

Transitioning to Heat Pumps in Cold Climates: A *Systems Dynamics* Analysis

Authors: Harvey Michaels and Robert Nachtrieb

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Abstract

How we heat our homes, especially in cold climates, remains a major challenge for achieving a world climate solution. Buildings consume a third of all energy worldwide, and in colder climates, residential heating energy is frequently the largest source of carbon emissions. A carbon emission solution element often considered is to electrify home heating, using the most efficient available heat pumps, combined with home thermal efficiency upgrades.

To provide insight on timely climate policy questions, we examined various configurations of heat pump systems, deploying a *Systems Dynamics* approach which helped relate the numerous factors that influence heat pump market adoption at scale: including economics, carbon, grid, and equity.¹ With support and collaboration with policymakers, we began by examining Massachusetts as case.

This paper describes an ongoing analysis and current recommendations for pathways to meet aggressive state targets to lower space heat carbon emissions in existing residential buildings in the decade ahead, while preserving a stable electric grid, and offering good economics for participating consumers.

A key finding is that auxiliary systems are needed in the majority of homes to provide needed backup for heat pumps during the coldest winter weather, with a few exceptions: new homes built to recent energy codes, deep retrofitted homes, and geothermal heat pump systems. We explored the implications of auxiliary systems including electric resistance, pipeline gas, and site-stored oil or propane.

These auxiliary system choices, as well as heat pump sizing and control strategies, were found to be important factors when evaluating electric grid and natural gas pipeline system impacts once scale is achieved, as well as on carbon emissions and consumer economics. With an effective auxiliary system strategy, heat pump systems can be widely adopted without causing a statewide winter peak electric load that exceeds the summer peak, and also serve to help lower average electric rates, while mitigating pipeline gas price increases for non-participants.

The process of study and analysis continues, and findings may adjust as heat pump technology, costs, incentives, installation practices and experience, energy prices, and social preferences are all rapidly changing. This study will continue to embed new information as available from heat pump installers and manufacturers, utility, research, and advocacy groups, and integrate rapidly updating empirical data on installation and experience.

¹ We acknowledge and appreciate the support provided by the MIT System Dynamics Group at the MIT Sloan School of Management, under direction of John Sterman, the Jay W. Forrester Professor of Management, a leader in the Systems Dynamics field.

I. Why examine pathways to rapid market penetration of heat pumps?

In Massachusetts, policies are being developed to achieve a 2021 legislated goal of 50% decarbonization by 2030, measured from 1990. The state is about halfway to this goal, in aggregate for all sectors.²

While a state path to carbon neutrality by 2050 has been required by legislation since 2008, the 2021 legislation made *50% mitigation by 2030* a hard goal, not only a milestone, reflecting recent IPCC guidance³ that near-term decarbonization was essential to stabilize the climate not higher than 1.5C warmer than pre-industrial levels.

A study performed by Massachusetts government to achieve this goal concluded that a large-scale transition of building space heat from fossil sources to heat pumps was needed, as well as to continue to decarbonize the electric and transportation sectors.⁴ A heat pump adoption rate of about 100,000 homes a year (4% annual penetration) was targeted as a result of this study. But the study also acknowledged the challenge to ramp up quickly, within just a few years, from about 20,000 homes per year now.⁵ To accomplish this rapid adoption rate, heat pumps would need to be economically attractive for consumers, and as well provide desired comfort, with reliability especially in extreme weather; and there are challenges for achieving these things in cold climates with current technologies. The study found that building thermal energy efficiency upgrades are also essential to achieve the 50% goal.

To support policy decisionmakers on this intended transition to substantial clean heat by 2030, MIT is conducting an ongoing study of cold weather heat pump technologies and policies.⁶ The goal is to better understand the economics, carbon, grid, and equity impacts of potential pathways to rapid heat pump adoption, including the implications of various system configurations and control strategies. Frequently updating information on technologies, market trends, programs and incentives, and empirical evidence continues to be applied to the analysis and Systems Dynamics modelling; incorporating ongoing interviews with leaders of state policy and utility heat pump programs, heat pump installers and manufacturers, as well as members of research and advocacy communities.

Initially, with Massachusetts as case, the focus is on existing single-family pipeline-gas-heated homes, which dominate the residential building sector, and have more challenging market economics for conversion to heat pumps than homes currently heating with oil or propane, due to the lower cost per BTU of pipeline natural gas in recent years.

² Commonwealth of Massachusetts: 2021 Next Generation Climate Roadmap Law, which updated the 2008 Global Warming Solutions Act.

³ Intergovernmental Panel on Climate Change (IPCC), Global warming of 1.5°C, 2018

⁴ Commonwealth of Massachusetts, *Clean Energy and Climate Plan to 2030*, 2021

⁵ ISO New England, Final 2022 Heating Electrification Forecast, April 2022

⁶ MIT Clean Heat Transition Project, led by MIT Sloan Sustainability Initiative and Systems Dynamics Group.

