Gas Foundation concludes that in its high resource potential scenario, approximately two trillion Btu per year could be produced at a cost of $20/MMBtu or less. The total technical potential to produce renewable gas in that scenario is 4.5 trillion Btu per year, roughly equal to total average annual residential natural gas demand between 2009 and 2018, but only about 25% of total average annual natural gas consumption across all sectors combined.[62] Consequently, especially given that demand for renewable gas would likely not be limited to the residential sector, the price of renewable gas will likely be set by the cost of Power2Gas technology. This cost is estimated using a bottom-up model of the manufacturing cost of renewable gas via Power2Gas, as explained in greater detail in the **Technical Support Document**. Using a variety of sensitivities, it results in an estimated cost of renewable gas via Power2Gas of $30/MMBtu by 2050, with a range between $10/MMBtu and $47/MMBtu. This range is in line with the estimated range of costs for renewable gas derived from various biomass feed stocks, as well as other studies estimating the cost of renewable gas, as illustrated in **Figure 21**.

The analysis of renewable oil is informed by the Power2Gas model, by currently observed costs for biodiesel (B100) in New England and the United

62 See American Gas Foundation, Renewable Sources of Natural Gas: Supply and Emission Reduction Assessment Study, 2 page summary.

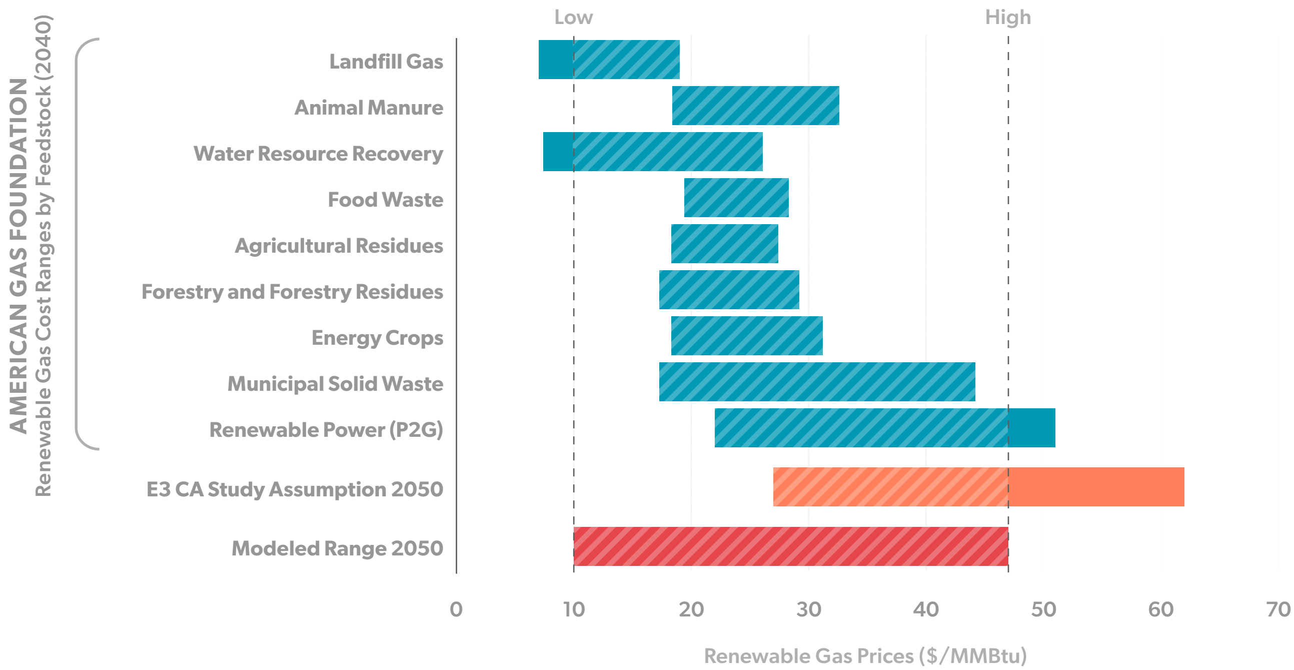


FIGURE 21: ALTERNATIVE COST ESTIMATES OF RENEWABLE GAS

Source: American Gas Foundation, Renewable Sources of Natural Gas, December 2019, E3. Draft Results: Future of Natural Gas Distribution in California, June 6, 2019.

States, as well as by other studies estimating the cost of renewable fuel using Power2Liquids technology, to estimate the potential range of renewable oil cost in 2050. As with renewable gas, limited supply potential from inexpensive sources means the 2050 price of renewable oil is likely to be set by the cost of Power2Fuels technologies, which again here is subject to considerable uncertainties.

At present, the New England B100 price of $2.75/gallon is actually $0.39/gallon lower than the price of diesel, though nationally, B100 is consistently about $0.3-0.8/gallon more costly than diesel.[63] Current biodiesel prices are linked to regular diesel (and underlying world oil) prices and, therefore, provide limited insight into the long-term production cost of renewable oil.[64] But current sources of biodiesel (largely vegetable oils and waste cooking oil) are unlikely to be able to provide the volumes necessary to utilize it widely as a heating fuel, forcing the market to turn to other, more costly sources such as Power2Liquids. This is particularly true considering that biofuels can also be used in the transport sector, which represents an extremely large and relatively price-insensitive potential demand for decarbonized liquid fuels. The cost (per barrel) of P2L has been estimated to be approximately 3.3 times the average cost of the electricity source used to make it.[65] Using a cost of $60/MWh (e.g., low-cost offshore wind power plus transmission costs) would result in a cost of approximately $200/barrel, or roughly $5/

63 U.S. Department of Energy, Clean Cities Alternative Fuel Price Report, January 2020, p.21, which shows diesel and B100 prices between 2011 and January 2020.

64 In addition, biodiesel and other advanced fuels benefit from a number of financial support mechanisms. Biodiesel currently receives an investment tax credit of $1/gallon; several other incentive programs are summarized at https://afdc.energy.gov/fuels/laws/BIOD?state=US.

65 See http://euanmearns.com/lcoe-and-the-cost-of-synthetic-jet-fuel/

gallon.[66] This would represent a little bit less than a doubling of the cost of B100 relative to current diesel prices in Rhode Island.

Since Power2Liquids technology generally converts renewable gas into liquid fuel using an additional production step, it is likely that, per unit of energy, the cost of renewable oil will be slightly higher than renewable gas. This $5/gallon estimated renewable oil cost corresponds to $36/MMBtu,[67] slightly higher than the $30/MMBtu estimated cost for renewable gas. While both renewable gas and renewable oil are materially more expensive than their fossil counterparts, the proportional increase is much larger for gas. The long run cost of renewable oil is likely to be 15%-160% above the current cost of fossil oil, but the long-run cost of renewable gas may be 40%-300% greater than the current fossil gas cost. This is because, on an energy basis, natural gas is currently much cheaper than heating oil. This could have implications for the relative attractiveness in the long run of renewable oil vs renewable gas. If their prices are similar, liquid fuels can have some advantages over gaseous fuels – they are easier to handle, store and deliver, and do not require a costly, long-lived and dedicated delivery infrastructure.

66 Other bottom-up modeled costs are similar. For example, Fasihi et al. estimate the cost of P2G diesel at $160.85 USD/barrel. They also observe that the ratio of diesel to crude oil prices is approximately 1.14, which means that to compare biodiesel to regular diesel prices via the price of oil requires an additional adjustment. See Fasihi et al, Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants, Energy Procedia 99 (2016) 243 – 268, p.255

67 Based on an assumed energy content of heating fuel of 139,000 Btu/gallon. See https://www.engineeringtoolbox.com/energy-content-d_868.html

Analysis of Decarbonized Heating Pathways for Rhode Island

Section IV considers the economic and other factors that may affect the choice of the preferred heating transformation pathway(s) for Rhode Island in terms of the decarbonized heating solutions identified above. Section IV compares the economics of the decarbonized alternatives for a representative residential home, assuming for each technology that the corresponding Bookend Scenario prevails. For example, the cost of heating with an ASHP is evaluated based on the electricity system and power prices that would prevail if all of New England relied on ASHPs for heat. This would cause an extreme electric load peak at the coldest times in winter, and the electric system resources required to meet this peak would result in higher electricity prices than in the other Bookend Scenarios. Similarly, the cost of heating with decarbonized fuels is evaluated based on renewable fuel prices that are consistent with all heating in the region relying on decarbonized fuels. That implies that demand for decarbonized fuels would be high, and so the price must be high enough to bring forth this amount of supply. In addition to considering a "mid-range" cost estimate for each of the alternatives, an uncertainty range around this estimate is built up from uncertainties on both up-front costs and ongoing operational costs. At the end of this section, the scope of the analysis is broadened to consider the impact of decarbonizing the other major energy sectors – current electricity consumption and electrified transportation – in combination with decarbonizing heat (using the same Bookend Scenarios) and the resulting cost implications for consumers' overall "energy wallet" relative to today's costs.

ECONOMIC MODEL RESULTS – SINGLE-FAMILY HOME

Applying the methodology outlined above allows for a comparison of the future economics of the various heating decarbonization solutions. In this section, the results of this analysis are presented for a representative existing single family home from three different perspectives:

- The first perspective presents several Bookend Scenarios, i.e., the analysis assumes that either consumers maintain their current heating fuel and hence volumes of delivered gas and oil remain constant (in the cases examining the economics of renewable oil and renewable gas), or it assumes that all consumers adopt either GSHPs or all ASHPs (with corresponding impacts on electricity prices). These Bookend Scenarios highlight the feedback effects on individual consumers under relatively extreme assumptions about the adoption rates of individual decarbonization solutions. In reality, these Bookend Scenarios are unlikely for a number of reasons, including that the relative cost and attractiveness of decarbonization solutions will likely vary significantly

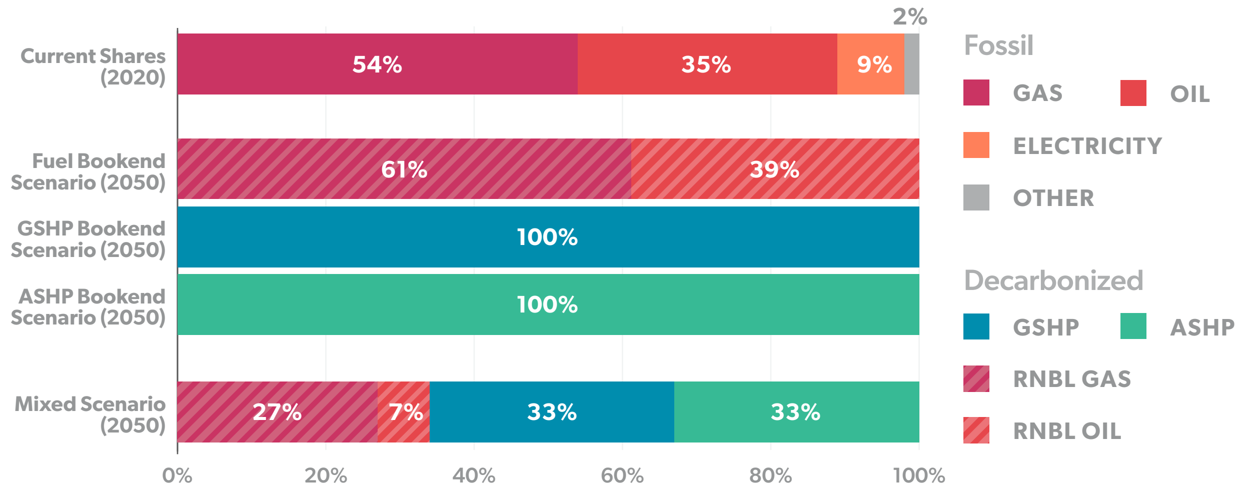


FIGURE 22: HEATING SHARES BY FUEL (NUMBER OF BUILDINGS) CURRENT SHARES VS MIXED SCENARIO (2050)

by building-specific conditions and because of different consumer preferences and other qualitative factors discussed below.

- The second perspective examines the economics of the various decarbonization solutions from a consumer's perspective, assuming an illustrative "mixed" adoption pattern (recognizing that the relative shares of each of the available decarbonization solutions in the future remains highly uncertain).
- Finally, a third perspective uses the mixed adoption scenario to assess how the economics of various decarbonization solutions affect an individual consumer's overall "energy wallet" that compares current costs with potential future costs with each of the decarbonized heat solutions, in the context of a fully decarbonized economy. The energy wallet perspective is instructive since statewide and regional adoption rates of various decarbonized heating solutions will have impacts in particular on electricity prices, which in turn impact other energy related spending, including in the short run current electricity bills and in the longer run likely also spending on transportation assuming personal transportation is decarbonized via a switch to electric vehicles.

Figure 22 illustrates the shares of each heating solution that exist now, in the three Bookend Scenarios, and in the Mixed Scenario.

1. Bookend Scenarios

Figure 23 compares the annualized cost of residential space heating solutions, both fossil and decarbonized, under these Bookend Scenarios for a representative Rhode Island single family home, using projected costs for the year 2050 for alternative heating systems that provide the home's entire heating needs, not just a partial or supplemental system. The traditional carbon-emitting options of fossil natural gas, oil or propane are on the left using projected 2050 costs, and on the right are the decarbonized options of renewable gas, renewable oil or decarbonized electrification with ground-source or air-source heat pumps (or electric resistance).[68] The analysis assumes an annual

68 As noted above, the analysis of renewable gas here provides a good proxy for a renewable hydrogen solution, since the projected cost of renewable hydrogen is generally within the range considered for renewable gas costs (perhaps toward the lower end, since producing hydrogen with P2G can avoid the methanation step). Such a solution might involve either blending hydrogen with renewable gas, or using it as a standalone heating fuel, though in the latter case, the renewable gas analysis does not account for upgrades to the gas delivery infrastructure that may be necessary to accommodate hydrogen.

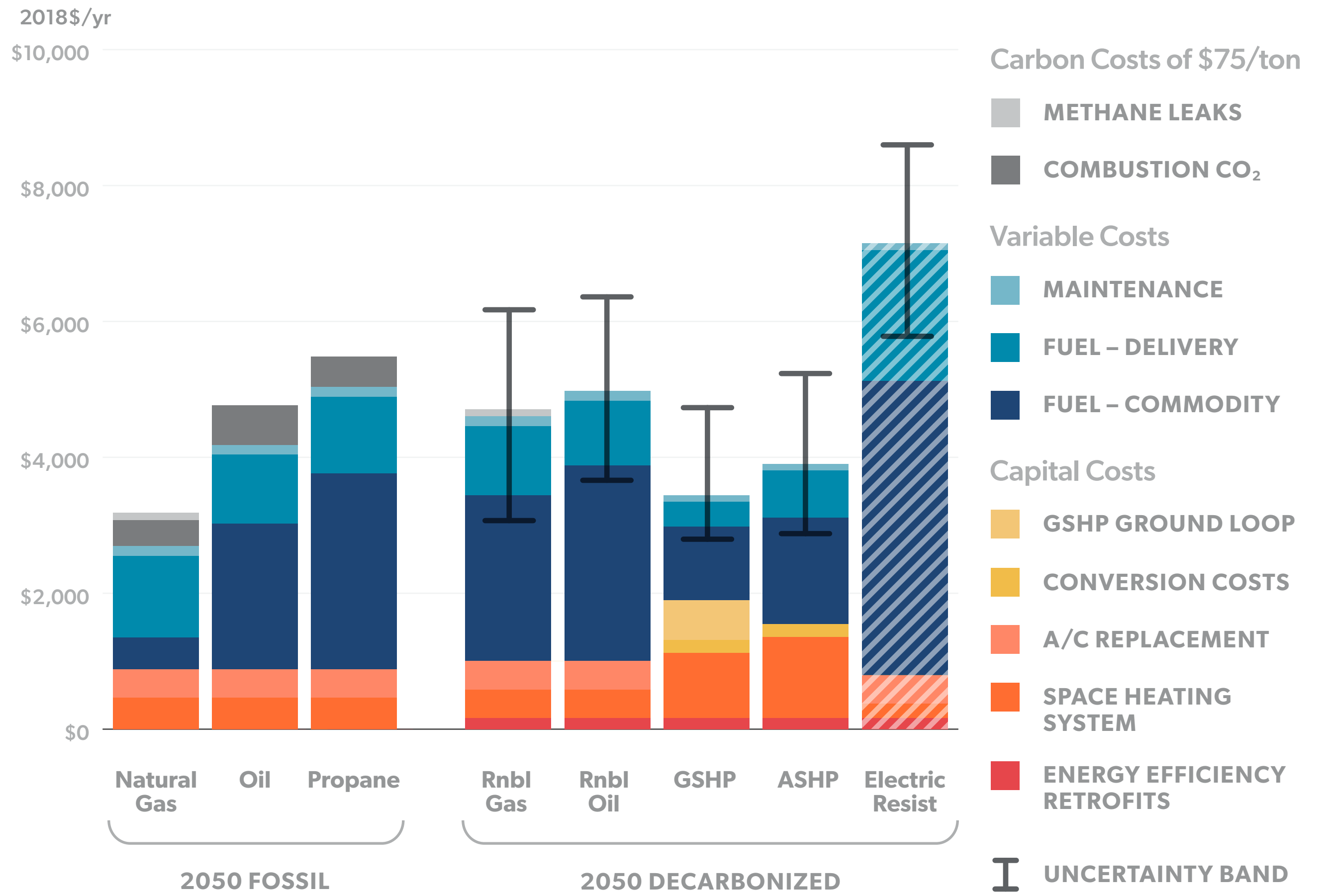


FIGURE 23: ANNUALIZED COST OF SPACE HEATING, SINGLE-FAMILY HOME IN 2050 BOOKEND SCENARIOS (2018$)

