Don’t Freeze! The Heating Electrification Train is Barreling Towards Us

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ABSTRACT

Many states are aggressively pursuing energy optimization strategies to reduce the use of fossil fuels, (Gold, 2021). Because heat pumps provide both heating and cooling, sizing and design can affect both winter and summer loads of both home and the serving utility. While there have been vast improvements in newer heat pump products that allow them to function at some level at low temperatures, the evaluation industry lacks the true measurement of these products’ performance in actual homes of varying thermal efficiency, where the heat pump system was designed and installed by non-specialized HVAC installers. We need a better collective understanding of what happens to real heat pumps during extreme cold conditions. Units sized differently will have varying comfort levels, capital and fuel costs, and utility peaks. In homes where no alternative heating source is included, the design decisions become more critical. Studies modeling the impact of heat pumps in summer-peaking jurisdictions have mostly ignored the winter peak impacts of heat pumps. While the impact to the grid of installing heat pumps with backup electric heat in a few percent of homes is unlikely to shift a utility from summer-peaking to winter-peaking, adding millions of heat pumps to the grid in northern climates will have significant winter peak impacts, if not done carefully. Policies need to be revised to consider the peak impacts of full electrification and consider promotion of partial electrification at greater scale in parallel with additional research to improvement performance at extreme cold conditions.

Introduction to the Problem

The Federal government and several states are developing aggressive goals to reduce fossil fuel and greenhouse gas emissions to combat the impending climate crisis. One policy that is gaining traction is the movement to electrify buildings, the key component of which is the promotion of heat pumps to replace fossil fuels for the heating of buildings and hot water. Buildings contribute around 13% of greenhouse gas emissions, and within buildings, space and water heating make up the vast majority (Over 95%) of fossil-fueled end uses, with space heating making up 50-90% across most climates.[1] To date, many advocates for building electrification have focused on full electrification, getting to zero fossil fuel consumption within buildings. This paper further focuses on the most impactful building electrification technology: heat pumps for space heating.

Heat Pump Operation as Temperatures Drop

1. **A heat pump for space heating works by pumping heat from outside to inside in the winter**, when people want more heat in the indoor space and pumping heat from inside to outside in the summer, when people want less heat in the indoor space. A cold climate heat pump is capable of speeding up the heat pump compressor (increasing the number of cycles per minute), which maintains capacity at cold temperatures, but does so at lower efficiency.
2. **Heat pump performance declines as it gets colder, even for cold climate heat pumps.**

[1] Cooking, clothes drying, within building transportation (e.g. forklifts), and lawn and garden equipment make up the remaining 5%.

   a. **As it gets colder outside, it takes more electricity to pump the same amount of heat inside.** The efficiency drops as it gets colder.
   b. **As it gets colder outside, heat pump can deliver less heat.** At very cold temperatures, cold climate heat pumps also lose capacity, just like regular heat pumps.
3. **At some point, even the best heat pumps are no longer able to extract heat from the outside air.** Manufacturer claim their cold climate heat pumps continue to operate at temperatures as low as -15 degrees F.[2] For a non-cold climate heat pump, this happens at a milder temperature. At this point the heat pump stops supplying any heat and the unit shuts off or switches to an electric resistance heater.

Figure 1 below shows how the rated capacity drops off as the temperature drops for 3 nominal heat pumps and a typical single stage furnace in a mild climate.