II. Summary study findings to date.

The implications of various heat pump strategies were examined at the target scale required for climate policy goals. Our key finding is that the state goal to rapidly achieve an annual 100,000 per year adoption rate (4%) in the state's 2.5 million homes is reasonable based on recent technology advances, and market forces spurred by new Massachusetts incentives; *but importantly the market is driven disproportionately by consumer air conditioning decisions*, rather than heating decisions. To achieve this goal, however, we will need to overcome some significant roadblocks which our examination identified:

- *The marketplace needs adjustments to electric rates, heat pump controls, and conventional wisdom* to encourage optimum use of heat pumps for heating purposes. Since air conditioning is a dominant market driver and likely will remain so, many homes have two heating systems once heat pumps are installed. The consumer transition towards heat pumps may be better enabled with three actions:
 - 1) *Communication of accurate conventional wisdom* to help people operate their heat pumps well in relation to their other heating system.
 - 2) *Integrated dual system controls* to align the systems with simplicity, to improve personal economics, and improve electric grid management.
 - 3) *A new form of electric rates*, perhaps incorporating demand response, to accurately signal electric system cost to the dual heating system configurations.
- *We need to avoid a serious winter peak electric grid problem.* The vast majority of retrofitted heat pump systems require some auxiliary heat today in climates such as Massachusetts, and may for some time unless heat pump technology substantially improves. Notably even those systems considered “full heating”, or “cold-climate optimized”, in average existing homes require some auxiliary or backup for the 5-15% of annual heating needed at temperatures of 15F or below. This is the case even in homes that have made conventional thermal efficiency improvements.⁷ At any significant scale, our modelling shows that the electric grid cannot accommodate reliance on electric resistance heat for all of this auxiliary need, without exceeding the state's summer electric peak demand. But if electric resistance is avoided, and oil or gas is used instead, then peak demand is manageable, even if high heat pump adoption is achieved.
- *Using pipeline gas as auxiliary heat is also a problem.* If a consumer mainly uses pipeline gas in a large pulse, for a few hours per year when temperatures are below 15F, and very little otherwise, the aging gas system will be difficult to maintain for the shrinking amount of energy it serves once heat pumps achieve the target scale, potentially causing the costs for pipeline natural gas for all remaining consumers to rise sharply.
- *Site-stored fuels, such as propane, oil, and ultimately renewable fuels, are preferable for auxiliary heat* as measured in terms of emissions, grid, gas network, and personal economics. While this leaves 10-15% of heat continuing to be provided by fossil sources, using these fuels for auxiliary heat is an economic solution today that accomplishes

⁷ The Mass Save home energy audit, along with implementation of recommended thermal efficiency measures with 75% incentives, is now required for the maximum heat pump rebates.

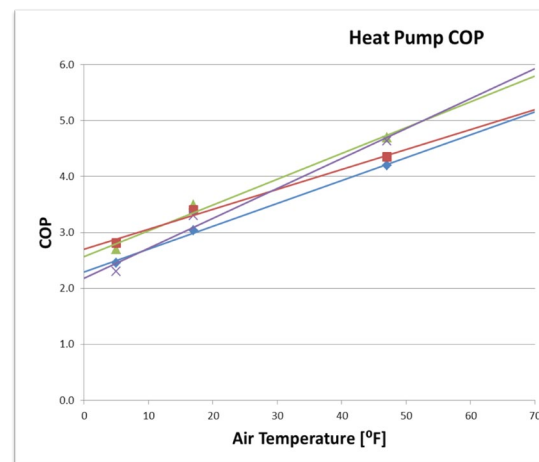
85-90% decarbonization at scale. And there are improving opportunities to switch from propane to renewable gas⁸ in the years ahead, for this peak winter heat. Also, a promising strategy may be to transition pipeline-gas-heated homes to heat pumps with site-stored backup fuels, which require only modest tanks for this limited use.

- *Fossil-free heat pump homes can be accommodated at greater scale, when feasible with no resistance backup.* Incentives, building codes, and local ordinances may encourage the market for all-electric in new homes built to high thermal efficiency standards, in older homes that have deep retrofits for thermal efficiency, or in homes deploying geothermal heat pumps including those participating in a community GeoGrid system (discussed later.) With lower but still significant winter peak contribution, they can be adopted at greater scale than those with resistance backup with less winter peak problem.

Elements of this analysis are described below.

III. Heat pump performance in mild, cold, and extreme temperatures.

Heat pump efficiency falls as outside temperatures drop, while home heating requirements increase in proportion to the difference in inside temperature and outside temperature (Delta T), together creating an accelerating electric demand growth as temperatures drop. This figure shows a linearized temperature trend for the manufacturer data for COPs⁹ for four ductless mini-split units at various outside temperatures.^{10 11} COPs are much higher at milder temperatures, and as a result, even with the resistance backup described above, the seasonal average COP's average is about 3.5 in Massachusetts, cost-competitive with oil or propane heat with similar annual costs, but have higher annual costs than natural gas heat.¹² Above



⁸ <https://www.epa.gov/lmop/renewable-natural-gas>

⁹ COP: Coefficient of Performance, a measurement of heat pump efficiency, defined as the ratio of thermal BTU's delivered to heat the building, to the site thermal BTU content of the electricity consumed.

¹⁰ Northeast Energy Efficiency Partnerships. <http://www.neep.org/initiatives/high-efficiency-products/emerging-technologies/ashp/cold-climate-air-source-heat-pump>. Box points are manufacturer COP data.