Notes: Discounting at 3% to reflect social discount rate. Carbon price $75/ton. Heater capacities: 7.5 ton furnace or boiler with energy efficiency and 9 ton furnace or boiler without energy efficiency (sized to meet two times peak demand), 5.0 ton heat pumps (sized so that the system meets at least 120% of peak demand, with ASHP using supplemental electric resistance heating capacity).* Efficiencies: 93% for gas-fired furnaces, 84% for oil-fired furnace/boiler, 360% for GSHPs, 285% (weighted average based on temperature and load) for ASHPs, and 100% for electric resistance. Prices: natural gas $17.43/MMBtu, oil $4.14/gal, propane $3.83/gal, renewable oil $5.33/gal, renewable gas $42.57/MMBtu; electricity price 23 cents/kWh (GSHP), 28 cents/kWh (ASHP and electric resistance). Additional inputs and data sources can be found in the Technical Support Document. The modeled heat pump size differs from typically installed heat pumps today as it is sized to meet all heat requirements except on the most extreme days. Design capacity is slightly above the 100-115% size design suggestion by NEEP (See NEEP, Guide To Sizing & Selecting Air-Source Heat Pumps in Cold Climates rev. 12/7/18, p.5 (Full System Replacement)

heat demand of 76 MMBtu per year, which is 15% below the current average of 89 MMBtu per year for single-family homes in Rhode Island, reflecting cost-effective building efficiency improvements assumed to be implemented for essentially all homes by 2050. The "representative" home modeled is not an actual home, but rather represents a home with the average annual heating energy demand in the state (calculated by dividing total heating energy consumption by the total number of single family homes). Still, given the Rhode Island housing stock, a "representative" home would be at least several decades old with 1,500 to 2,000 square feet of livable space. The impact of cost-effective energy efficiency measures is based on the range of reported impacts of weatherization programs – expressed in percentage improvements over existing heating demand – from weatherization programs in New England. The precise amount of heat needed for any particular home will have little impact on the relative costs of the alternatives, and the broad conclusions from this analysis apply across a wide range of building sizes and heat needs.

Figure 23 includes a breakdown of the annualized cost into operating costs (in shades of blue) and annualized capital costs (in shades of orange). Operating costs are mostly the cost of "fuel" – fossil natural gas, oil or propane for the carbon-emitting options, versus renewable gas, renewable oil or electricity for heat pumps for the decarbonized options. The fuel costs are split roughly according to the cost of the commodity itself (lighter blue) vs the cost of delivering that commodity to the building (darker blue). The annualized capital cost of the heating technologies (which includes installation cost) is shown in shades of orange. Furnaces or boilers must be replaced periodically, but the cost is modest since the equipment and installation are reasonably simple and modifications to the home are not necessary. For heat pumps, the capital cost is larger because the heat pump equipment and installation can be more costly, and may also require additional components – a ground loop for GSHP, and additional costs for adapting the existing building to a different way of providing heat (e.g., ductwork, electrical upgrades).[69] The capital cost comparison also includes the cost of replacing a central air conditioning system if a furnace or boiler is used; that cost can be avoided with a heat pump, which also provides cooling.

To allow for a better comparison of fossil with decarbonized heating options, **Figure 23** also includes an assumed cost of carbon emissions. Including such a cost is important since it reflects actual costs to society of continued carbon emissions. In addition, it is likely that by 2050 (and earlier), fossil fuel prices faced by consumers will reflect these costs, for example in the form of a carbon tax or fee, cap and trade program, or other mechanism. The analysis uses a cost of $75/metric ton, in line with current benefit-cost analyses performed by the state.[70] This cost is applied to the net GHGs from the combustion of fuel (assumed to be zero for the renewable fuel options, which implies that the fuel is carbon neutral),[71] and also the GHG contribution of methane leaks (at the current leak rate).[72] Renewable gas includes the leak component as well, since even if the source gas itself is carbon-neutral, methane leaks still create GHG

69 The idiosyncrasies of individual buildings may have a substantial impact on the relative economics on a case-by-case basis. E.g., some particular building may find it much more costly to convert to a heat pump due to the need for extensive ductwork and a major electrical system upgrade; a different building may not face such costs at all. Recognizing these possibilities, and acknowledging that it is very difficult to obtain representative costs for such retrofit requirements due to the wide diversity of circumstances in individual buildings, the economic analysis assumed that replacing a fossil heating system with a heat pump would require about $5,000 in upgrades (e.g., ductwork and electrical) to enable the transition.

70 A carbon value of $75/metric ton ($68/short ton) is used currently as the avoided carbon value in evaluating Rhode Island's energy efficiency programs. Synapse Energy Economics, "Avoided Energy Supply Components in New England: 2018 Report", prepared for AESC 2018 Study Group, originally released March 30, 2018 (amended October 24, 2018), available at: http://rieermc.ri.gov/wp-content/uploads/2019/04/aesc-2018-17-080-oct-rerelease.pdf. For purposes of this analysis, the same value is used for 2050 comparisons even though, as described above, the value of avoided carbon emissions is likely to increase as reflected in rising values of the social cost of carbon over time.

71 As described above, most renewable fuels using biological feed stocks are currently not carbon-neutral. The long-term potential to achieve (near) zero net carbon emissions depends on both the feedstock itself and the conversion process. For example, overall carbon intensity can be very significantly reduced if transportation and process energy used in the production of biofuels is itself carbon-free (such as renewable electricity).

72 The analysis assumes a distribution system leak rate of 2.7%, from Deeper Decarbonization in the Ocean State: The 2019 Rhode Island Greenhouse Gas Reduction Study, September 2019, Stockholm Environment Institute, et al. It uses a 100-year global warming potential for methane of 30, based on the U.S. EPA range (U.S. EPA, "Understanding Global Warming Potentials", available at: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials), and adjusts for the different masses of methane vs. CO_2. Successful efforts to reduce gas leaks would reduce the costs of methane leaks correspondingly.

emissions since methane is a much more potent greenhouse gas than CO_2.

Figure 23 also indicates an uncertainty band around the mid-range estimate, illustrated by the vertical black line that shows plausible high and low cost estimates based on reasonable estimates of the uncertainty in future installed cost for equipment (heat pumps), and uncertainty in the price of renewable fuels and electricity.

For heat pumps, the high initial cost makes up a substantial share of their total annualized cost, whereas renewable fuels have low initial equipment costs but fuel costs that are both substantially higher and also highly uncertain. GSHPs have even higher initial costs than ASHPs, though annualizing the cost makes the difference less pronounced, given that GSHP equipment life is longer (it is housed indoors) and ground loop costs are spread over a longer operating life.[73] These higher upfront costs are offset by lower operating cost of GSHP: due to higher average efficiency (especially during cold temperatures as explained above), GSHPs use about 20% less electricity overall, and if ASHP is adopted widely, it would likely raise power prices.

Overall, this analysis shows that among the various decarbonization solutions for a representative single-family home, while there are some differences in the mid-range estimated costs, the uncertainties are significant and the uncertainty bands are largely overlapping. The ranges of annualized costs for all four decarbonized heating solutions are broadly overlapping (around \$3,000-\$5,000 per year). This means that no one technology is a clear winner based on economics, making it difficult to choose one of these decarbonized pathways over the others given the information that is available now. Ground-source heat pumps appear nominally to be the least costly option, followed by air-source heat pumps and renewable gas. However, the range of uncertainty about the future cost of each of these heating options exceeds the differences in the nominal cost estimates between them, indicating that an alternative (but very reasonable) set of assumptions about how the costs of these technologies may evolve over the coming decades could lead to a different ranking.

It is also worth comparing the estimated cost of decarbonized heating with the cost of continuing to use fossil fuels for heat. Using projected fossil prices for 2050, the decarbonized heating solutions are generally more costly than natural gas heating, but could be competitive with heating oil and propane. Decarbonized heating with renewable fuels is likely to be more costly unless these renewable fuels end up near the low end of their cost uncertainty band. If carbon costs (here illustrated at \$75/tCO_2) are included, the decarbonized alternatives become somewhat more competitive. Still, an overarching observation is that the range of uncertainty makes it difficult to draw any firm conclusions, either comparing decarbonized solutions or comparing those with the continued use of fossil heating (acknowledging that there is also uncertainty about future fossil fuel costs, not characterized here). Current fossil heating costs are modestly lower than the projected 2050 costs (see **Figure 10**), so it is reasonably likely that – for the average consumer – decarbonized heating may increase 2050 heating costs from their current level, *but perhaps not by much more than costs would rise with continued use of fossil fuels.* Importantly, the actual impacts of decarbonizing heating systems may differ significantly for individual consumers, due to the idiosyncrasies of individual buildings. And even if increases in heating costs due to decarbonization are modest on average,

73 Another advantage of GSHP is that it does not require a backup heat system to cover peak heat needs in the coldest weather. With an ASHP, by contrast, output is lowest when heat demand is highest, so a backup system is needed. However, this backup can be provided by electric resistance heat, which has little operating penalty in cold weather and has small up-front cost.

policy – discussed below – must take into account that cost increases could be more pronounced for some consumer groups, and that even modest cost increases may put a significant burden on already disadvantaged consumers, in which case mitigating policy measures will be even more important.

To understand some of the other factors that may drive a heating sector transformation, it is useful to consider another perspective in addition to the societal economic view presented above – that of a consumer contemplating the economics of alternative heating systems. For a variety of reasons, consumer behavior often does not reflect the long-run economics characterized above. Rather than choosing the alternative with the lowest long-run total cost, consumers generally require energy investments to pay back any up-front investment within just a few years, or they will decline to make the investment.[74] This is a very real issue for a consumer contemplating a switch from fuel-based heat to a heat pump, which can require tens of thousands of dollars of up-front investment and potentially significant modifications to the home (ductwork, electrical upgrades), vs. a few thousand dollars to replace the old fuel-fired boiler or furnace with a new one.

The higher up-front costs of heat pumps might lead customers to remain with the fuel-burning solution (whether the fuel is fossil or renewable) even if the heat pump's much lower operating costs offer significant lifetime savings. This effect is further exaggerated for ground source heat pumps which have the additional ground loop cost. This suggests that even if heat pumps do have lower long-run economic costs, significant policy intervention and program support may be required to induce customers to adopt them. Such policy intervention could take the form of direct incentives or no-to-low cost capital financing that reduce the up-front costs. For example, a GeoMicroGrid may not only reduce the up-front cost of GSHP, but utility ownership of the ground loop could help to reduce the initial cost barrier.

2. Mixed Adoption Scenario

The Bookend Scenarios analyzed above assume that all New England heat is provided by a single technology (or that current fuel types are maintained in the case of the renewable oil and renewable gas scenarios, respectively) to illuminate their potential impact on other systems. Of course, the actual decarbonized future will almost certainly include a mix of the candidate technologies. To reflect such a more realistic outcome, while still incorporating the feedback effects on electricity prices and gas delivery costs discussed above, a Mixed Scenario, in which the New England heating sector is decarbonized using a mix of the candidate technologies, was also developed. Of course, the particular mix analyzed here reflects only one possibility, but it does illustrate some important potential effects. For this illustrative Mixed Scenario, half of existing gas customers are assumed to electrify their heating, along with 80% of oil customers and essentially all customers using other fuels.[75] In aggregate, two-thirds of customers switch to electric heat pumps, split equally between ASHP

74 This does not necessarily imply that customers are behaving irrationally in such situations. Such a high investment threshold may reflect, for example, the personal disruption associated with a construction project; the possibility that the homeowner may move within a few years and thus would recoup only a few years' operating cost savings; or the fact that consumers' financing costs are typically much higher than the low discount rate used for the societal perspective above.

75 This is just one assumption regarding the shares of customers who may electrify; it is not intended as a prediction of customers' switching propensity based on their existing fuels. But a lower electrification rate for gas customers might result from the lower current cost of gas heating vs. other current fuels, and perhaps some customers' desire to keep gas as a cooking fuel rather than from the lack of available renewable oil. In fact, considering building efficiency improvements and the potential for customers to use a heat pump to cover just part of their heat needs, retaining their fossil system as backup perhaps as an interim solution, there are many different ways in which decarbonization could reduce the demand for gas and other traditional fuels. This Mixed Scenario yields insight into such alternative scenarios as well.

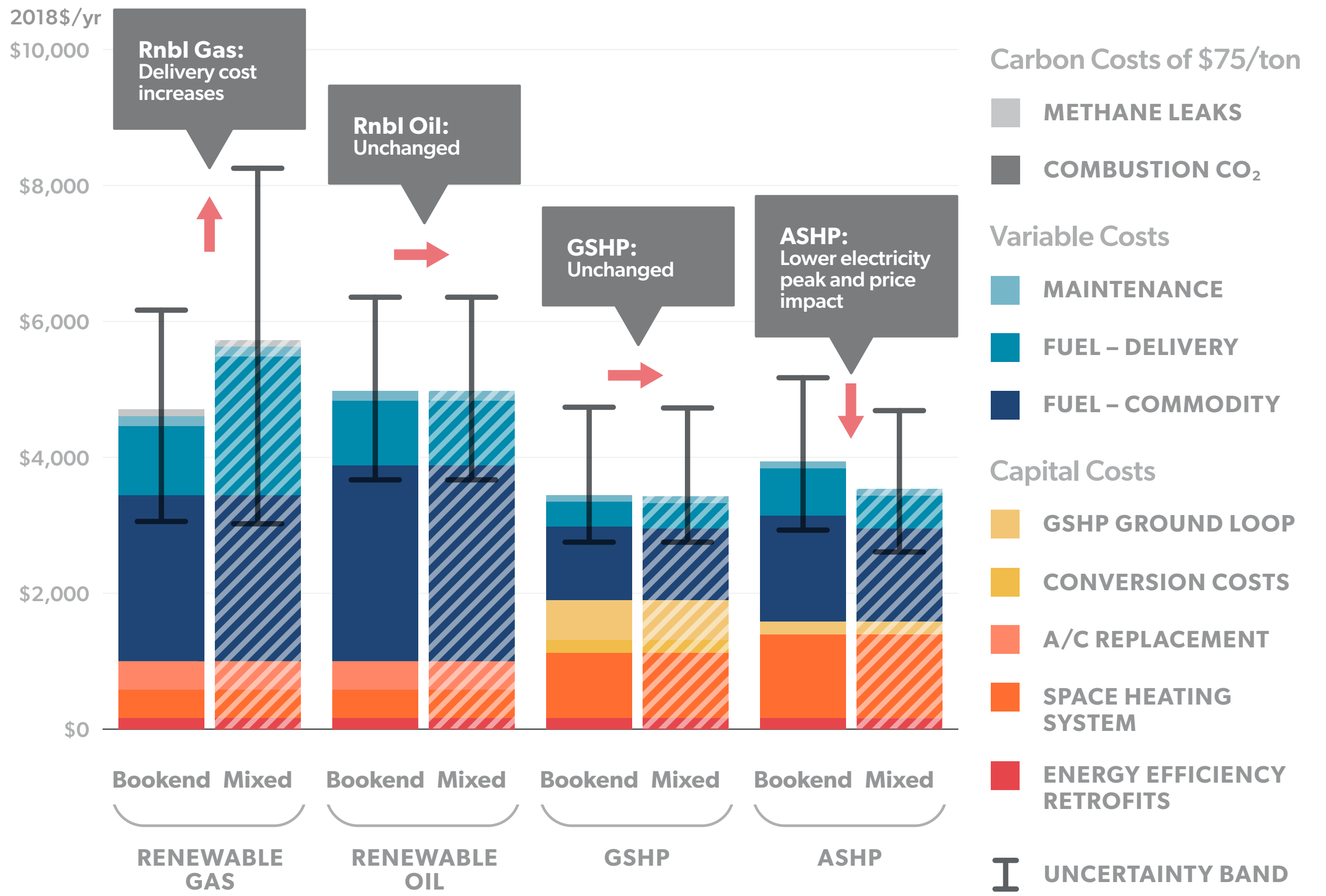


FIGURE 24: ANNUALIZED COST OF SPACE HEATING, SINGLE-FAMILY HOME IN 2050 MIXED SCENARIO VS. BOOKEND SCENARIOS (2018$)

and GSHP. Those customers keeping their existing fuel type would burn a renewable version of that fuel in 2050. **Figure 22** above illustrates the current heating fuel shares, as well as the shares assumed in the Mixed Scenario.