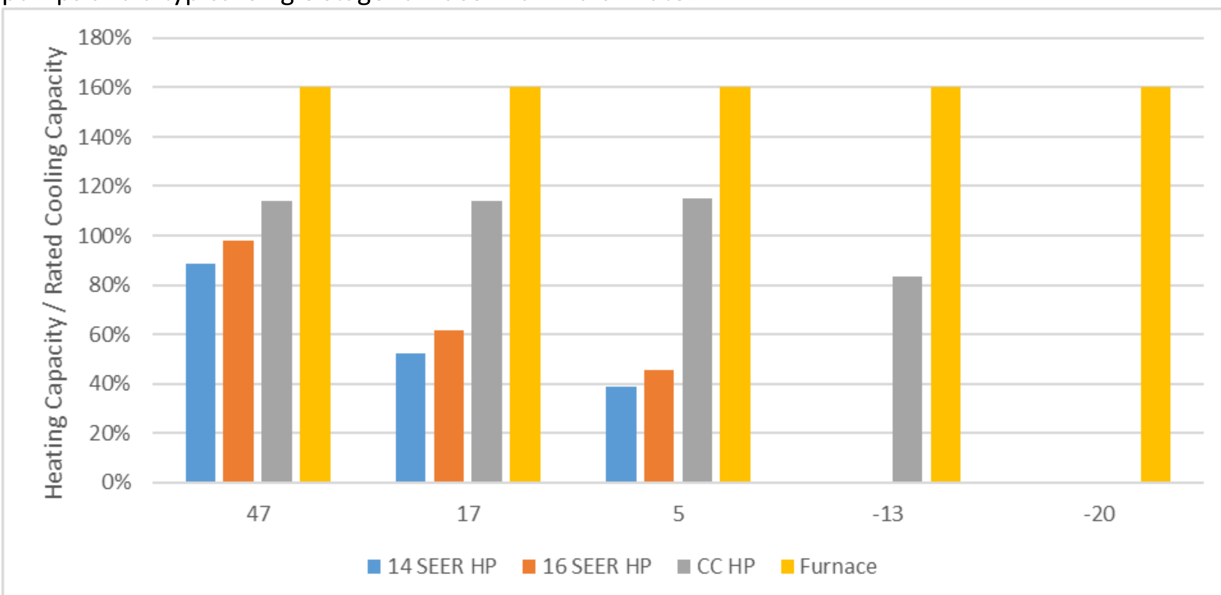

Figure 1. Heating Capacity as a Fraction of Rated Cooling Capacity Across Equipment Types

For a cold climate heat pump, the heating capacity stays high relative to the rated cooling capacity. This is accomplished by a combination of increasing the compressor speed at cold temperatures and derating the capacity of the equipment – the cold climate heat pump is just a bigger heat pump relative to its rated cooling capacity, but it can operate down to -13. However, below that, its capacity goes to zero. Even without the oversizing/derating component, the cold climate heat pump still delivers double the capacity of a non-cold climate heat pump at 5 degrees F.

What Happens at Extremely Cold Temperatures?

Given how heat pumps currently perform and the loads that they will face, we need to consider what happens during extremely cold temperatures. In all but the warmest climates in the United States (places like Phoenix where a heat pump sized for cooling will meet the entire load), or in buildings that are super insulated in mild climates, at some point the increasing heating load of the building will exceed the decreasing capacity of the heat pump. Current best practice for sizing of HVAC equipment is to install sufficient capacity to meet or slightly exceed ASHRAE design conditions. Typical ASHRAE design conditions capture a condition that happens for a few hours each year on average. However, we need to consider

[2] Heat pump performance at cold temperatures continues to improve over time. Some commercial VRF systems can operate down to -30 F. The DOE is currently sponsoring a competition to develop systems running down to -20 F.

what happens at even colder temperatures. Figure 2 below compares the ASHRAE 99.6% design heating temperature to the record temperature and coldest temperature since 1990 for a range of representative cities.

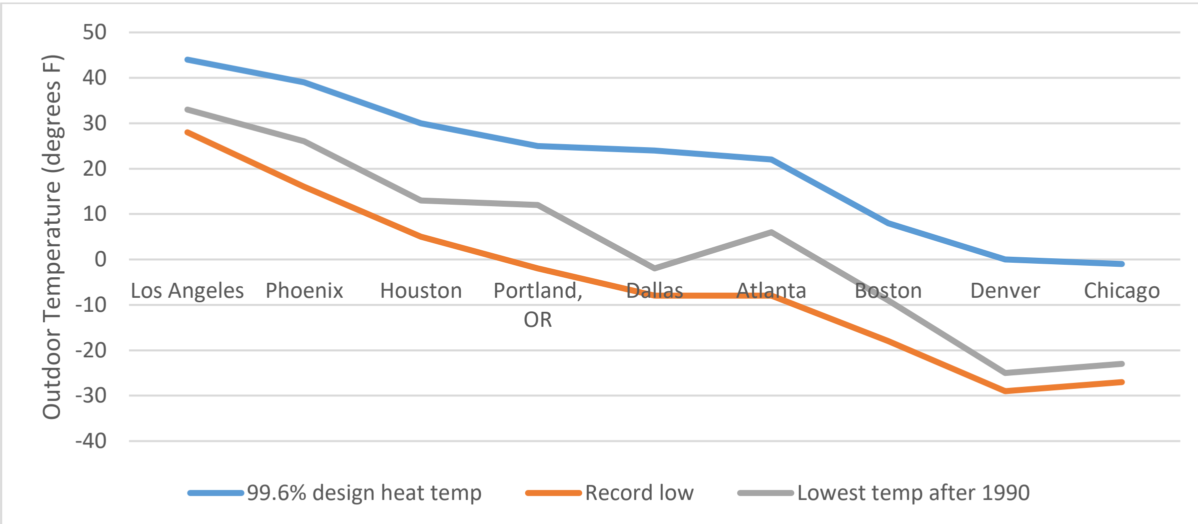

Figure 2. Design Heating Temperatures Compared to Extreme Low Temperatures for Representative Cities

It is true that it never ever gets very cold in Los Angeles, but for the rest of the country, the record cold temperature is generally around 25 to 30 degrees colder than the design temperature.

When comparing the extreme temperature conditions experienced by city above to the heat pump capacity, we can see that a regular heat pump will not be able to deliver the load in most climates, while the cold climate heat pump will not be able to deliver ANY heating at record cold temperatures in Boston, Denver, or Chicago. As an aside, a cold climate heat pump should still deliver heat in the coldest temperatures experienced in warmer cities like Houston and Portland, OR, and might still deliver in Dallas and Atlanta.

In a heat pump home, the indoor temperature could keep dropping to a much colder temperature if there is no backup heating system available, or if the system is not purposely greatly oversized. HVAC designers generally install heat pumps with a backup, either electric resistance heating strips in the air handler (more common) or a gas furnace (less common).