¹¹ There is dispersion in the field data on COPs in very cold weather, with some evidence that they are lower at coldest temperatures, and as well product-specific variation. We used cold weather COPs for calculation for the most recent and best equipment. Note that cold weather deficits were made using these possibly optimistic COPs, and therefore the deficits noted might be greater in practice with less current and optimal equipment.

¹² As a sample case, we can see that electric resistance heat (COP=1) would have a cost per million BTU of about \$75 at current Massachusetts prices. A heat pump at an average COP of 3.5 would therefore cost \$21.50

35F however, where the COP is over 4, heat pumps are frequently less expensive than natural gas, with specifics depending on the electric rates and fluctuating fuel prices.

The implications of the COP drop with temperature is that heat pumps in dual system homes have been typically set by installers to turn off and rely on the legacy fossil heat system below a *crossover temperature*, usually set between 30 and 35F. And system installers, if sizing the system only to meet air conditioning needs, with non-cold climate heat pump equipment, set the crossover point in this range because heat pump output will be inadequate for comfort below it.

Cold climate heat pumps: Today's cold climate heat pumps are more efficient and can be sized much larger. With variable speed drives, these systems modulate lower for air conditioning and milder winter temperatures, while allowing the system to provide typically up to twice the winter heat output as compared with the cooling BTU needed for air conditioning in summer.

As a result, a quality heat pump system in northern climates will typically be sized for cold weather optimization, often at about double the size needed for air conditioning. But there are two important considerations in that sizing:

Peak electric demand: These systems will use twice the power in peak winter conditions, compared with peak summer - of significant concern at scale for electric grids. A quality whole home cold weather heat pump system, installed in an average insulated home (Mass Save level but not deep retrofitted)¹³, will draw twice its peak summer demand at about 15F and below, when it reaches full load. For a 2000 square foot home, this is typically 2.5-3KW summer, 5-6KW winter, as will be shown in the analysis below.

Auxiliary Heat: At temperatures below 15F, occurring 50-150 hours per year, home heat load continues to rise, and typically a whole home system begins to have a *deficit* in being able to provide all the heat that many consumers want. As a result, recent heat electrification forecasts assume that almost all heat pump consumers will require some auxiliary heat: resistance electric, wood stove, gas fireplace insert; or retaining the legacy gas, oil, or propane system.¹⁴

With a winter-optimized cold climate heat pump system, the auxiliary system is used for only 10-20% of the annual home heat, which mitigates the cost of inefficient electric resistance as auxiliary, especially since Massachusetts current flat electric rate structures do not charge a higher price during peak conditions. Suppliers indicate that, while 5 KW backup is often installed, the peak power of the resistance auxiliary system is typically 3-4 KW, 50-75% of the peak power of the heat pump itself.¹⁵

Exceptions to the need for auxiliary heat include:

per million BTU of thermal energy delivered to the home. This is near the cost per million BTU delivered for heating oil in recent years (excluding the current spike) and is below the cost of propane per delivered BTU, but above the cost of natural gas per BTU.

¹³ The Massachusetts ratepayer-funded Mass Save program provides free energy audits, and heavily subsidized home efficiency improvements, including thermal measures of free air sealing, and insulation where needed. Our modelled reference home includes these upgrades, but not those of deep retrofits. See info on HERS ratings and deep retrofits next page.

¹⁴ ISO New England, Final 2022 Heating Electrification Forecast, April 2022;

¹⁵ VEIC, *Heat Pumps in the Northeast*, 2018

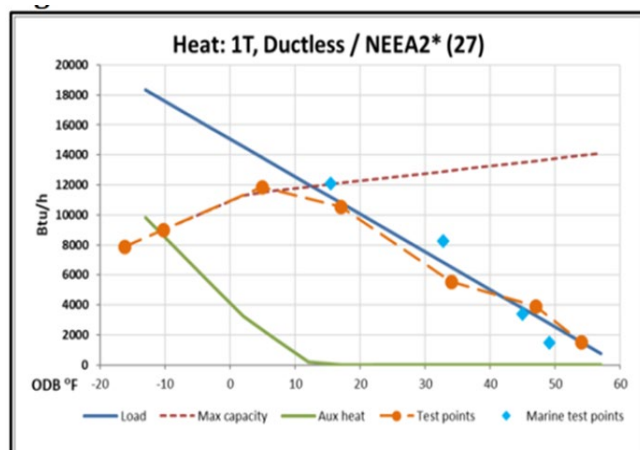
- Deep retrofitted homes, as the analysis below shows.
- New homes built to stringent energy standards, which are highly thermally efficient.
- Ground-source heat pumps, which have much more efficiency and output during cold weather, by drawing their heat from the ambient 50F ground, resulting in much higher COPs and fully eliminating any need for auxiliary heat.

Deep Retrofits: HERS ratings are an estimate of a home's thermal efficiency, proportional to heating requirements; where the average in new construction in 2006 was indexed as HERS 100, and new highly efficient homes have HERS 50 ratings or lower. In Massachusetts, the average existing home is currently HERS 140.¹⁶ Our modelling estimates that with standard Mass Save measures, existing homes can average HERS 100.