Figure 24 compares how this Mixed Scenario changes the results from the Bookend Scenarios examined in **Figure 23**. Electric demand and price in the Mixed Scenarios are similar to the GSHP Bookend Scenario, so GSHP costs are very similar, and ASHP costs are lower than in their respective Bookend Scenarios.

The most substantial impact is on the cost of heating with Renewable Gas. Since volumes delivered through the gas distribution system are substantially lower in this scenario (and assuming the cost of maintaining and operating the gas delivery system is essentially fixed), the delivered price of Renewable Gas would increase markedly. **Figure 25** provides a simple illustration of the potential dynamics affecting delivered gas prices in a decarbonized future. The left side of the figure shows fossil gas prices now and projected in 2050 at current delivery volumes. The right side illustrates how the future delivered cost of 100% renewable gas might be influenced by the gas commodity cost (here, assumed to be $30/MMBtu independent of the amount delivered)[76] and reduced delivery volumes. At current volumes, the delivery

76 As noted above, the commodity price of renewable gas in Rhode Island will likely not depend on local demand, since a future renewable gas market is likely to be regional or national in scope.

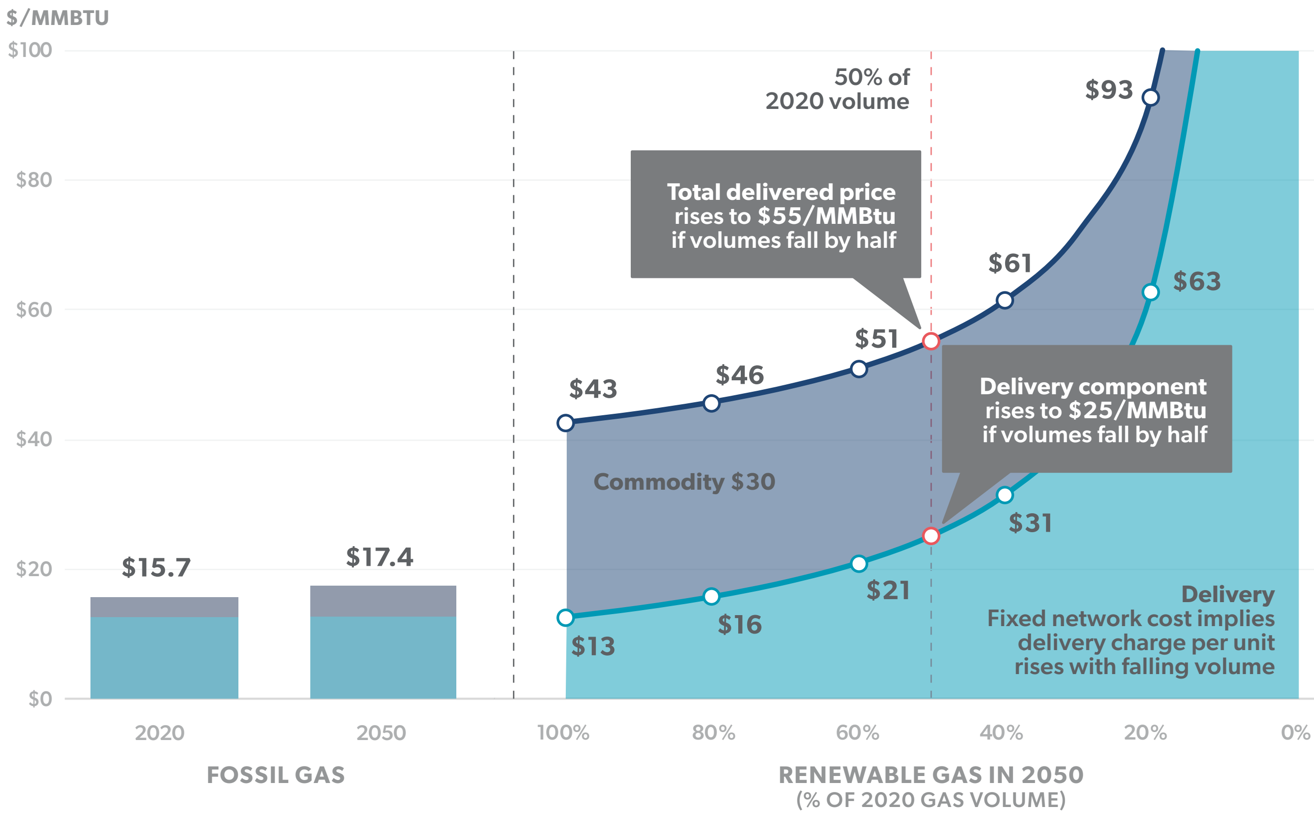


FIGURE 25: DELIVERED PRICE OF GAS: 2020 FOSSIL GAS VS POTENTIAL 2050 RENEWABLE GAS (2018$)

charge would be $13/MMBtu as it is today, resulting in a $43/MMBtu delivered price of renewable gas. If delivery volumes decrease, the delivery cost per unit would rise, since total distribution system costs would not change. For example, if volume fell by half as assumed in the Mixed Scenario, the delivery charge component could double, with the delivered gas price reaching $55/MMBtu – over three times the current delivered gas price.

A reduction of half or more in gas volumes may not be a particularly extreme assumption; the efficiency improvements assumed here alone would reduce gas demand by 15%, even with no gas customers switching to a different heating solution. This points out an important potential challenge for the gas system: Any volume of gas sales lost to electrification (or to improved building efficiency, or even to renewable oil which does not have a fixed-cost delivery network) will increase the delivered price of gas as the fixed distribution costs are spread over less gas. This could prompt further volume loss and an upward cost spiral for remaining customers. In turn, this would impose significant risks for customers who cannot easily switch away from gas, as well as for the gas utility. The most obvious way to avoid these issues would be to retain most of the gas volume while decarbonizing the gas. Other approaches could include reducing delivery system costs as volumes fall (e.g., by concentrating losses in some parts of the system and pruning those branches entirely), or sharing the costs of the gas infrastructure more broadly across all "energy" customers, acknowledging the widespread social benefit of decarbonization while protecting individual customers.[77]

77 However, even if gas system costs are spread more broadly across customers, it will be important to continue to monitor the mostly fixed costs of maintaining the gas system. This must be compared with the cost of alternative solutions, such as electrifying all remaining gas demand (including the infrastructure requirements that entails), to ensure that the approach pursued is best for consumers overall.

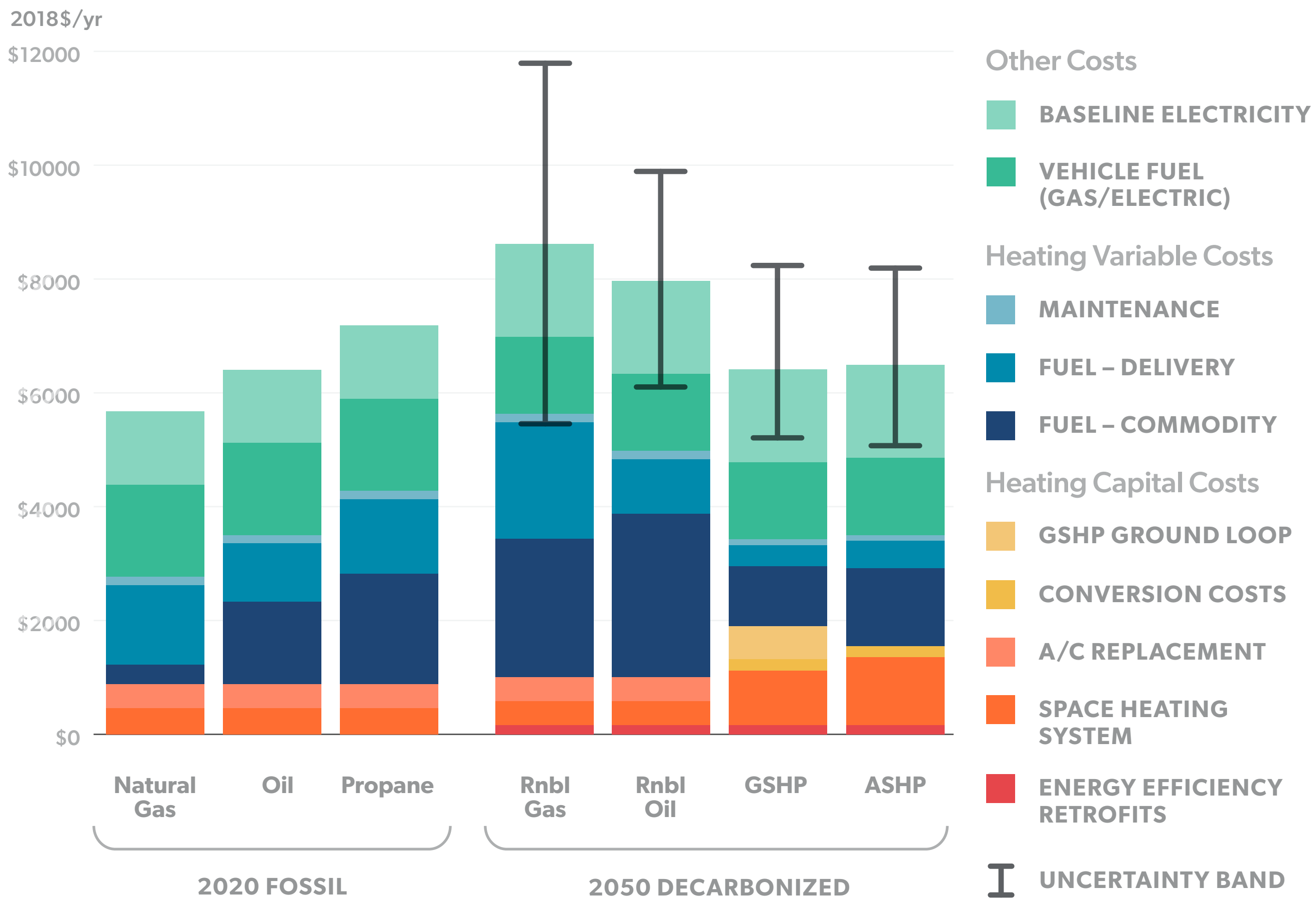


FIGURE 26: TOTAL ANNUAL ENERGY WALLET COMPARISON FOR SINGLE-FAMILY HOME, 2020 VS 2050 MIXED SCENARIO (2018$)

Note: Uncertainty band reflects uncertainty on heating costs as above, plus the effect of electricity price uncertainty on other end uses. Gasoline price excludes federal and state taxes. Water heating cost is not broken out explicitly, though to the extent electricity is currently used for water heating, this is included implicitly in Baseline Electricity usage.

3. Energy Wallet

It is also important to recognize that heating is only one element of a representative consumer's overall energy wallet, which also includes spending on traditional electric end uses and transportation. Figure 26 considers a customer's total energy wallet comparing current energy expenditures across all sectors on the left with a 2050 projection that shows the cost of various decarbonized heating solutions combined with the average cost of charging electric vehicles and traditional electricity consumption. This analysis assumes that light duty vehicles are fully electrified across New England, and that electricity and gas prices are consistent with the Mixed Scenario that employs a mix of decarbonized heating technologies, projecting a plausible future. One notable feature of this comparison is that even though total costs for decarbonized heating may be higher than some forms of fossil heating, and electricity prices are likely to be higher with a decarbonized grid, consumers will not necessarily spend significantly more in total energy costs than they do today in a fossil-fuel based environment. Partially offsetting any increase in the cost of heating for some customers, electric vehicles are more efficient, making it somewhat less costly to "fuel" an automobile with electricity than it is today with gasoline, even though the 2050 decarbonized electricity price is higher than today's price. Still, the energy wallet perspective does not change the fundamental conclusion above. The uncertainty in future costs still outweighs the relatively small differences in expected costs across options (and relative to today), and no single heat decarbonization approach is clearly preferable.

4. Conclusions for Existing Single-Family Home

In sum, for a representative detached single-family home – the most common building type in Rhode Island – a quantitative comparison of annual heating costs for the various decarbonized solutions suggests that, at least according to what can be known now, no single solution provides a clear economic advantage over the others. Rather, which option will have the lowest annual heating costs depends on how several uncertain factors – including the availability and price of renewable fuels and renewable electricity, the installed cost and performance of electric heat pumps, the cost of installing ground loops, etc. – evolve over the coming decade. Any state-level policy promoting decarbonization of the Rhode Island heating sector must take this uncertainty into account.

IMPLICATIONS FOR SPACE HEAT IN LARGER BUILDINGS

The representative single-family residential home analyzed above represents the most common building type in Rhode Island, at the low end of heating demand on a "per-building" basis since they are smaller buildings. There are a significant number of larger buildings in the state as well, both larger multi-family residential buildings and commercial buildings, and of course they must also be addressed in order to decarbonize the heating sector. The same issues discussed above regarding existing vs new buildings tend to apply for larger buildings as well. That is, building efficiency is relatively straightforward and very cost effective for new buildings, and can dramatically reduce the need for heat in those buildings. But with few new large buildings being constructed and many existing large buildings remaining in use in the state, the heating sector transformation among larger buildings must also focus for the most part on retrofitting existing buildings. Also, as with single-family homes, larger buildings may have some relatively low-cost and cost-effective opportunities to improve building energy efficiency; this will help reduce overall customer costs, but cannot approach full decarbonization. Large buildings will still need heat and that heat must be decarbonized.

The basic decarbonization pathways described above – decarbonized electrification with heat pumps and decarbonized fuels – are also relevant for medium and larger buildings, though the long-run cost tradeoffs, relative to each other as well as relative to typical fossil heating systems, may differ. This is a result of their different scale, different heating (and cooling) equipment with different capital costs and operating efficiencies, and thus different tradeoffs between renewable fuel solutions with lower capital cost but higher operating costs, vs. heat pump solutions with relatively higher capital costs, and often some building conversion costs to reconfigure the building to heat with a different system.

To represent the potential tradeoffs, **Figure 27** shows a comparison of the economics of alternative decarbonization approaches for a stylized larger building. This example uses an average sized commercial building in New England (14,250 square feet), which would correspond to a medium-sized office building. Heating demand is based on Buro Happold's analysis, which estimated that commercial buildings currently consume 38,305 Btu/sq. ft. annually; like the residential analysis above, this is reduced by 15% for assumed building efficiency improvements, yielding an annual heat

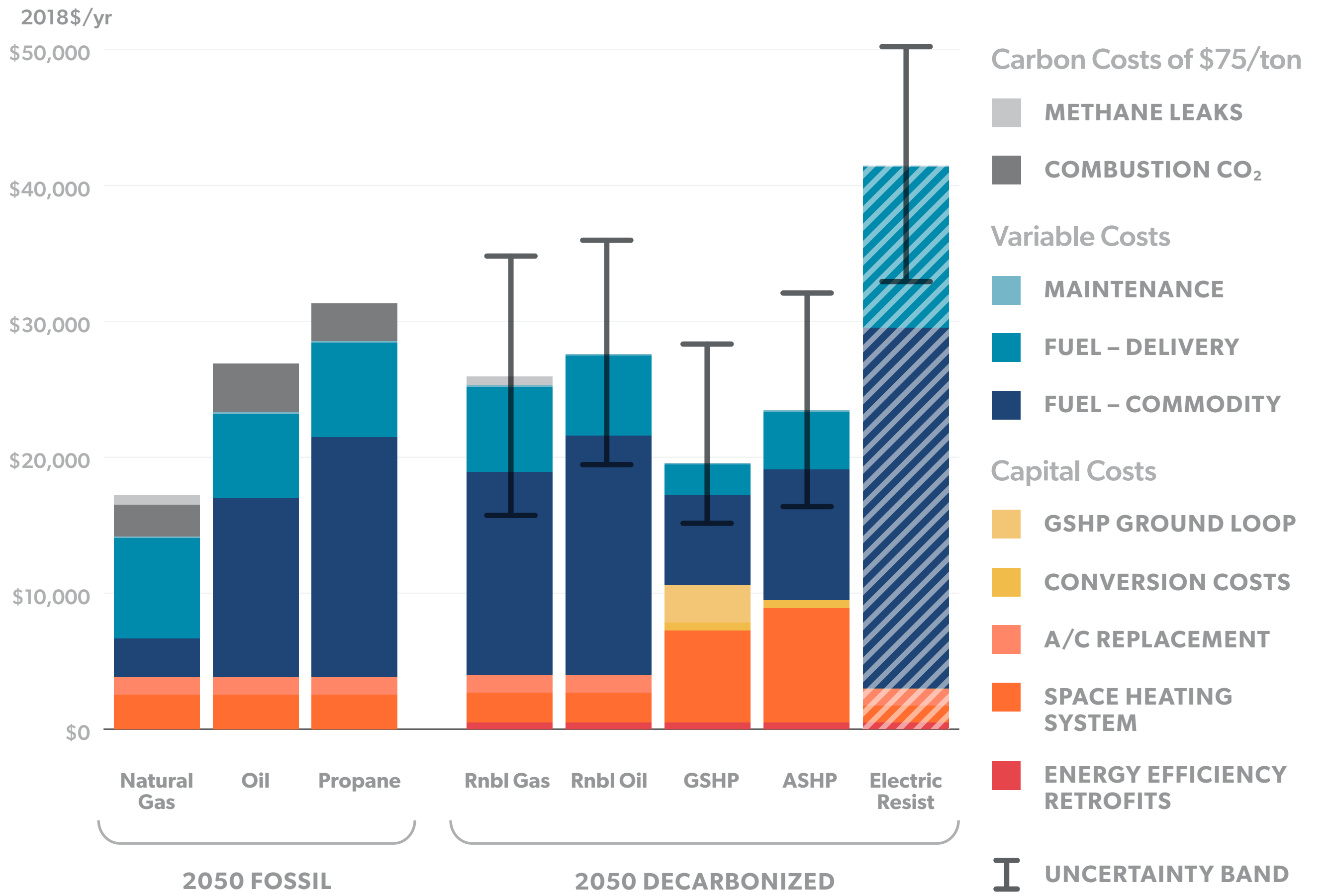


FIGURE 27: ANNUALIZED COST OF SPACE HEATING, STYLIZED LARGE BUILDING IN 2050 BOOKEND SCENARIOS (2018$)

demand of 464 MMBtu. Heating equipment is more costly because it is larger, though it scales up slightly less than proportionally; in particular, the ground loop cost for GHSP is assumed to exhibit declining unit costs for larger installations. Many of the factors do not depend on the size or type of building. For example, ASHPs face the same declining efficiency in cold weather and the price of renewable fuels does not depend on building size. Similarly, renewable gas leaks contribute to GHG emissions and the per-unit cost of gas distribution rises if the gas volume delivered declines. Still, Figure 27 shows relative costs that are very similar to those in Figure 23 for a single family home. Heat pumps have much higher capital cost but lower operating costs; the decarbonized options are generally more costly than natural gas and broadly on par with the cost of oil and propane; and the uncertainty ranges on the decarbonized options overlap considerably.

Since larger buildings tend to be more idiosyncratic, a comparison like this may be less broadly applicable than the analysis above for a representative single family home. But some additional observations may be possible. For instance, because large buildings often need some cooling even in the heating season, there may be some waste heat available that could provide a useful heat source for a heat pump – either to heat a different part of the building or to store for a later time. Large buildings may also offer some flexibility, e.g., to convert part of a building at a time (such as converting one or more floors of an office tower as it is remodeled between tenants), and to connect different heating and cooling sources simultaneously to the building's internal distribution systems. As an example, the hot water loop in a building could be configured with both a boiler and a heat pump, which can trade off and supplement one another in operation, with usage potentially transitioning from one to the other over time. Because the heat needs are greater in larger buildings, higher capital cost solutions (such as heat pumps and possibly GSHPs) may be relatively more attractive since there are larger operating costs to be saved, and there may be scale economies in equipment and installation costs.

WATER HEATING

As shown above, domestic water heating represents more than 15% of total energy demand in residential buildings in Rhode Island and moderately less in commercial buildings, making it the second most important source of heating demand. This section considers the relative costs of various decarbonized approaches to water heating. Most of the options are similar to existing water heating approaches, but involve decarbonizing the fuel – renewable gas instead of natural gas or renewable oil instead of heating oil – or using emissions-free electricity in an electric resistance water heater. Electric heat pump water heaters represent a relatively new and promising alternative to traditional electric resistance water heaters. These (air-source) heat pumps integrate the heat pump with the water tank, drawing heat from the surrounding (and typically conditioned) space to heat water in the tank. While a heat pump water heater also utilizes electricity, it does so much more efficiently than an electric resistance heater.

Figure 28 compares the annualized cost of several water heating solutions for a representative single-family home: two fossil options (natural gas and heating oil) and four decarbonized options: renewable gas, renewable oil, electric resistance and electric heat pump. As shown, annualized water heating costs with an electric heat pump are expected to be lower than the other decarbonized options, lower than fossil oil, and comparable to natural gas if carbon costs are included. Although it has slightly higher capital cost than most of the other options, its variable operating cost is much lower, largely because of the efficiency with which it uses electricity. This results in electric heat pumps having not only a lower total annual cost relative to the other decarbonized technologies, but also a notably short payback period of less than two years relative to those other decarbonized technologies. This suggests that electric heat pump water heaters may be the most cost-effective decarbonized water heating alternative in the long run, as well as an attractive energy investment opportunity from a customer's perspective, given their short payback period. Moreover, since this analysis conservatively uses cost and efficiency parameters for heat pump water heaters available today, improvements over time for this still relatively immature technology could make heat pump water heaters relatively more attractive in the future.[78]

The above analysis assumes the choice of water heating solution is independent of the choice of space heating. In reality, the two choices are potentially linked. Since essentially every building in Rhode Island is connected to the electric system (and will be in 2050), a heat pump or electric resistance water heater can be used with any space heating technology. This may not be true for water heaters using gas or oil. If space heating is converted to an electric heat pump, maintaining the gas distribution

78 One potential impact whose effects are not yet fully understood and thus not included here is the potential impact on space heat requirements if – as is typically the case – a heat pump water heater is installed in conditioned space and thus draws heat from inside the building. This could increase the total space heating needs in winter, adding to the cost of space heating. This effect, if present, would work in the opposite direction in summer to reduce the building's cooling needs, particularly if there is a way to circulate the cooled air within the building.

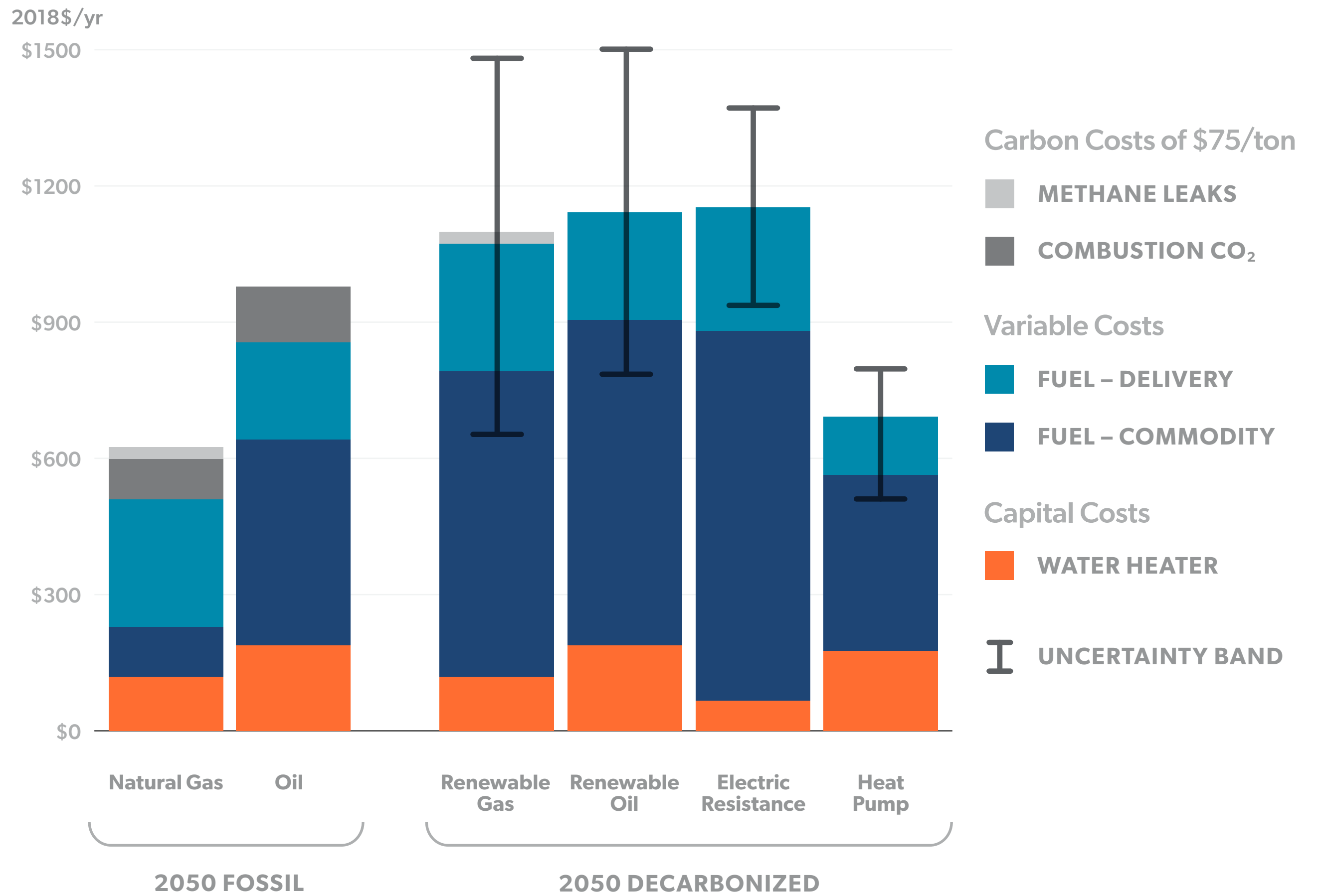


FIGURE 28: ANNUALIZED COST OF WATER HEATING, RESIDENTIAL IN 2050 (2018$)

Notes: Assumes 50-gallon capacity, 15 million Btu annual consumption, and a $75/metric ton carbon price. Efficiency assumptions: 67% for gas water heaters, 95% for resistance water heater and 200% for heat pump water heaters.* Price assumptions: $17.4/MMBtu for natural gas, $4.1/gal for oil, $42.6/MMBtu for renewable natural gas, $5.3/gal for renewable oil, and $0.23/kWh for electricity. Assuming 5% discount rate and an average economic life of 13 years for all technologies except for heat pump water heaters (10 years). Data sources in Technical Support Document. ENERGY STAR® Residential Water Heaters: Final Criteria Analysis, April 1, 2018.

connection (or an oil tank) just for water heating may be much less cost-effective. This may further increase the potential for heat pump water heaters.

In larger buildings, such as large multi-family apartment buildings and large commercial office buildings, water heating systems, like those for space heating, tend to be more idiosyncratic and specific to the particular building. The qualitative tradeoffs for water heating would generally be similar, though the larger scale could enable cost savings or improved efficiency in heat pump water heaters. In some buildings, water heat is currently integrated with the space heating system, and thus might be addressed with the same decarbonized system as space heat.

INDUSTRIAL HEAT

Beyond the residential and commercial applications for space and water heating discussed above, Rhode Island's industrial sector also requires heat, which must be decarbonized as well. The state's industrial sector accounts for approximately 15% of total energy use. Although detailed information is not available on the breakdown of energy uses within the industrial sector, some of it is for space and water heating for buildings (much like in residential and commercial buildings), some is for industrial process heat needs, and some fuel may also be used as a feedstock. That said, Rhode Island's industrial sector as a whole is not characterized by large industrial sectors where process heat is an important input to production (such as steelmaking), nor as feedstock (fertilizer or plastics). This suggests that a substantial portion of industrial sector heating needs may be for space and water heating. Where this is the case, the decarbonized solutions and their relative attractiveness discussed above for larger buildings would apply similarly to industrial needs.

Beyond space and water heat in industrial facilities, there is also an array of specialized industrial process heat needs and applications that may go beyond the technologies discussed so far.[79] These can vary widely, with the type of heat required and the technologies able to provide it often being highly specific to the particular industrial process. Heat pumps can only provide relatively low-temperature heat; while this is adequate for space heating, it is not well suited for most high-intensity industrial process heat needs. For some industrial applications that require intermediate temperatures, electric resistance heat may be useful, though whether a heat source can be utilized in a particular instance is a function not only of the temperature it can provide but also how the heat source can be physically integrated with that particular industrial process. Very high temperature applications typically require burning fuel which, if it is to be decarbonized, would require renewable gas or oil, or possibly renewable hydrogen. Other applications that can use induction, lasers, microwaves, etc. likely exist but will tend to be less common and the opportunities are highly specific to the particular application in question.

Because industrial process heat needs tend to be very specific to particular industrial applications, the availability and cost of decarbonized solutions is also likely to be process-specific. In many instances where natural gas or fuel oil are used today, it should be possible to substitute renewable gas or renewable oil. Renewable (green) hydrogen could play a more important role in the industrial sector than in the residential and commercial sectors. Unlike in those sectors, hydrogen could be stored on-site or potentially delivered via dedicated pipelines to targeted industrial sites that have large, concentrated demand. Given the diversity of industrial applications and the sparse information about both current industrial activities and especially how decarbonized alternatives might be implemented, this study has not attempted to analyze the relative economics of decarbonization solutions for the industrial sector.

However, where industrial decarbonization involves substituting renewable fuels (gas, oil, hydrogen) for the current fossil fuels used, the cost of fuels will be higher – potentially much higher, especially for gas fuels – and this may increase manufacturing costs for energy-intensive industries. These higher operating costs may create a competitive disadvantage for firms whose competitors do not comply with similarly ambitious decarbonization goals, unless otherwise mitigated through state- or utility-administered incentive structures. Further, to the extent industry does relocate to regions without similar decarbonization targets, this may simply relocate overall global GHG emissions, rather than reducing them. The Policy section below discusses some ways to address this, and the **Technical Support Document** accompanying this report provides further detail on issues related to the industrial sector.