The deep retrofit option creates excellent thermal efficiency, achieving HERS ratings of 75 or lower, with 25% lower demand than the reference HERS 100 home with Mass Save standard thermal measures, and as a result can support heat pump use without any auxiliary heat, as will be shown. Deep retrofits, which often include new exterior elements as well as energy recovery ventilation, now receive a large Mass Save incentive to encourage adoption. But in practice there is rarely confluence in the decision to consider a heat pump, driven by a near-term interest in new heat or air conditioning equipment, and a remodeling-level deep retrofit decision. Therefore, rapid adoption of heat pumps is unlikely if conditioned on these retrofits, and recognizing this fact, the new Mass Save heat pump program only requires standard thermal efficiency measures for the maximum \$10,000 incentive.

Auxiliary Heat Demand at Low Temperatures. For illustration of auxiliary heat dynamics, let's consider this figure from a 2020 study by Bruce Harley for the Canadian Standards Association, in British Columbia weather similar to New England. It shows, for a range of temperatures, the heat output provided by a 1 ton ductless mini-split unit, with winter-optimized sizing, alongside the heat requirement of the space (load), and the deficit resolved by supplementing with auxiliary heat.¹⁷

While this is an individual system test, it has characteristics representative of typical heat pump installations in practice in average-to-good efficiency homes, although such homes would typically have 4 tons of heat pumps, provided either by 4 such systems, a central system, or a mixed configuration.



¹⁶ MA Dept. of Energy Resources, Updated Stretch Code presentation, February 2022. Standard Mass Save improvements can reduce the thermal heat requirements of an average Massachusetts home from the current average HERS 140 rating to about HERS 100. Deep retrofit programs, just beginning, can reduce the home to HERS 75 or below.

¹⁷ Bruce Harley, *Load-based and Climate-Specific Testing and Rating Procedures for Heat Pumps and Air Conditioners, Interim Lab Testing and Rating Results*, 2020

However similarly, this cold weather heat pump, with variable speed drive, throttles the load at mild temperatures, reaching its rated heat output at about 12F, when it matches the heating needed by the space. Below that temperature, the heat requirement (load) continues to rise, while the heat output drops, and as a result auxiliary heat is increasingly needed as the temperature falls below 12F.

If the backup heat is electric resistance, let's consider the power drawn by the system at 5F, 0F, and -5F. While there is a significant reported variation, the best systems may achieve average COP's of 2.35 at these temperatures, or 235% efficiency of heat output to electric input, which by calculation is equal to about 8000 BTU per kilowatt, or 1.5KW per 12000 BTU of rated heating (i.e. per ton).¹⁸

Typically sized, a 2000 square foot Massachusetts home will have a 4-ton heat pump (48,000BTU)¹⁹, drawing 6 KW at 12F, using these ratios. But with electric resistance auxiliary, and dropping heat pump output, the total power demand below 12F is as follows:

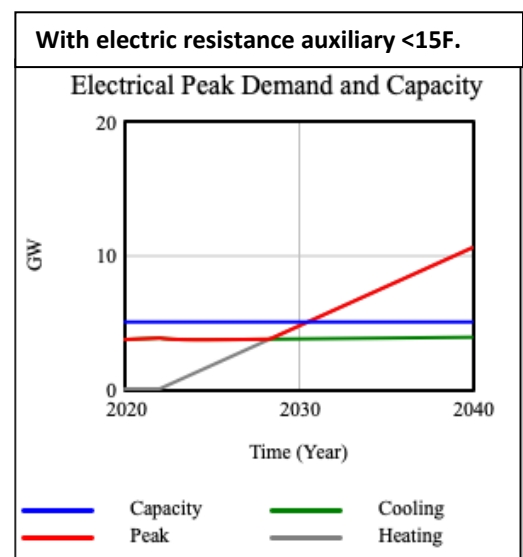
- At 5F: 55,000 BTU per hour provided by 6KW Heat pump, plus 2 KW backup = 8KW.
- At 0F: 60,000 BTU provided by heat pump, plus 4 KW backup = 10KW.
- At -5F: 65,000 BTU provided by heat pump, plus 6 KW backup = 12KW.

By calculation, we can see that if heat loss is reduced 25% or more in a highly thermally efficient home, through deep retrofit or efficient new construction, to 45,000 BTU per hour or less at 0F, then a 4-ton heat pump should be adequate throughout the winter.

IV. Impact of Heat Pumps at Scale on the Electric Grid

The exponential growth in peak demand caused by resistance backup, as well as the needle peak in pipeline gas demand caused by gas backup, are serious concerns for their respective networks.

It is projected that New England's winter peak will remain about 5 GW lower than summer in 2030. However, since winter peak hours occur in darkness, and often in light wind, system capacity from renewables in winter is lower. Outages are also of greater risk in winter, and potentially life-threatening in extreme cold.²⁰ Therefore, it is important to try to remain within the grid capacity in mid-winter, and for grid economics, to avoid the need for additional capacity only for winter peak use.



¹⁸ Manufacturer data confirmed by Mitsubishi.

¹⁹ MA Heatsmart Advisory Council meeting, March 2022.