79 Overall industrial heat needs represent a smaller share in Rhode Island than in the U.S. as a whole.

QUALITATIVE ASSESSMENT AND OTHER FACTORS

In addition to the results of the quantitative assessment of alternative heating decarbonization solutions presented above, a number of other, more qualitative factors need to be considered. Many of these factors were raised by heating sector stakeholders. In some cases, the ideas presented here represent perspectives expressed by some particular stakeholders, but may not be shared by all. Broadly, qualitative factors that impact the attractiveness and feasibility of certain decarbonization solutions in various applications fall into the following categories:

- **Information deficits.** In addition to the unavoidable uncertainty about future developments that may affect the performance and cost of decarbonized heating solutions, there is a significant lack of current information among consumers, installers, and even utilities and policymakers about the available alternatives, how they work when applied at scale, the buildings and geographies where they may be applicable, what they cost and how they perform. This is, in part, because these decarbonized technologies are relatively new and not yet widespread, especially in the United States. Related to this, there is also no "one-stop shop" where stakeholders can go to understand and compare heating alternatives. The providers of various heating solutions tend to be small and, while each may be familiar with the solutions they deliver, few are able to put the alternatives into context and compare among the options. Greater industry collaboration, coupled with strategic partnerships with the utility and state government, may assist in reducing this barrier.
- **Affordability of energy is key.** Energy costs throughout New England have long been higher than in other regions of the country. Keeping energy affordable throughout the transition to a decarbonized economy is imperative for all the state's residents and its businesses. This is particularly true for low- and moderate-income consumers and disadvantaged populations; policies aimed at decarbonizing the heating sector (as well as other sectors) should be designed to protect these populations in particular. One approach that can help with this is to improve the efficiency with which energy is used, and therefore the state's cost-effective energy efficiency programs must remain in place as a way to help reduce energy consumption and manage longer-term customer costs.
- **Acknowledge the needs of vulnerable customers.** Many low-income customers live in lower-quality housing with less effective, less efficient heating systems. Energy costs are already a burden for many of these customers. It will be important to ensure that decarbonization does not add to the burdens of these customers and policies create opportunities for them to participate in the advantages of decarbonization – both as consumers and potentially offering employment on the supply side.
- **Health and safety concerns about natural gas.** Natural gas use presents both real and perceived health and safety risks that can be avoided by electrification. Gas is combustible and creates risks when gas leaks occur indoors. In addition, indoor combustion of gas causes indoor air quality problems (NOx) that lead can lead to detrimental health effects. In this respect, the use of natural gas for cooking can have a greater impact than heating; while heating consumes much more gas than cooking, heating is almost always vented outdoors, but gas cooking is often not vented, or not completely.
- **Consumer preferences.** Some consumers' unwillingness to give up their gas cooking stoves creates a barrier for switching away from gas as a heating fuel. Electric induction cooktops offer

performance comparable to gas (arguably better), but induction is not a well-known technology.

- **Methane leaks mean renewable gas also emits GHGs.** Even renewable gas that is produced entirely without GHG emissions will contribute to GHGs through leaks, due to methane's high global warming potential (about 30 times that of CO_2 over a 100-year timeframe; 85 times over 20 years). Current leak rates are substantial, on the order of 2.7%, which means that the GHG impact of leaked methane can add roughly 30%-85% to the GHG of the CO_2 in the combustion products. While leaks may be reduced, they will not reach zero. This limits the ability of renewable gas to provide fully decarbonized heating.

- **Weatherization effectiveness.** Even if weatherization measures are cost-effective, adoption rates are relatively low. This can likely be attributed at least in part due to non-cost barriers such as the fact that even the kinds of weatherization measures covered by programs like EnergyWise involve "intrusions" into individuals' homes and potentially disruptions to normal use of the home. This is even more the case for deeper retrofits. Energy efficiency policy has evolved to address some of these barriers – for example, by bundling the timing of some energy efficiency measures with the energy audits – but "convenience" likely remains an important barrier to more adoption of cost-effective weatherization measures.

- **Availability of installers.** There is a shortage of available installers for heat pump technologies and stringent licensing requirements may create a barrier to increasing the number of licensed installers. A countervailing concern is that heat pump technology requires a well-trained installer to design and implement a system that will perform well. Effective training programs and industry coordination may help to address these concerns.

- **Electrification depends on decarbonizing electricity production.** Electrifying heat, such as with heat pumps, only results in decarbonization to the extent the electric grid itself is decarbonized. Both perceived and actual delays in decarbonizing the electric system could reduce consumer willingness to switch to electrified solutions. Full decarbonization of the New England electric system to meet traditional and new sources of demand, such as electric vehicles and heat pumps, by 2050 is likely a very significant challenge.[80]

- **High initial costs are a barrier to adoption.** Heat pump technologies, particularly ground source heat pumps, have high initial costs that create a significant barrier to consumer adoption. This is particularly the case for low-income consumers in the absence of policies to mitigate upfront costs. Utilities may be able to help address this to the extent they can finance the initial costs through on-bill financing or rate-basing some of the cost. Mechanisms such as securitization or financing with green bonds may help to further reduce the cost to consumers.

- **Low deployment levels mean non-competitive pricing.** Heat pump technologies, particularly those relevant for heating in Rhode Island (GSHP and cold climate ASHP), are relatively new and costly. This results in consumers facing a relatively immature (and perhaps not very competitive) market

80 For details on the magnitude of this challenge, see The Brattle Group, Achieving 80% GHG Reduction in New England by 2050, September 2019. The report suggests that an acceleration of annual renewable energy deployment of 4-8 times the annual pace currently planned for the decade 2020-2030 will be necessary to accomplish a fully decarbonized system with significant demand from electrified heating and transportation.

of installers, with pricing for heat pumps higher than pricing for installations of more mature technologies such as boilers and furnaces. This is likely particularly true for GSHPs, where the market for geothermal wells is also immature and pricing of drilling such wells potentially higher than it would be in a more fully developed market with higher volumes enabling economies of scale and competition.

- **Local codes and standards.** Rhode Island's building codes and permitting requirements should be reviewed through the lens of wide scale heating sector decarbonization. In particular, the state should work with local communities and the construction industry to ensure heat pump installations can be viably deployed, while reducing construction-related soft-costs to improve affordability. Examples include rules for drilling geothermal wells in dense urban environments, set-back requirements for outside condenser units and different permit requirements across localities.
- **Split incentives.** A large share of the Rhode Island population, in particular more economically disadvantaged populations, do not own their residence. When non-tenant owners make decisions about heating technology, their economic incentives may disfavor high capital costs since they tend to incur those while they tend to pass on fuel and other operating expenses. This in turn may create a barrier to heat pump adoption.

Table 2 is organized according to the various solutions for decarbonized heating technologies, and summarizes some of the less easily quantified attributes that may impact their attractiveness from the perspective of individual consumers or the state, and identifying whether these factors have positive or negative implications for the given technology.

CONCLUSIONS FROM ANALYTIC MODELING AND STAKEHOLDER INTERVIEWS

The analytic modeling efforts and the series of stakeholder interviews and public workshops that were undertaken in this project have raised a number of important issues and conclusions about the transformation of Rhode Island's heating sector. In addition to reinforcing many of the analytical conclusions, stakeholders pointed out further implications that were beyond the scope of the analyses.

Decarbonizing the heating sector in Rhode Island will mostly mean decarbonizing residential and commercial space heating, since these account for the majority of heating needs in the state. And it will occur mostly by retrofitting existing buildings, since the rate of new building construction is quite low; most of the buildings that will exist in Rhode Island by 2050 already exist now.

Energy efficiency improvements to existing buildings will be an important component of decarbonization, since they reduce the amount of heat that must be provided. Heating requirements for an existing building can typically be reduced by roughly 15% at reasonable cost with simple efficiency improvements (weather stripping, air sealing, attic insulation), saving consumers money while reducing emissions. But much greater efficiency improvements tend to be costly and disruptive in existing buildings, and may not be cost-effective. This means that it will still be necessary to deliver significant amounts of heat to these buildings, and that heat must be decarbonized.

Two broad pathways to decarbonize space heating exist – electrifying heating using heat pumps with decarbonized electricity or using decarbonized renewable fuels (gas or liquid fuels) in boilers and furnaces like those in current use with fossil heating fuels. Each of these pathways and the technologies

Approach	Challenge	Comment
ASHP, GSHP	**Market Maturity**	• The market for ASHPs and GSHPs is underdeveloped. Knowledge about quality of installation, competitiveness of bids, etc. are underdeveloped among both consumers and contractors.
GSHP	**Installation Constraints**	• Installing GSHPs requires drilling or digging. There are both physical and potentially permitting constraints that make installing GSHPs challenging in certain instances, such as densely populated neighborhoods and certain geologic formations.
GSHP (some ASHP)	**Upfront Cost**	• GSHPs require significantly higher upfront costs than ASHPs and traditional boiler and furnace systems. This creates adoption barriers due to the unwillingness or inability to afford these higher upfront costs (even if beneficial on average over the life of the equipment).
GSHP, ASHP, Energy Efficiency	**Split Incentives**	• Solutions with high capital cost can be challenging to implement in rental situations; since the tenant benefits from energy savings, the landlord may have little incentive to invest in a more efficient heating system.
Renewable Gas	**Methane Leakage**	• Renewable gas delivered over pipeline infrastructure will result in residual methane leaks. Given the high climate forcing potential of methane, this reduces the ability of renewable gas to provide fully decarbonized heating.
Renewable Gas	**Indoor Air Quality**	• As with natural gas, the use of renewable gas for heating and especially cooking results in indoor combustion, which can lead to poor indoor air quality and health risks.
Renewable Gas	**Effects of gas leaks**	• As with natural gas, indoor leaks of renewable gas present health and safety risks.
Renewable Fuels	**GHG Reductions**	• Largely due to land-use issues, it is difficult or impossible to eliminate all GHG lifecycle emissions of some renewable fuels, such as those derived from fuel crops.
Deep Retrofits	**Implementation and Disruption**	• Deep energy efficiency retrofits (wall insulation, window replacements, etc.) require disruptive interventions, which create additional barriers beyond potential issues of cost-effectiveness.

TABLE 2: QUALITATIVE CHALLENGES AFFECTING DECARBONIZED HEATING ALTERNATIVES

Note: Challenges for one solution represent an advantage for those alternative solutions that do not face a similar challenge.

that implement them has advantages, and each faces challenges.[81]

Renewable fuels have a significant advantage in that they allow for the continued use of existing infrastructure with little or no changes, both for the supply infrastructure and at the customer site. However, there are likely to be only limited quantities available at moderate prices, and if they are used widely for heating (anywhere in the United States since the market for such fuels will be regional or national), the price of renewable fuels is likely to be quite high, especially the price of renewable gas compared to current very affordable natural gas. Renewable gas faces additional challenges. Leaks from the pipelines, the distribution system, and on the customer's premises create substantial GHG emissions, even if the gas itself is entirely decarbonized. Indoor leaks can also create safety risks, and indoor combustion is associated with health risks due to the effect on indoor air quality.

Among the decarbonized electrification solutions, both ground source heat pumps and cold climate air source heat pumps are able to deliver the heating requirements of Rhode Island buildings. Even though air source heat pumps do experience efficiency loss at low outside temperatures, they are able to provide all of a building's heat requirements.[82] This efficiency loss may create some challenges if ASHP is implemented widely, though. The electricity needed to power many ASHPs operating inefficiently in extreme cold would create a significant spike in electric system peak demand, which would raise electricity prices. Ground source heat pumps draw heat from underground where the temperature is nearly constant, so they do not experience this efficiency loss at cold outside temperatures or contribute unduly to peak electric load and prices. They do, however, require a significant additional up-front cost to install the ground loop. For both ASHP and GSHP, installing heat pumps by itself does not decarbonize heat – it is also necessary to decarbonize the electricity supply.

All the alternatives for decarbonized heat are likely to be somewhat more costly than fossil natural gas heat is today, and perhaps very roughly on par with the cost of heating with oil, propane or electric resistance. Based on information available now, and accounting for the substantial uncertainties that affect the future costs of all decarbonized heating solutions – renewable fuel price, the initial cost of installing heat pumps and ground loops, and the price of electricity – it is not clear that any of the decarbonized solutions will be materially more cost effective than the others. This is true both for single-family residential homes, and by extension, for larger multi-family residential and commercial structures.

In fact, the wide diversity of existing buildings and situations suggests that the cost effectiveness and sometimes the feasibility of any approach depends significantly on local and building-specific circumstances. As an example, there may be challenges installing GSHPs in dense urban environments and where the local geology is unsuited for a ground loop. This will lead to different solutions being chosen in different circumstances, and Rhode Island will likely have some broad mix of these decarbonized heating technologies – ASHP, GSHP, renewable gas and renewable oil – in 2050 and beyond. This likelihood of a mix of technologies is reinforced by the fact that relying entirely on any one of them for all heat needs would tend to exacerbate

81 One of the practical challenges will be funding the incentive and consumer education programs necessary to achieve the decarbonization objectives. This report does not address the aggregate cost of such initiatives nor the best means of funding them, but they will be crucial to ensuring delivery of a decarbonized heating future that works for all Rhode Islanders and the state's economy.

82 For an air source heat pump system, it may be economical to use a supplemental heat source (e.g., electric resistance, or maintaining an existing fossil heat system for an interim period) to avoid having to install a very large ASHP to cover peak heat needs.

its own disadvantages: the electric peak impact of ASHP, the high initial cost of GHSP, and the limits on supply for renewable fuels. And the analysis of a mixed solution highlights a particular challenge for the current gas system – that gas volume lost to electrification or efficiency will increase the delivered cost of gas, imposing risks on customers who cannot easily switch away from gas.

This observation about a lack of a dominant technology solution is reinforced by a qualitative observation from stakeholder interviews. On top of the unavoidable uncertainty about future performance and cost, there is a "huge information deficit" and lack of understanding of the decarbonized heating alternatives among consumers, installers, and even policymakers. There are also few providers of decarbonized heat solutions, and no one-stop shop for information that would allow consumers to understand and compare them. This lack of information itself presents a barrier to getting started on the transition.

One important implication that can be drawn from the inability to identify a "preferred decarbonization pathway" is that it is likely premature to cut off options. For example, it is not time to begin dismantling the existing gas infrastructure, since maintaining it, at least for now, keeps options open. By the same token, it may also be best to avoid large, long-lived investments in any particular technology or infrastructure, since there is no guarantee the investment will continue to be useful in the long run.

The next section explores in some depth a number of policy implications of these observations that came from the analytic effort and the stakeholder interviews.

Policy Choices to Transform the Rhode Island Heating Sector

The heating sector is characterized by a number of features that justify policy intervention, including the presence of externalities or public goods, economies of scale, information failures, financing barriers, natural monopolies, etc. Greenhouse gas emissions are a classic externality, though not the only one here – the impact of individual heating technology choice on peak load and electricity price is another. There is also a considerable lack of awareness among consumers, policymakers, and even installers about the current state and likely future development of decarbonized heating technologies. And there are natural economies of scale and scope where coordinated action may facilitate, accelerate, and reduce the cost of heat decarbonization. The widely shared benefits and system interactions that will accompany decarbonization make policy interventions both warranted and necessary. Such interventions can accelerate and facilitate the transformation of the heating sector, and share the disparate individual costs that will likely be borne by individual customers.

The analyses underlying this report conclude that, based on the currently available information, none of the identified decarbonization pathways is clearly better than the others. The most appropriate and most economical decarbonized heating solution remains uncertain, and may depend on a customer's unique circumstances. For example, the long-run cost of renewable fuels is highly uncertain, particularly if they must supply fuel volumes similar to today. Also uncertain is the ability to overcome deployment barriers for ground source heat pumps, and the cost of heat pumps and the price of electricity from a fully decarbonized grid. In addition, the cost and applicability of these solutions to any particular (existing) building will often depend on its unique circumstances. It does seem likely that, on a purely economic basis, decarbonized heat will be more costly than the cheapest fossil solution today (natural gas), though not necessarily when compared to oil or propane.

For these reasons, rather than discrete technology mandates that may prematurely dictate technological and economic outcomes, it is appropriate to develop a set of policy principles to guide policy development, giving flexibility to respond to changing circumstances and information. In the short- to medium-term, policy should remain technology-agnostic about the long-term transformation, while promoting early demonstration and development of a number of promising technologies and program structures to learn and fill the information gap, and taking action to future-proof the heating system by not locking into any particular path. The focus should be on early activities that not only achieve emissions reductions (though that is important), but also facilitate a dramatic acceleration of decarbonization in the future.

POLICY PRINCIPLES

The uncertainty about the best long-run decarbonization approaches, the lack of information and experience, as well as the need to make early progress on the heating transformation suggest several principles for policy development, laid out below in this section.

Ensure progress: Collectively, the chosen set of policies should ensure that material progress is being made on decarbonization. One way to do this is to decarbonize all possible heating pathways, so that whatever path is chosen by individual consumers, the overall heating sector in Rhode Island is making progress toward decarbonization. This could take the form of decarbonizing the electricity that will power heat pumps that are deployed, while simultaneously decarbonizing fossil-based heating fuels for customers who continue to rely on traditional furnaces and boilers. On the electric side, Governor Raimondo's Executive Order requiring 100% renewable electricity by 2030 (EO 20-01) is an important step forward.[83] Rhode Island has also taken an initial step toward decarbonizing traditional fossil heating fuels with a 5% biodiesel blending requirement for heating oil in the state. Extending such a blending requirement to the natural gas system and increasing the share over time, ultimately to 100% for both gas and oil, will ensure ultimate decarbonization, regardless of which pathway is ultimately chosen by customers.

Take advantage of "natural investment opportunities": Heating infrastructure, such as building envelope components, boilers or furnaces, gas distribution pipes, power lines, etc., is very long-lived and is replaced or updated only infrequently. It is generally much less costly (and thus more cost-effective) to change such infrastructure at a time when the existing infrastructure would otherwise be replaced (or is soon to be replaced), serviced, or even just accessed in the normal course of operations. This has two implications. First, it will often be best to time a change to the heating system to coincide with such interventions, since at that point it will involve less incremental cost and less disruption – for instance, by timing the installation of a heat pump with the end of life of a furnace to save costs. Since a typical furnace or boiler life is roughly 25 years, a prompt start means that such natural investment opportunities may occur about once on average for each building by 2050.[84] Similarly, modifications to improve the efficiency of a building envelope are most economical when the building shell is otherwise being modified, particularly for some of the more invasive and costly interventions. Such intervention points may only occur once over the next 30 years. For customers with recently-installed heating systems and/or newly-constructed homes, it may not occur at all. This principle applies at several levels – to the replacement of a furnace or boiler in an individual residential home at the end of its normal life, as well as to the gas and electric distribution infrastructure when components of it are being replaced or upgraded. In either case, it will be less costly to transform the system if decarbonization activities are timed for when a significant investment otherwise must be made in the normal course of business. Taking advantage of natural investment opportunities also implies avoiding lock-in to GHG emitting heating solutions when larger investments are being made.

83 Even with Rhode Island achieving a 100% renewable goal by 2030, the state remains interconnected and dependent upon the regional New England generation and transmission system. Since it will continue to be affected by fossil-fired electricity in this way, efforts to reduce greenhouse gas emissions in the rest of New England will be equally important.

84 This raises another point, which is that it may be quite difficult to transform a building's heating system when the heating system has actually failed. The urgency to restore heat will probably lead to an emergency replacement with a similar furnace or boiler (quick and relatively simple since other parts of the system need not change), which would not allow time to consider, plan and implement a different heating solution. This points to the value of planning such changes systematically and well in advance to occur when the heating system is aging but prior to actual failure.

Extend the planning horizon, and future-proof: Because many heating-related investments will last for decades, investments should be made keeping this in mind. This may be particularly important for the electric transmission and distribution system, where upgrades to the distribution system will likely become necessary over the coming decades to accommodate electric vehicle penetration and potentially more decentralized energy production (such as rooftop solar PV). Since distribution system upgrades likely involve a significant element of "fixed costs" (deploying workers and equipment), the incremental cost may be modest to make larger upgrades than those immediately needed, and would create additional capacity to accommodate longer-term needs, including potential electrification of heating, thus avoiding the need to upgrade capacity multiple times in smaller increments.

Implement no-regrets improvements – but don't stop there: There are likely some changes that can be made that would qualify as "no-regrets" actions in that they will be valuable regardless of future developments in the heating sector. Such policies should be pursued where they can be identified, but policies will likely need to go well beyond such no-regrets actions. The magnitude and speed of the transformation needed means that a broad array of approaches must be implemented in order to make enough progress quickly enough. This will include some that may not be guaranteed to be "successful" in all future states of the world, though even policies that appear unsuccessful often yield valuable information and experience that can advance the ultimate objective. Fortunately, there are many policy actions that do not require large resource expenditures or irreversible commitments, or foreclose major alternative solutions. Many of these involve relatively small investments to learn or disseminate information about the cost and effectiveness of decarbonized heat technologies. Pilot and demonstration projects, or information campaigns directed at the public (consumers), equipment installers and even policymakers can be relatively low-cost ways to expand the information set and enable a faster, smoother transition. Planning is also relatively low-cost and facilitates considering multiple alternatives rather than foreclosing options. This includes developing plans for actions that may never be taken, where the act of planning draws out useful information and identifies what actions would be necessary to implement the plan, well ahead of an actual decision point. The gas and electric utilities may be in a good position to develop high-level plans for how they might implement or facilitate a transformation along any of the pathways, and can identify barriers so they can be addressed before they slow progress.

Learn and share information: Given the limited state of information about decarbonization pathways in the heating sector, there is substantial scope for efforts to promote learning and information sharing. Efforts could take the form of public information campaigns, pilot and demonstration projects (best if well-publicized), etc. Such efforts can accelerate and facilitate decarbonization along several of the potential pathways, in part by helping to generate the public and political support necessary. Much can be learned from projects already done or in process, and systems already available elsewhere. But local pilot and demonstration projects can also be useful for learning about how technologies and approaches may apply in Rhode Island circumstances, and they can also play an important role in publicizing and disseminating information.

Plan for contingencies: In light of the scope and unfamiliarity of the transformation that is necessary, and the uncertainties about the ultimate cost and performance of alternative pathways, an early start to planning the transition is crucial. This does not mean (only) planning what specific actions will be taken, though that is ultimately necessary. It also means developing reasonably well-specified though still high-level contingency plans for a range of potential pathways and possible futures, as a way to identify the opportunities and obstacles that may be encountered and to begin to make progress on addressing them. For example, given there is at least a possibility of heavy reliance on air-source heat pumps, it will be useful to explore how the electricity peak impacts might be handled, and potential ways to mitigate them. Similarly, while it is not yet clear that decarbonization would involve a large decrease in delivered gas volumes, it will nonetheless be useful to understand how this would affect the gas system and develop approaches to address it. Over time as the transformation progresses and more is learned, the contingency plans can be updated, and ultimately some of them will likely be implemented.

Keep options open: Because of the large uncertainties about the cost (and to a lesser extent, the performance) of the various decarbonization pathways, it is not clear now which, if any, will ultimately dominate. In this circumstance, it is important to avoid foreclosing potentially promising decarbonization pathways, and will be equally important to open up potential pathways by using some of the principles noted here to determine how they might be implemented and learn about their benefits and costs. Learning and contingency planning activities can be used to identify and select the right pathway, and will also facilitate its ultimate implementation. As an example, it is almost certainly too soon to commit to abandoning or paring back the gas delivery system, but it will be useful to plan how to optimize it to take advantage of renewable gas where it is most important. This might involve expanding the gas system in industrial zones with few alternatives to burning fuel, while perhaps restricting new residential connections where alternatives are available.

Planning ways to decarbonize both paths (renewable fuels and electric heat pumps) can preserve a diverse set of alternative solutions while clarifying the tradeoffs. In fact, because of the diversity of buildings, geology, infrastructure, etc. in Rhode Island, it is very unlikely that any single decarbonization technology will dominate in all instances. This implies that the ultimate solution will probably include at least some of each approach – building efficiency, ground and air-source heat pumps, renewable fuels. Since the amount of each that must ultimately be implemented will almost certainly be more than currently exists, beginning now to pursue all these pathways simultaneously is likely to be a positive step toward decarbonization, and can be particularly useful where actions are targeted to learning and information sharing opportunities. As more is learned, if one of the technologies begins to look relatively better than the others, implementation efforts can shift toward it, giving it a larger role in the ultimate mix without regretting the early implementation of other approaches.

A POLICY ROAD MAP FOR THE NEXT 10 YEARS

Transforming Rhode Island's heating sector over the next three decades is a major challenge and requires making significant progress not just in the distant future, but also (and perhaps critically) within the coming decade. While it may be tempting to try to identify the single best technological solution or strategy, the analyses conducted for this project and presented above suggest that, at least at present, such a policy approach would be at best premature.

Hence, a policy roadmap for the next ten years must address the lack of clarity about what specific decarbonization approach(es) are most cost effective and hence worthy of support, the reality that both cost and implementability will likely be customer and application specific, and that making real progress and establishing the groundwork for accelerating heating sector decarbonization in the following decades is an urgent task for the coming decade. This comes against a background in which decarbonized heat is, in many cases, not currently economic when compared against the continued use of fossil

Ensure	Increase efficiency and reduce carbon content of all fuels to zero over time – ensures progress no matter which technologies are used
Learn	Data collection, R&D, pilot projects to understand technologies, infrastructure, and customers
Inform	Educate stakeholders – customers, installers, policymakers – about pros and cons of options, system interactions, etc.
Enable	Facilitate deployment with incentives; target natural investment opportunities; align regulations, rules, and codes; expand workforce
Plan	Expand planning horizon; develop long-term, high-level contingency plans now (do not commit yet) and use to guide near-term policy

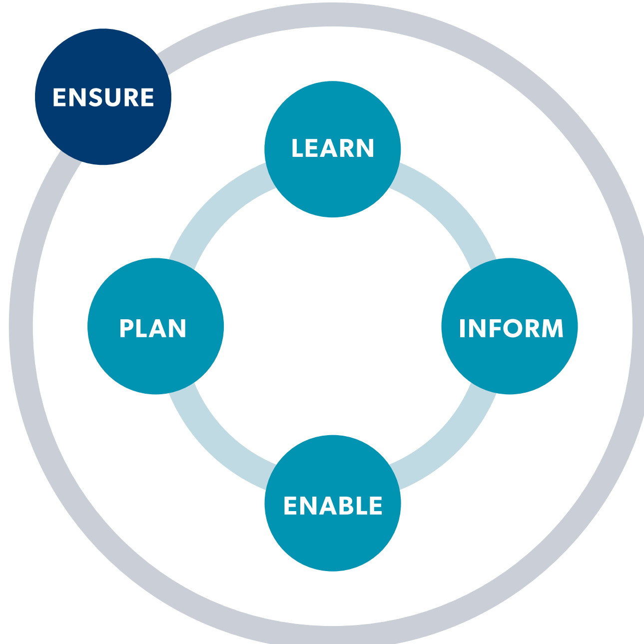


FIGURE 29: THEMES TO GUIDE EARLY POLICY RECOMMENDATIONS

fuels, in particular natural gas – although it may be in time, based on the analysis performed. On the positive side, policy measures that help advance any of the identified approaches are unlikely to cause large regrets in hindsight. With learning and more information becoming available over time, it will be valuable to periodically reevaluate the relative attractiveness of the various solutions and potentially revise policies accordingly.

1. Policy Themes for the Near Term

Against this backdrop, several themes should guide concrete policy actions over the coming decade. They are summarized in Figure 29 and described further below, along with some specific policy suggestions. These themes overlap to an extent; they are not mutually exclusive categories but rather serve as a useful way to organize the policy ideas below, based on their objectives and effects.

a. Ensure

Policy measures that ensure early progress towards zero-carbon heating is made, independent of which heating technology may ultimately be favored, represent the backbone of more specific policies designed to learn, inform, enable and plan. For example, to the extent the carbon content of all available heating "fuels" declines over time to (near) zero, successful decarbonization can be assured. There are many policy approaches to ensuring progress. They include fuel- and technology-neutral GHG reduction policies, maintaining or expanding support for ongoing activities contributing to heating decarbonization, etc. If structured properly, policies that ensure early GHG reductions may also offer longer-term benefits such as learning, informing or expanding delivery capabilities, which can increase their impact. Some of these policies can be relatively easily implemented by Rhode Island alone, while others would likely benefit significantly from regional or even national coordination. Examples of such policies include:

- **Develop policies that guarantee gradual decarbonization of all heating "fuels,"** so that even if fuels continue to be burned, GHG emissions will fall.[85] Policies in this category include, but are not limited to, renewable "fuel" standards or fuel-specific decarbonization mandates, cap-and-trade programs, or a carbon tax construct. Given the size and connectedness of Rhode Island to New England, it is likely that any such policy would benefit significantly from regional coordination. Some existing policies could be expanded or used as a blueprint for developing heating related approaches. For example, the Regional Greenhouse Gas Initiative (RGGI) is a cap-and-trade program that covers emissions from most power plants in the electric sector. It could be broadened to include more plants or sectors, just like the cap-and-trade program in place in California was expanded over time to include sources of greenhouse gas emissions other than those in the electricity sector. Similarly, renewable energy standards (RES) can be expanded to the heating sector, requiring decreasing carbon content (or an increasing share of clean or renewable "fuel") across all heating "fuels" or for each fuel separately. Examples include California's low carbon fuel standard (LCFS), which is a program that requires decarbonization across all transportation fuels, or fuel-specific blending requirements, such as the 5% biodiesel blend requirement for heating fuel currently in place in Rhode Island. Finally, Renewable Thermal RPS programs are beginning to be introduced in a number of states, including elsewhere in New England. Renewable Thermal RPS can take many forms, but they generally result in the creation of "renewable energy certificates" (RECs) that are counted against an increasing target. In some states, renewable thermal requirements are bundled with renewable electricity requirements, while in others thermal and electric targets are developed separately.[86]

The Rhode Island electric sector already has both regional and state-level decarbonization targets such as those included in RGGI,[87] the existing Rhode Island Renewable Energy Standard[88] as well as the recently issued executive order to reach 100% renewable electricity supply by 2030.[89] One approach would therefore be to develop similar decarbonization policies for the other heating fuels, either under one program or on a fuel-specific basis, with fuel-specific approaches being likely more easily implemented than policies covering multiple fuels. The biodiesel blending requirement currently in place could be used as a basis for requiring decarbonization of delivered fuels over time. Depending on the desired pace of decarbonization, the biodiesel blend requirement would ramp up over time as illustrated in **Figure 30**.

To achieve full decarbonization by 2050, the renewable content of heating fuels would have to increase by almost 3.5% each year, which would result in a biodiesel blend requirement of about 36.5% by 2030.

It is currently not clear how such a mandate (or a broader Clean Heating Fuel Standard) would affect the price of delivered fuel over time, or how potentially increasing fuel prices would affect the demand for each heating fuel. However, given the uncertainty about how the costs and supply

85 "Fuels" refers to all sources of heating energy including electricity, natural gas, oil, propane and wood.

86 For a description of recent renewable thermal RPS approaches, see Clean Energy States Alliance, Renewable Thermal in State Renewable Portfolio Standards, July 2018

87 For details on RGGI see https://www.rggi.org/program-overview-and-design/elements

88 For details on the Rhode Island RES, see http://www.ripuc.ri.gov/utilityinfo/res.html

89 http://www.governor.ri.gov/documents/orders/ExecOrder_17-06_06112017.pdf

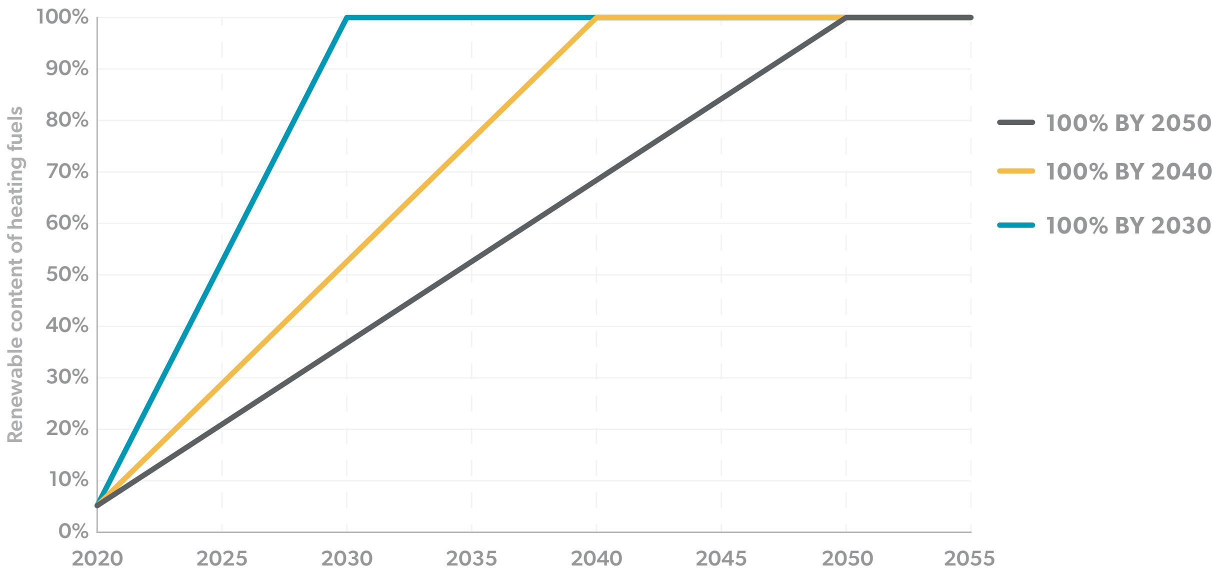


FIGURE 30: **ILLUSTRATIVE BIODIESEL BLEND MANDATES RESULTING IN FULL DELIVERED FUEL DECARBONIZATION BY 2030, 2040 OR 2050.**

of various decarbonized heating solutions evolve over time, mandating gradual decarbonization of all heating fuels provides precisely the ability needed to let market forces, technological progress and consumer preference determine how the heating sector in Rhode Island decarbonizes over time.