²⁰ ISO-NE, *Final 2021 Heating Electrification Forecast*, May 2021. Forecasts 13% full electrification for heat pump installs in 2022, rising to 43% in 2030, including homes with resistance auxiliary; the remainder are hybrid.

Modelling the Massachusetts target adoption rate of 100,000 new heat pump installations a year, we found that an incremental addition of 8 kw per home to system peak²¹ would use up Massachusetts' share of the New England slack, before exceeding summer peak, once only 12% of all homes convert, if resistance auxiliary was commonplace, as will be described below.

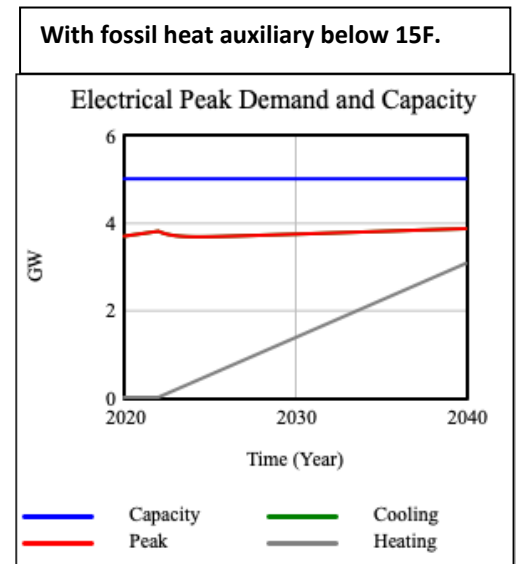
Winter-Optimized Hybrid Heat Conversions: By comparison, we modelled an alternative of 100,000 conversions to winter-optimized cold weather heat pumps per year that used fossil heat as auxiliary below 15F, with oil, gas, or propane instead providing 10-20% of the annual heating requirement. With this approach, there is little contribution to winter peak since the in-place heating system typically provides most of the heat during winter peak hours.

Of note is that these are *winter-optimized systems*, frequently sized with cold-weather heat pump technology at about double the size needed for air conditioning. By comparison, the common definition of *hybrid heated homes* – conventional heat pumps sized for air conditioning with fossil backup, the most common heat pump installations in recent years – only displace about half of the annual fossil energy use.²²

The new 2022 Mass Save heat pump incentives greatly favor *winter-optimized heat pump systems*, which should reduce fossil energy consumption at least 80%. To receive the \$10,000 per home incentive being offered (compared with \$2500 - \$3750 for a conventional hybrid heat pump installation), Mass Save requires installation of standard thermal measures, winter-optimized heat pump sizing, and cold weather heat pump technology. Interviews indicate that heating and air conditioning installers in Massachusetts have taken note: such winter-optimized systems are now what the installers routinely recommend when heat pumps are requested, and even propose these systems when called for air conditioning systems that need replacement. Net of the incentives, winter optimized heat pump systems are often the lowest first-cost option in both circumstances.²³

Based on our analysis to date, these recommendations can be made:

- *Electric resistance auxiliary heat should be highly restricted;* because of the exponential impact on electric peaks during extreme cold weather that occurs with them. Electric resistance heat COPs are less than 1, as compared with 2.35 for good heat pumps in coldest temperatures, and therefore provide less than half the heat per kwh. As described above, an average home conversion from fossil heat to all-winter heat pumps with electric backup will on average add an incremental 8kw contribution to the winter system peak. Therefore



²¹ Calculated based on 0F peak of 10 KW/home, less current system KW, less a small diversity factor.

²² CLASP, *3H 'Hybrid Heat Homes, An Incentive Program to Electrify Space Heating and Reduce Energy Bills in American Homes*. May 2021

²³ MA Heatsmart Advisory Council meeting, March 2022.

300,000 additional homes, about 12%, would add 2.4GW, using up approximately the Massachusetts share of the New England available surplus in winter capacity. Targeting 4% annual penetration, 12% conversion is needed within 3 years. Beyond that, new generation, transmission lines, substations, and transformers may be needed to serve the winter peak, and also increased electric reliability concerns during subzero weather, a time of critical power for health and safety. While avoiding electric resistance backup with deep energy efficiency retrofits, geothermal, or new construction increases the grid's ability to absorb heat pump use on winter peak, we still may run out of grid space at about 25% penetration, in about 6 years, unless also many homes use non-electric auxiliary heat at peak times.²⁴

- *We should be requiring more “smart” building features* that can adjust use of electricity on short notice in response to grid congestion. To mitigate the costs associated with grid upgrades in support of electrification, we need our homes and buildings to provide a form of *virtual peak power*; some combination of batteries, controlled water heaters and car chargers, and demand-responsive thermostats, as examples. Over time, we will be able to orchestrate these to accommodate periods of grid congestion, without interfering with comfort or activities in the home or building. A promising opportunity is to unify the control of ductless mini-split heat pumps and auxiliary heating systems, to avoid the need to expand electric transmission and distribution systems to accommodate growing winter electric heat load. And as well, such systems will provide value to consumers, and resilience to the building.