- **Acknowledge the cost impacts of decarbonizing fuels and proactively address them.** Decarbonizing fuels through one of the approaches outlined will create cost impacts for customers of all classes. Consider policies that account for and potentially mitigate these impacts. This may be particularly important for low- and moderate-income customers, as well as industrial customers competing in globalized markets. It is crucial that state policymakers, agencies, and regulators actively collaborate with utilities and consumer advocacy organizations to thoughtfully structure heating investment strategies, and unlock creative opportunities for cost efficiencies. These strategies should be developed within the context of other crucial climate change-related investments, such as accelerating renewable generation and transforming the electric grid to enable higher penetration of clean energy resources.

- **Expand cost-effective energy efficiency improvements** to reduce overall heat needs and support delivery of no-to-low carbon heating solutions. Rhode Island has exhibited national leadership and innovation on energy efficiency and least cost procurement measures. It should maintain and expand these efforts to further develop the workforce, supply chain and markets needed to deliver additional cost-effective building efficiency measures, e.g., by renewing and strengthening the least cost procurement statute.[90] This should include finding additional opportunities for intervention, particularly at "investment moments" where efficiency can be improved at low incremental cost in connection with building improvements or maintenance that is being undertaken for other reasons. Also, building efficiency programs should

90 http://www.energy.ri.gov/policies-programs/ri-energy-laws/least-cost-procurement-2006.php

be fuel-neutral, independent of the heating fuel used, and coordinating the delivery of alternative heating solutions through energy efficiency programs may facilitate their delivery. Recent experience shows that National Grid is essentially on pace to perform efficiency audits of all Rhode Island buildings in the next few decades, though only about one-third of audits lead to weatherization projects.[91] In line with the policy theme of taking advantage of natural investment opportunities, this suggests that increasing the conversion rates of audits into weatherization should be one of the focal areas over the coming decade. Additional cost-effective efficiency measures reduce overall costs to Rhode Islanders – particularly important in the context of decarbonizing the heating sector.

- **Voluntary green tariffs** that allow customers to source a higher share of their energy from renewable sources (perhaps for gas as well as electricity) could engage customer sentiment to accelerate the pace of decarbonization.

Once policies to ensure progress towards heating sector decarbonization no matter what heating fuel or technology is being used are in place, efforts over the coming decade should focus on learning, informing, enabling and planning.

b. Learn

One obvious response to uncertainty is to learn more about the costs, performance and practical feasibility of the decarbonized heating system alternatives. Learning can be supported by policy via theoretical and applied research as well as pilot and demonstration projects. In particular, applied research requires data, and the collection of relevant data – not just about the decarbonized technologies, but also about Rhode Island's buildings and electric and gas utility infrastructure – represents an important precondition for learning. Installing decarbonized heat systems that yield near-term GHG savings will often also create opportunities for learning more about how (or how not) to implement these technologies and the programs that deliver them; similarly, early experience can guide a better understanding of consumer reactions, preferences and information needs. Some specific ideas about policies that could foster learning include:

- **Gather information.** Additional information in a number of areas would be very helpful in developing more targeted policies and incentives and in evaluating progress. Information that should be gathered falls into several categories: more detailed information about the "status" of the current heating sector, such as type, and remaining life of customer-sited equipment; cost and performance information on deployed new technologies such ASHP and GSHP, and issues affecting use of these in individual buildings (need for ductwork, electric upgrades, ground loop, etc.) This information gathering might be implemented by expanding existing efficiency program EM&V work to also include collecting such data. Recognizing that customers likely cannot be required to provide information, policy could tie incentives (or other "carrots") to voluntarily providing relevant information, which can help target or refine policy. For example, information about the remaining life of current heating systems may help target incentives to heating systems when they need to be replaced, rather than replacing systems only upon failure.

- **Research.** Given the uncertainties about various heating decarbonization solutions and the fact

91 In its most recent update, National Grid reports that of the more than 10,000 customers receiving energy audits under the EnergyWise program, 3,700 proceeded with weatherization measures. The Narragansett Electric Company d/b/a National Grid, 2018 Energy Efficiency Year-End Report, May 15, 2019, p.8

that Rhode Island is not alone in attempting to decarbonize heating, policy over the next decade should have a significant research focus. Research and studies to provide more information about the performance, cost, barriers and policy solutions outside of Rhode Island can help focus and improve policy measures in the State. Since Rhode Island is a small state and markets for renewable fuels are likely to be national or international in scope, it may be most effective for the state to partner with other jurisdictions on research (and demonstration) projects. Some examples of research activities include:

- Studies for all of the pathways to identify experience gained elsewhere, understand how that may apply to Rhode Island.
- Studies to identify information gaps, which may then be amenable to studies, pilots or demonstration projects in the state, or in partnership with other states.
- Studies to better understand the potential local, regional and national sources for renewable fuels as well as barriers to their development, including conditions for interconnecting potential renewable gas supplies to the existing gas delivery infrastructure.
- Studies to understand potential geological obstacles to deploying GSHPs or at least to better understand how ground loop costs may differ by area, based on sub-surface conditions and other factors.

- **Understand how the gas distribution system responds to volume loss.** Develop a much better understanding of how the operations and costs of the gas distribution system are likely to respond to heating sector transformation, which may cause both increasing commodity cost (as an increasing share of more costly renewable gas is blended with fossil gas) and decreasing delivered gas volumes (as customers displace some or all of their gas heating needs with alternative heat sources such as heat pumps). Identify opportunities to reduce costs by concentrating volume loss in particular sub-parts of the distribution system and selectively paring back those sub-parts, as opposed to experiencing more or less proportional reductions in volume across the entire system, which would require that the entire system continue to operate with little opportunity to save costs.
- **Understand opportunities and limitations on GSHPs, particularly regarding the ground loop and GeoMicroDistricts.** These may face constraints because of geology and may also be affected by the density of buildings and other infrastructure, perhaps differently for individual ground loops vs GeoMicroDistricts. E.g., can GeoMicroDistricts be used in more dense areas where individual ground loops might be difficult, perhaps by taking advantage of public rights-of-way?
    - Understand the feasibility and cost of GeoMicroDistricts, identifying what types of areas are suited to them in terms of geology, presence of other infrastructure (which might complicate installation) and density of buildings and heating requirements. Understand what extent and participation levels are necessary to make a GeoMicroDistrict viable, e.g., for retrofitting an existing neighborhood with GSHP.
- **Use pilot and demonstration projects to explore options.**
    - For example, use pilot projects to characterize the peak implications of air source heat pumps on the electric system peak in the coldest weather, and options to mitigate, shift or otherwise address them. Potential solutions could include onsite thermal storage systems that shift electricity usage away from peak to

nearby hours, battery backup to store power, or a backup (non-electric) heat system. Pilot and demonstration projects could help to estimate the cost of these measures, and barriers that may exist to implementing them.

  - Similarly, use pilots or demonstrations to understand technical issues with blending renewable fuels into the existing fossil fuel streams during a transition period. Identify operational issues that arise with retrofitting equipment to handle very high blends of biodiesel, up to B100.

- **Understand the industrial sector and its heat needs to identify energy-intensive industries that may be vulnerable to the higher cost of decarbonized heat** (e.g., substituting higher-cost renewable fuels for fossil), especially those with competitors in other jurisdictions that may not need to decarbonize.

c. Inform

The current level of knowledge about low- and zero-carbon heating solutions remains low, as was raised several times in stakeholder interviews and public workshops. The transformation of the heating sector will require better information on the part of many stakeholders in the heating system. The individual owners of most or all existing buildings must adopt new heating approaches, and they will be better equipped to take the necessary actions if they have a better understanding of the technologies, and confidence in their advantages (and disadvantages) in terms of cost, comfort, and disruption and in the quality and reliability of installation. It is not only end-use customers who would benefit from better information about the available decarbonized heating alternatives. Even installers and policymakers often do not have good information or shared knowledge bases. Some potential policy options to create better information for all stakeholders include:

- **Use public information campaigns**, such as utility bill inserts, billboards, online or television and radio advertisements, to create familiarity with the alternative technologies and approaches, and to communicate their advantages and disadvantages.

- **Use demonstration projects to inform.** Well-publicized projects, such as public buildings heated with ASHP, GSHP or renewable fuels, can inform customers and make decarbonized heating solutions more familiar and acceptable. Such projects can include not only publicly-owned buildings (Town Hall, library, etc.) but also private buildings frequented by the public (retail stores, restaurants, movie theaters, hotels). Providing consumers the ability to experience decarbonized heating in action can play a major role in overcoming adoption barriers. This also applies to other heating applications that are deemed essential by consumers, such as cooking. Highlighting restaurants that cook with induction stoves might be one opportunity to begin addressing misconceptions about this and similar technologies.

- **Formalize training and certification programs** for professional installers to improve their understanding and make them more willing to undertake installations, and to recommend them to clients where they are warranted. An additional benefit is that this may avoid under-performing installations that could give the technology an unrealistically negative word-of-mouth reputation.

- **Provide information about qualified installers.** Often, consumers are worried about whether or not a given installer is skilled and qualified. Public agencies could provide information about installers that have received proper training and certification and perhaps additional information, such as the number of installations performed and potential consumer feedback (assuming private sector information sources do not provide sufficient information about consumer experiences).

d. Enable

Decarbonization of heating along any of the identified pathways will likely require significant ramping up of a range of activities. The next ten years must set the stage for the deployment of decarbonized heating solutions at large scale by enabling the transformation at many levels. This includes removing barriers and addressing challenges to enable the technologies themselves, the workforces needed to install and implement them, customers' willingness to adopt them, and utility programs, regulatory structures, etc. There is still uncertainty about the long-run cost and performance of many of the potential decarbonization technologies, and it is not yet clear which one (if it is one and not multiple) may ultimately be the best solution in the long run. But that is not reason to wait; it is in fact a reason to push forward, since experience, and not just the passage of time, accelerates the resolution of this uncertainty.

- **Provide buyer incentives for "all."** Depending on the policy approach adopted to ensure decarbonization of all heating "fuels", it is possible that all decarbonized heating solutions remain more expensive than current fossil-fuel based heating. Also, as shown above, payback periods for some solutions may well be longer than the short payback often demanded by consumers, even if they are lower cost in the long run. This is particularly the case for solutions with higher upfront cost, such as heat pumps and especially ground source heat pumps. Finally, learning about the performance and potential cost trajectory of various solutions requires some ramp up of experience across all the decarbonization solutions. For these reasons, incentives that encourage (early) adoption of each of the promising technologies (i.e., all those identified here) are likely needed to jump-start the market for decarbonized heating solutions. These incentives can take many forms, ranging from incentives directed at installers or manufacturers, to purchase price rebates for equipment, on-bill financing or full ratepayer funded installations (via utility ownership) directed at consumers. They could potentially be supported by "green bonds." Ratepayer funding and/or utility ownership are likely most appropriate for solutions that are similar to those traditionally provided by utilities, such as the GeoMicroGrids discussed above (where utility ownership of ground loops would mirror electric distribution wires or natural gas distribution pipes, with end-user equipment such as heat pumps being privately owned). The specific design of incentive programs for various stakeholders is beyond the scope of this study, but, any such undertakings must be planned and implemented carefully, understanding the cost impacts on various consumer groups, and interactions with other initiatives.[92]
- **Improve regulatory structures.** The current gas distribution revenue decoupling law in Rhode Island has the effect of encouraging gas growth and discouraging electrification as an alternative means of heating. Specifically, when the gas utility increases the number of gas distribution customers on its system, the utility receives more revenue per customer in between rate cases. Conversely, when the number of gas distribution customers decreases, the gas utility loses revenue. This ratemaking principle is referred to in the industry as a "revenue per customer" decoupling mechanism. The mechanism was put in place before the impacts of carbon emissions were fully appreciated and policymakers understood that the addition of gas customers would lower the unit cost of gas distribution for the benefit of all gas distribution ratepayers. The regulatory

92 Caution may be particularly important in the near term, given the unpredictable impact of the economic crisis resulting from the COVID-19 pandemic.

framework should be changed to provide the Public Utilities Commission with the authority to develop a framework that de-emphasizes gas growth and encourages decarbonizing solutions in a fuel-neutral way. However, in Rhode Island, the “revenue per customer” mechanism for the gas business is embedded in statute and, thus, prevents the commission from changing this ratemaking mechanism. An amendment to the law would be required to alter it.

- **Enable a regulatory planning process.** A comprehensive and objective planning process could be created by a funding mechanism in gas and electric distribution rates that facilitates a study and statewide planning process that is coordinated and guided by the state energy and regulatory agencies in collaboration with the utility and other stakeholders.

- **Improve rate design**, both existing rates and potential changes, where existing rate structure may give incentives that are inconsistent with decarbonization, or changes may create opportunities to encourage the transition. For example, decoupling rates so that they better reflect fixed and variable cost causation (perhaps adjusted to better reflect GHG costs which do not actually appear in rates, absent a carbon price) may improve incentives. Including the initial gas interconnection cost in the rate base may not be consistent with the potential for scaling the system back in the relatively near future. Similarly, if the transition may cause gas system assets to have a useful life that differs from traditional assumptions, consider adjusting asset lives, both for assessing proposed investments and potentially for recovering the costs of existing assets. Rate design issues may be a useful way to address the peak impact of heat pumps, e.g., with capacity pricing, or time-of-use or real-time pricing. And of course, issues regarding the ability of low-income consumers to have access to low-carbon heat sources can be addressed through rate structures and ratemaking.

- **Explore a combined energy utility.** Consider a joint ratemaking framework and rate design to enable a single combined rate base for both the electric and gas distribution company. Since the primary electric and gas distribution company in Rhode Island provides both services, utility customers could be treated as “energy distribution” customers for purposes of allocating decarbonization costs, rather than segregating “gas distribution” and “electric distribution” customers. This will address the costs of decarbonizing as a single inter-related initiative, which can facilitate a more equitable distribution of costs and protect customers (including low-income customers and renters) who might otherwise be forced to bear high transition costs as a result of their historical energy system.

- **Take advantage of “natural investment opportunities.”** As discussed above, any time the building envelope or heating infrastructure is being replaced, serviced, etc., this creates a scarce opportunity to reduce heating requirements or change the heating system. It will help to find ways to identify such situations prospectively so that efficiency improvements and heating decarbonization alternatives can be fully considered, and to take steps to encourage interventions at these points, e.g., through LCP efficiency programs. Also, the addition or replacement of a central air conditioning system in an existing building (which may become more frequent with warming summers) creates a similar opportunity, and could become an important driver of heat pump adoption.[93] Such intervention points can be used to upgrade electrical systems to accommodate future electrification demands from both heat and transportation. One challenge will be to gather and systematize data that will enable the identification of these natural investment points.

- **Substantially tighten building efficiency standards.** New buildings, and also major building interventions such as rehabs, should meet very high efficiency standards, perhaps net zero energy use. Consider also requiring the use of decarbonized heating systems, perhaps electric heat pumps, in new and renovated buildings, since a missed opportunity is unlikely to arise again soon.

- **Identify and remove barriers.** Enabling will involve identifying and removing important barriers to technology deployment (such as rules, building codes and permit requirements for deploying both ground- and air-source heat pumps, developing clearer rules for biofuels, etc.), efforts to increase the number and skill-level of the work-force that will be needed to deploy rapidly advancing heating technologies, overcoming unwillingness to give up gas for cooking, etc. In part, pushing the early implementation of these technologies will help to identify these barriers.

- **Build supply capacity.** Since heat pump installation is not currently a fully-developed market, Rhode Island will likely need considerably more installers of heat pump systems. To achieve that, it may be necessary to destigmatize the building trades and provide incentives to attract enough talent. Installers will also need high quality training provided to them to properly design and install heat pump systems for the Rhode Island climate.

- **Create separate incentives for heat pumps and for building envelope improvements.** Each helps reduce GHG emissions, independent of the other, and requiring the two to be linked may inhibit adoption.

- **Reserve limited resources for high-value uses.** Renewable fuels likely have an increasing supply curve, with modest quantities available at costs that are not too high, but high demand pushing prices very high. Consider decarbonizing in ways that reserve renewable fuels for high-value uses, like some specialized industrial uses, that do not have a ready substitute, and using other decarbonization approaches where they are available.

- **Understand and consider strategies to mitigate adverse effects.** As the analyses above indicate, decarbonizing heating in Rhode Island may increase the cost of heating for some consumers, particularly those currently using natural gas, and it may similarly increase total energy wallet expenditures for some consumers. The diversity among customers means that cost impacts will likely differ across customer groups and individual customers. Some customers, such as economically disadvantaged customers and industries exposed to competition, may be particularly exposed to any such cost impacts. In this context, it will be important in the near term to identify policies that promote solutions that reduce overall long-term system costs. This will put the state in a better position to consider additional policy alternatives to mitigate remaining impacts on vulnerable customers.

93 In the most recent evaluation of Maine energy efficiency programs including heat pump incentives, 64% of survey respondents listed "Add air conditioning" as the install reason, the third most frequent response after improving energy efficiency and saving on heating costs. See West Hill Energy and Computing, Efficiency Maine Trust Home Energy Savings Program Impact Evaluation, Program Years 2014-2016, August 23, 2019, Appendix G, p.4

e. Plan

Finally, policy could support a change in approaches to planning by various entities including state agencies and regulated entities, notably National Grid. Today's planning activities often have a relatively limited time horizon of ten years or less, and presume that the utility systems will continue to operate much as they have in the past. The focus is on planning for "expected outcomes" – forecasting and planning for the most likely future developments, perhaps considering a few sensitivities. Transforming Rhode Island's heating sector over the next three decades in the presence of the fundamental uncertainties discussed throughout this report likely requires an augmented approach to planning. This should include developing a broader set of high-level contingency plans with longer time horizons – likely with a view at least towards 2050, in addition to current planning horizons – and planning for outcomes and actions that may never materialize, in order to be ready in case they do. Developing such plans does not imply an intention to implement all of them; in fact, some of the plans developed may be inconsistent with others. But developing such plans now will serve several purposes. First, they can guide near-term actions to ensure they are consistent with long-term goals. Second, the process of developing these plans will promote a better understanding of what is likely to be involved with each of the pathways, including the identification of major barriers, allowing solutions to be developed early and avoid delays later. Finally, such plans help provide "shovel-ready" responses if/when some of the contingencies studied should in fact arise. Some concrete examples of this enhanced type of planning include:

- **Use longer-term planning for the electric distribution grid.** Current planning of the distribution grid, including grid modernization plans, tend to be focused on shorter timer horizons such as ten years and based on expected demand as well as its potential evolution. Understanding the implications of electrification of both transportation and heat for demands on the electric transmission and distribution system over the long-run, i.e., through 2050, would allow improving investment decisions. For example, the cost of building out the distribution system as the heating system decarbonizes may be reduced through a better understanding of the additional cost of future-proofing. Rather than expanding system capacity to accommodate expected demand changes over just the coming decade, the planning process should also consider potentially larger capacity increases that could accommodate greater demand growth in the longer term due to high penetration of heat pumps and electric transport. Such planning may also allow targeting first those areas that may be likely to electrify earlier – e.g., non-gas areas where the economics of electrified heat are better.
- **Develop a gas system transition plan.** There is much uncertainty about how usage of the natural gas system will evolve as it delivers an increasing share of lower carbon gas at potentially higher cost, while the cost and availability of other decarbonized heating solutions improve. In this light, the question of the long-run role of the gas distribution infrastructure is one of the most complex and important questions. As the analysis in this report shows, it is too early to draw conclusions about this ultimate role, but developing plans for various eventual roles of the gas system will help the state to prepare for alternative trajectories, as well as identify mechanisms for reducing the impact and cost of a transition away from gas, should it need to be reconfigured, reduced in scope, or even ultimately decommissioned. Such planning should consider possibilities such as paring back some branches while retaining or perhaps even expanding others, e.g., if some industrial customers have no alternatives to gas or for whom renewable gas is substantially more attractive than using decarbonized liquid fuels.

- **Develop a heating transformation implementation plan.** While this report and the Meister Report provide important policy guidance, neither is sufficient to drive the choice and implementation of concrete policy proposals. But these studies could provide a starting point for state agencies to develop an implementation plan with a coherent set of concrete policy proposals that could be implemented directly. Since it is likely that over the coming decade new information will help better understand the attractiveness and barriers to the various heating decarbonization approaches analyzed here, both the heating transformation strategy (this document) and the resulting Heating Transformation Implementation Plan should be revisited periodically. Revisions of the Implementation Plan will be warranted if key metrics such as the ones developed in this report change significantly. For example, while this report suggests policies to scale up any and all of the promising decarbonized heating options are beneficial, from today's perspective, future revisions may conclude that certain approaches become clearly preferred and should be the focus of further policy measures, and others should not.

- **Plan a centralized heat pump conversion effort.** Although it is too early to commit to mass conversion to heat pumps, it will be instructive to begin to develop a plan for how the state and its utilities would organize and implement a widespread decarbonized electrification program for heating (e.g., installation of ASHP and/or GSHP, and perhaps community GeoMicroDistricts) for many buildings across the state. The plan should be informed by smaller programs focused on supporting early adopters and currently cost-effective conversions. The plan could also proactively identify existing heating systems near end-of-life to facilitate the economics, and making the program opt-out rather than opt-in would increase participation. Planning should consider what costs should be recovered and how, and whether the cost recovery mechanisms could be tailored to address equity issues.

- **Expand planning horizons.** State agency and utility planning may require longer horizons than have been used historically. For example, while it might be appropriate to plan component replacements and upgrades just 5-10 years in advance on an "evergreen" system that is expected to last longer than the components being replaced, this is not true when the system must change fundamentally over a shorter horizon. Facing the need to decarbonize over the next few decades, system planning needs to take into account not just the lives of the components that will be replaced, but also the potential life of the system that they are a part of. Policy could therefore encourage or require that any planning processes be enhanced by adding a decarbonized 2050 perspective to all existing planning time horizons.

Conclusions and Next Steps for Rhode Island

The quantitative and qualitative analyses presented here for heating sector decarbonization solutions lead to the conclusion that, as of today, no dominant heating sector solution fits all situations and is sure to minimize the cost to consumers and businesses. The analysis does suggest that overall, the cost of decarbonizing the heating sector along several possible pathways is likely to be relatively modest on average. The increased heating costs for some customers may be at least partially offset by savings in other energy sectors. However, the cost of decarbonizing heat remains uncertain, both on average and especially as it relates to any particular building, business, or customer.

For these reasons, Rhode Island's heating transformation strategy must ensure that early progress towards decarbonization is made, regardless of which solution or solutions are ultimately adopted. For example, by increased implementation of cost-effective energy efficiency measures and by putting all the energy sources used for heating on a pathway to decarbonization. Beginning with the insights here, Rhode Island can promote this transformation through a range of policy options that focus on learning and informing, to help address inherent uncertainties, and by taking steps to enable and plan for the transformation. These steps will include and are not limited to, creating incentives for customers to decarbonize, while ensuring that vulnerable populations are protected and that policies do not have unintended consequences.

Policymakers should use the coming decade to lay the groundwork and build the infrastructure for increasing the scale and speed of heating sector decarbonization – at least initially pursuing multiple different solutions. As time passes and learning increases, it may become clear that some solutions are better than others, at least for some customer segments, but that will not invalidate the early progress made with other solutions. Indeed, that early progress and the lessons learned from it will lay the foundation for later progress along whatever pathways are ultimately most advantageous.

Although three decades may seem a long time, the scale of the transformation needed in over 400,000 existing residences, corresponding numbers of small and large commercial buildings and industrial facilities, and an entire energy delivery infrastructure is a difficult challenge that will require sustained and careful attention, beginning urgently today.

Glossary

District Heating	A heating solution that provides heat to a number of buildings through a common system, rather than each building providing its own heat. District heating systems traditionally use a centralized boiler and distribute heat through a series of pipes, but the concept has been broadened to include a common ground loop to support GSHP systems in a number of buildings
GeoMicroGrid	A district heating system consisting of a common ground loop that supports GSHP systems in a number of buildings
GHG	Greenhouse Gas
GSHP	Ground Source Heat Pump
GWP	Global warming potential, the heat-trapping potential of a gas, relative to CO_2
MMBtu	Million Btu, a unit of heat energy (approximately equal to 10 therms)
MW	Megawatt, a unit of electric capacity (rate of delivering electric energy), equal to one thousand kW
MWh	Megawatt hour, a unit of electric energy, equal to one megawatt for one hour , equal to one thousand kWh
Power2Fuels (P2Fuel)	Power2Gas or Power2Liquids
Power2Gas (P2G)	Conversion of renewable electricity into renewable gas via electrolysis and methanation
Renewable Gas	Methane made from renewable sources, e.g., landfill gas, anaerobic digesters, gasified biomass, Power2Gas
Renewable Oil	Oil made from renewable sources, e.g., waste cooking oil, oil crops, Power2Liquids
TWh	A unit of electric energy, equal to one million MWh, or one billion kWh

Study Participants and Stakeholder Process

This study involved an extensive stakeholder outreach effort and interactions with a number of key stakeholders to help inform the work. Stakeholder engagement was an integral part of this study and an invaluable source of information and insights. Personnel from the Rhode Island Office of Energy Resources and Division of Public Utilities & Carriers, the state agencies responsible for directing this study, were integral members of the study team. This team benefitted from numerous meetings, calls and communications with National Grid, the electric and gas utility in Rhode Island, throughout the process. The effort also included interviews and meetings with over 20 individual stakeholder organizations, as well as three public workshops (the first two held in Providence, the third conducted virtually as a webinar due to restrictions imposed by the COVID-19 pandemic). These workshops were held to share information, present intermediate results and collect feedback from stakeholders. Throughout the process, stakeholders provided guidance and commentary regarding the key issues that should be addressed, their own perspectives and positions on issues, what information they had and what they lacked. Stakeholders also provided substantial data input and validation, as well as insights to support the analyses.

Acadia Center

Aquidneck Planning Council

Brown University

Cadmus Carbon Pricing Team

Center for Justice

Conservation Law Foundation

Daikin

Efficiency Maine Trust

GEM Plumbing

Green Energy Consumers Alliance

HEET

National Grid

Oil Heat Institute of Rhode Island

Providence Housing Authority

Rhode Island Association of Realtors

Rhode Island Builders Association

Rhode Island Housing

RIMA

Stash Energy

Summit Utilities

Tec-RI

Maine Office of Energy Efficiency

References

American Gas Foundation, Renewable Sources of Natural Gas: Supply and Emissions Reductions Assessment, December 2019

American Gas Foundation, Renewable Sources of Natural Gas: Supply and Emission Reduction Assessment Study, 2-page summary

Baig, Altamash Ahmad and Alan S Fung, Impact of Carbon Pricing on Energy Cost Savings Resulting from Installation of Gas-Fired Absorption Heat Pump at A Library Building in Ontario, MDPI Proceedings, August 16, 2019

Black & Veatch, The Role of Natural Gas in the Transition to a Lower-Carbon Economy, May 2019

The Brattle Group, Achieving 80% GHG Reduction in New England by 2050, September 2019

Buro Happold, GeoMicroDistrict Feasibility Study, November 2019

California Public Utilities Commission, Order Instituting Rulemaking to Establish Policies, Processes, and Rules to Ensure Safe and Reliable Gas Systems in California and perform Long-Term Gas System Planning, Proceeding R2001007, issued January 27, 2020

Clean Energy States Alliance, Renewable Thermal in State Renewable Portfolio Standards, July 2018

DNV-GL, The Potential role of Power-to-Gas in the e-Highway, 2050 study, 2017

E3. Draft Results: Future of Natural Gas Distribution in California, June 6, 2019

E3, The Challenge of Retail Gas in California's Low-Carbon Future, Final Project Report, California Energy Commission, CEC-500-2019-055-F, December 2019

E3, Deep Decarbonization in a High Renewables Future, California Energy Commission, CEC-500-2018-012, June 2018

ENERGY STAR® Residential Water Heaters: Final Criteria Analysis, April 1, 2018

EPA, Rules of Thumb – Energy Efficiency in Buildings, available at https://19january2017snapshot.epa.gov/statelocalclimate/rules-thumb_.html (no longer available on the official EPA website)

Fasihi, Mahdi, Dmitri Bogdanov and Christian Breyer, Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants, Energy Procedia 99 (2016) 243 – 268

IPCC, Fifth Assessment Report, Chapter 8: Anthropogenic and Natural Radiative Forcing

KPMG, 2050 Energy Scenarios, July 2016

Life Cycle Associates, Life Cycle GHG Emissions for Fulcrum Sierra Biofuels LLC's MSW-to-Fischer Tropsch Fuel Production Process, LCA.6060.120.2015, December 2015

Mahdi Fasihi, Dmitrii Bogdanov, Christian Breyer, Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants, Energy Procedia 99 (2016) 243 – 268

Mahlmann, Justin and Albert Escobedo, Geothermal Heat Pump Systems for Strategic Planning on the Community Scale, ACEEE Summer Study on Energy Efficiency in Buildings, 2012

Meister Consultants Group, Rhode Island Renewable Thermal Market Development Strategy, prepared for the Rhode Island Office of Energy Resources, January 2017

M. W. Melaina, O. Antonia, and M. Penev, Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues, NREL, March 2013.

The Narragansett Electric Company d/b/a National Grid, 2018 Energy Efficiency Year-End Report, submitted to the Rhode Island Public Utilities Commission in Docket 4755, May 15, 2019

Navigant, Gas for Climate, March 2019

Navigant and Cadeo, Home Energy Services Impact Evaluation (Res 34), prepared for the Electric and Gas Program Administrators of Massachusetts, August 2018

NEEP, Guide To Sizing & Selecting Air-Source Heat Pumps in Cold Climates, revised 12/7/18

NOAA National Centers for Environmental Information, Climate at a Glance: Statewide Time Series, published January 2020

NYSERDA, Heat Pump Study: New Efficiency: New York Analysis of Residential Heat Pump Potential and Economics, Final Report, Report Number 18-44, January 2019

Resources for the Future, Social Cost of Carbon 101, August 1, 2019

RIEC4, Rhode Island Greenhouse Gas Reduction Plan, December 2016

(S&T)2 Consultants, BIODIESEL GHG EMISSIONS, PAST, PRESENT, AND FUTURE, A report to IEA Bioenergy Task 39, January 2011

State of Rhode Island, Division of Public Utilities and Carriers, Summary Investigation into the Aquidneck Island Gas Service Interruption of January 21, 2019, Investigation Report, October 30, 2019

Synapse Energy Economics, "Avoided Energy Supply Components in New England: 2018 Report", prepared for AESC 2018 Study Group, originally released March 30, 2018 (amended October 24, 2018)

Stockholm Environment Institute, et al., Deeper Decarbonization in the Ocean State: The 2019 Rhode Island Greenhouse Gas Reduction Study, September 2019

UK Committee on Climate Change, "Hydrogen in a low-carbon economy," November 2018

United States Government, Interagency Working Group on Social Cost of Greenhouse Gases, Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866; August 2016

U.S. Department of Energy, Clean Cities Alternative Fuel Price Report, January 2020

U.S. Energy Information Administration, Annual Energy Outlook 2019

U.S. Environmental Protection Agency, Rules of Thumb – Energy Efficiency in Buildings

U.S. Environmental Protection Agency, Understanding Global Warming Potentials, available at: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials)

U.S. Office of Management and Budget, Circular A-4, September 17, 2003

West Hill Energy and Computing, Efficiency Maine Trust Home Energy Savings Program Impact Evaluation, Program Years 2014-2016, August 23, 2019