V. Path to 100,000 per year, and highest carbon impacts:

Heat Pump vs. Air Conditioning Market: Our analysis projected penetration rates for various market segments, considering market preferences and consumer economics of various heat pump options. Accelerating the market from about 20,000 systems per year today in Massachusetts towards 100,000 additional heat pumps per year, looks doable perhaps as quickly as 2-3 years, with the current technologies and incentives, as follows:

- For the 30% of homes in Massachusetts with central AC, more than half will need replacement by 2030.²⁵ This provides about 40,000 prime candidates per year, since all winter heat pump alternatives to standard central AC replacement should be equal or lower in cost with the available incentives. 100% transition could potentially be required by appliance standards, or encouraged through upstream incentives.²⁶
- The remaining 70%, more than 1.5 million MA homes, are candidates for choosing heat pumps, as adoption of air conditioning has accelerated in recent years, likely driven by the new ductless mini-split heat pump technology, which is more practical in homes without heating ducts. Based on utility reports of market trends, ISO-NE projected 500,000 hybrid

²⁴ Calculated based on OF heating peak of 6 KW/home, less current system KW.

²⁵ Eversource appliance market penetration study, reported.

²⁶ CLASP, *3H ‘Hybrid Heat Homes, An Incentive Program to Electrify Space Heating and Reduce Energy Bills in American Homes*. May 2021

heated homes by 2030, driven mostly by air conditioning demand, based on utility/state estimates, an acceleration to 50,000 homes/year from 20,000 now.

- The number of heating-decision-driven homes choosing pumps is more speculative, and is likely to take more time to accelerate.²⁷ Assuming high penetration in new construction, deep retrofits, and ground-source heat pump early adopters, with new incentives an additional 10,000-20,000 such annual installations are possible within 3 years, up from estimated 2,000 rate now.

Encouraging Winter-optimized Systems and Operating Practices: New policy strongly incents the consumer to buy a winter-optimized system for use to 15F or below, when buying a heat pump. Our analysis shows that all but 15% of the heating load will be displaced by the heat pump, provided the home has no higher than a 100 HERS rating, achievable in most homes with modest thermal efficiency improvements. The step-up from commonplace hybrid heat pumps and existing HERS 140 average thermal efficiency is important, as without these, heat pumps will only reduce fossil energy for home heating by 50% typically.

As described previously, Massachusetts' new Mass Save program for 2022 strongly encourages this step-up, but to date, policy does not encourage the consumer to use it in all hours above 15F, if they have a fossil backup system. Consumers who are aware of how to minimize their heating costs may choose not to use their heat pumps below 35F if they have backup natural gas system. From 35F down to 15F, their backup heat may be less expensive than heat-pump heat, creating an incentive to keep heat pumps off.

However, the solution may be *electric price reform*. Our Systems Dynamics modelling of the scale use of winter-optimized heat pumps suggests that electric rates are higher than they need to be in this temperature range, for this use, since incremental heat pump-driven electric use would add substantial marginal revenue for electric utility networks without creating equivalent increases in network costs. There is a rate structure flaw – creating a perverse incentive to keep heat pumps off despite the potential of raising the *electric grid utilization ratio*²⁸ if used in most hours down to 15F. Doing so would lower electric rates for heat pump users and non-participants alike, as will be discussed below. Correcting this flaw is both economically efficient and critical to a climate solution. To do so, we need to find a way to reduce electric rates in this 15F to 35F temperature band for heat pump use, or alternatively increase the price for fossil heating fuels (same analysis holds true below 30F for oil, or 25F for propane).

Dynamic electric pricing or a dual fuel demand response programs are examples of electric price strategies that could improve the economic benefit of heat pump use, especially during the challenging colder hours between 15F and 32F, when fossil heat is slightly less expensive, although electric wholesale spot prices are low, and local transmission and distribution systems are typically not constrained. Avoiding all hours at temperatures below 15F, and as well the high peak hours between 15F and 32F, should substantially reduce costs and benefit the system. Passing some of this benefit to the consumer may encourage heat pump use during at least 80%

²⁸ Utilization Ratio is the fraction of the total available grid capacity used. The higher the grid capacity utilization, without requiring capacity additions, the lower the cost for electricity.

of the time in of these colder hours; otherwise a cost-optimizing consumer may choose not to use the system below a crossover temperature of 28-32F for oil or propane, and 35F for natural gas.

Service efficiency and innovation: Another key problem we need to solve for heat pump adoption is that we need greater capacity of efficient, quality, fairly priced contractor services. Mass Save should put emphasis on streamlining installation services, to a heat pump purchase more manageable, less costly, and lower in risk for the consumer. Recently the average cost for a 4-ton heat pump system in Massachusetts is near \$20,000, as compared with costs averaging only \$15,000 for the same sized systems in the state of Maine. Even with Massachusetts' heat pump incentives, up to \$10,000 per home, efficient delivery is needed to achieve the targets.²⁹

Heat Adaptation: Our analysis provides strong confidence that market forces, programs, and policies may influence future air conditioning purchase decisions, driving consumers to instead install heat pumps. But what about homes without air conditioning? Lower income urban housing also needs the benefits of heat pump incentives and technologies - which has financial, building structural, and institutional challenges that single-family homes don't have. And as well, urban heat islands have greater risk to health from summer heat, a risk that unfortunately continues to increase over time with climate change. For carbon and equity, as well as health benefits, it is worth considering how to encourage more heat pumps in low income urban heat islands - in homes without AC now, and not able to therefore make a heat pump choice. A heat pump direct-install program is an example of a program to accomplish this.³⁰

VI. Non-participant Impacts:

A key benefit of using a systems dynamics approach is to evaluate how the transition towards heat electrification will impact those not participating directly, such as:

Desirable Decarbonization: A key benefit worldwide is the decarbonization itself; and a successful heat transition policy tested in Massachusetts or elsewhere may have the leveraged impact of providing a solution that others will choose to follow.

Electric price Impacts: Transition to all-winter heat pump heated homes, even with optimum technologies, may add to the average cost of electricity since building heat load is highest during the 50-100 hours of extreme cold, below 10F and occasionally below 0F. And as well, heat pump demand patterns are *peakier* than the weather-related heat load would suggest, due to a decline in COPs (heat pump efficiency) as the temperature drops.

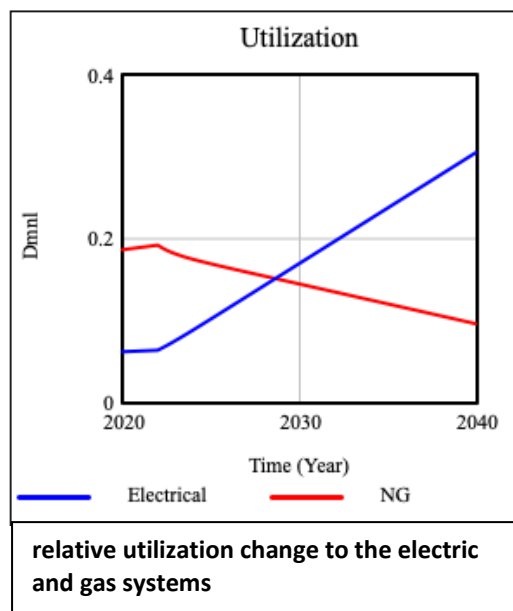
In addition, winter power peaks have more challenges to meet than summer peaks. Extreme cold peak load occurs regionally when there is no solar power availability, and frequently also low wind power availability. These peaks extend longer than battery storage systems can provide for. Peakier load shapes require greater use of marginal high cost peak power resources, which add to the average price. If all-winter heat pumps result in exceeding the available

²⁹ Prices reported for MA from Abode Energy, Municipal Heat Pump Support Program, May 2022; Maine estimates by heat pump supplier Mitsubishi, citing statewide data.

³⁰ RMI, *Decarbonizing Homes: Health in Low Income Communities*, 2021

capacity required for summer AC-driven peaks, then a very large incremental expense is required for new generation and/or upgraded transmission and distribution networks. And power system failures during extreme winter weather risk widespread pipe freezing, and emergency health conditions.

Winter-optimized hybrid heated homes, by comparison, should result in lower electric rates, based on our analysis to date, since they improve the power system *Utilization Ratio*. Our modelling showed that widespread adoption of hybrid heated homes reduce electric costs and should reduce prices, if heat pump use is limited to hours of uncongested power availability. Increasing the total KWH without adding to congestion means that the non-energy system fixed costs are shared across a base of more kilowatt hours, with these benefits:



Consumer surplus: The hybrid heat approach creates lower total heating costs for participants, providing them with higher discretionary spending that has benefits throughout the economy, and will likely contribute to additional jobs. However, non-participants also have a *consumer surplus* from lower electric prices from the adoption of this form of hybrid heat.

Carbon mitigation co-benefit: Lower electric prices support more economic use of EVs, electric hot water, dryers, cooking, and other electrification needed for our climate goals.

Pipeline Natural Gas price impact: Both all-winter and standard hybrid heated homes reduce gas sales volumes and thereby increase the average gas price, as shown in the figure. However, the impact of widespread hybrid heated homes with gas backup is larger: these leave the peak demand for gas intact, requiring all capacity to be maintained, and all high-cost compressed and liquified peak supplies will need to continue to be used. Meanwhile, there is a large reduction to gas sales during milder weather; a time of low-cost pipeline gas availability. Therefore, widespread hybrid heated homes may create a unit price of gas burden for non-participating gas customers, but will also, like the electricity impact of hybrid heated homes, support more economic electrification of homes by raising the cost of the gas alternative.

A recent study, referenced here, argues that the pipeline gas system can continue to operate successfully with widespread hybrid heating with pipeline gas backup. However, the study assumes mostly standard hybrids; which reduce gas use 50%, instead of the full-size cold weather heat pump systems that eliminate 85% of gas use, including in all hours over 15F.³¹ If successful at promoting these, as current incentives do, it will be challenging for the pipeline gas system can remain viable.

A solution may be for the natural gas utilities to manage the infrastructure change to site storage of increasingly decarbonized fuels in a tank, as backup.

³¹MA DPU 20-80; The Role of Gas Distribution Companies in Achieving the Commonwealth's Climate GoalsIndependent Consultant Report March 2022

Oil and propane price impact: No impact on gas or oil prices for non-participants is anticipated; however, for participants, since much lower amounts of these fuels are needed annually in hybrid heated homes, most tank fills can occur off-season, when prices are lower, and last through much or all of the peak season. Therefore, the average price paid by consumers in hybrid heated homes will likely be reduced.

Fuel conversion impact: Today's financial benefit for heating system conversion from oil or propane to pipeline gas will be reduced by the transition to heat pump-heated homes, due to the likely increase in natural gas prices described above. Further, should the oil or propane consumer also be a participant of hybrid heat, they will enjoy the seasonal decrease in consumer average oil or propane price. Since the trend towards hybrid heated homes is already underway, there should be fair consumer notice to those considering a switch.

VII. 2030's transition paths from hybrid heat pumps to fossil-free systems.

It is important to address the concern about “lock in” (staying on a natural gas network longer than we would prefer). There are several potential workable solutions to how hybrid heat systems installed in homes ubiquitously this decade, which can average 85% decarbonization in each instance if done well, can efficiently convert to be 100% site decarbonized homes in the 2030's. Refining strategies for the widespread use of heat pumps at scale below 15F is a problem we need to solve soon, although the transition itself may not occur this decade. Strategies to consider:

Large scale deep retrofit upgrades – many models for such programs are being examined at city, state, and federal levels. Very high thermal efficiency is needed for our grid to support a large fraction of all-winter heat pump heated homes. New homes should routinely have the latest well-proven air sealing technologies, mitigation of thermal breaks, energy recovery ventilation, cost-effective insulation, and high R-value windows, as examples. And adding solar to the roof, though laudable, should never be a reason to allow a less thermally efficient building below it.

Transition to GeoGrids – We should encourage/support air-source heat pump systems to be convertible to ground-source water loops. Neighborhood tempered water loops (called GeoGrids) permit equipment sized for 15F is air-sourced to operate efficiently all winter. Ideally, equipment installed in this decade for hybrid use could be attached to the tempered water loops when available, but this will require a new feature on the heat pumps being manufactured. Related, we're considering the potential role of gas utilities to transition to becoming neighborhood geothermal service providers - providing them with authorization and incentives to participate actively in a needed “end of gas” strategy. Locally, six pilot GeoGrids have been approved as demonstrations.³²

Site stored renewable fuels for auxiliary heat. There are improving opportunities to switch from propane to renewable gas; especially if the entire annual peak heat requirement is a small tankful of gas. We acknowledge that some consumers may desire stored fossil-like fuels heat

³² <https://heet.org/2022/02/28/six-geogrid-demos-approved-for-massachusetts/> . The author acknowledges that impactful work of Cambridge HEET leaders Audrey Schulman and Zeyneb Magavi in developing, advocating, and researching the potential of this option with support for the local gas utilities and the state.

services for perceived benefits of use of gas for cooking, fireplace inserts, dryers, barbeques, and resilience during power outages.

Heat Adaptation: The scenarios we studied are encouraging for heat pump adoption - future air conditioning purchase decisions may migrate to heat pumps. But what about homes without air conditioning? In moderate income homes, a program could perhaps have sliding scale incentive, and loans amortized by energy savings. And for equity, in urban multifamily and/or low-income housing, air conditioning provided by heat pumps should be a requirement through code or incentive. We need to acknowledge, and value, the health benefits of providing air conditioning for vulnerable populations. And for fairness, we can't fail to address this population while providing benefits of highly incentivized heat pumps for all other consumers who can afford air conditioning.

VIII. Conclusions

100,000 additional heat pumps per year is achievable if almost all central AC and ductless mini-split purchase decisions become properly sized cold weather heat pumps, and as well there is some penetration of heating system replacements with heat pumps. In addition, it is reasonable to target 75% or higher site-decarbonization of these homes.

We need to spread *accurate conventional wisdom* to help people operate their heat pumps well, and as well *adjust the form of electric rates* to better represent the time-varying cost of service, perhaps incorporating demand response.

The majority of retrofitted heat pump systems require some auxiliary, even those considered *full heating* in homes with conventional thermal efficiency improvements. At scale, the grid cannot accommodate reliance on electric resistance heat for this auxiliary need, even if only used for only 5-15% of the heating season. Site stored fuels, such as propane, oil, and ultimately renewable fuels, are preferable for auxiliary heat as measured in terms of emissions, grid, gas network, and personal economics.

Thermal efficiency upgrades need to be promoted as well. For proper sizing and performance, it is important to encourage at minimum Mass Save thermal measures at the time of such purchase decisions, as the recently adopted heat pump incentives do.

To complete the transition away from fossil fuels, and especially from pipeline gas in the 2030's, we need to have one or more of these alternative longer-term paths to 0 site emissions:

- more deeply retrofitted homes, adequate to reduce heat loss to below 50% of average homes today;
- decarbonized fuels in a tank, and/or
- community ambient temperature water loops tempered by ground-coupling (GeoGrids).

This process of study and analysis needs to continue, in many venues, since heat pump technology, incentives, installation practices, energy prices, and social preferences are rapidly changing. And it must continually embed new information as available from heat pump installers and manufacturers, utility, research, and advocacy groups, and integrate rapidly updating empirical data on installation and experience.

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