It is already established that current programs to promote heat pumps are exacerbating summer peaks by adding new cooling load, (Guidehouse 2021 and DNV 2019) . What is not recognized as well is that full electrification heat pumps as they are being installed in current programs will produce winter peaking issues for utilities more extreme than those already faced by utilities facing summer peaks. First it must be noted that temperature differences (the Delta T) between indoor and outdoor conditions in winter are at least twice what they are in the summer in most climates. Second, units in their cooling mode do not see the same precipitous drop in efficiency that units experience in heating mode at extreme temperatures. Third, and perhaps most important is the difference in extreme weather duration between summer and winter. In most of the country, even during an extreme heat event, the cooling load drops off significantly each day, as the sun goes down, eliminating solar gains, and the outdoor temperature moderates. During extreme cold events, the heating load continues to be high all day, or even for days at a time. This changes the kinds of load shifting or demand response technologies that can be used to meet heating-driven peaks vs cooling-driven peaks. Figure 3 below shows peak day total utility load shapes over time for a representative Midwest utility. The summer loads (on the left) show a much narrower peak, with lower overnight consumption than the winter peak loads (on the right). The load shapes are for a utility affected by the same cold snap that caused major issues in Texas, which is represented by the 2021 winter peak day on the right, which occurred on a Sunday and shows a minimum load for the day that is approximately 80% of the peak for the day, compared to the summer peak on the left, with minimum load for the day measuring approximately 50% of the maximum peak for the day.

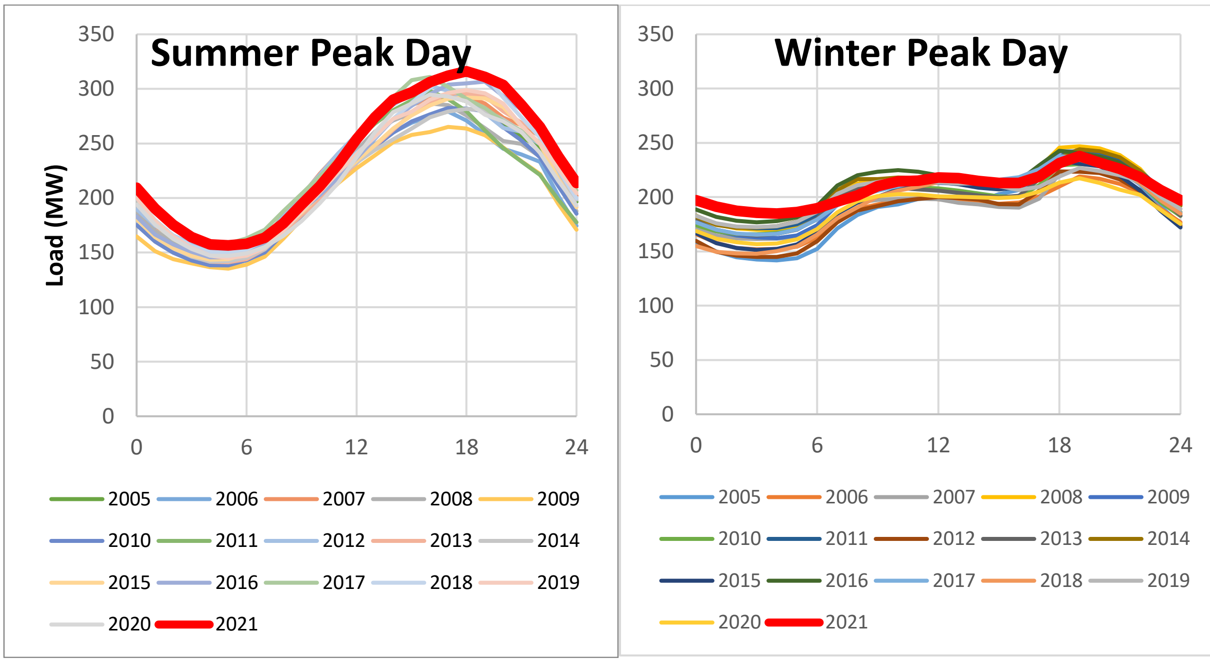

Figure 3. Midwest Utility Summer and Winter Peak Day Hourly Load Profiles

As a result, **meeting winter peaks driven by heating loads with traditional demand response technologies is much more difficult than meeting summer peaks driven by cooling loads.**

Beyond the daily peaks being more difficult to meet during extreme cold, extreme cold events can also go on for days at a time when an extremely cold polar vortex moves overhead. For example, during the Texas cold snap, the temperature in Dallas stayed below the ASHRAE design heating temperature for 3 straight days. This is how households exposed to wholesale prices racked up thousands of dollars of electricity bills and cooperatives exposed to the same wholesale prices and selling at fixed retail prices were unable to pay their bills and declared bankruptcy, (CNBC 2020). If the typical heat pump-heated home used backup electric resistance heat that ran at an average of 10 kW for 72 hours, that's 720 kWh in heating energy in 3 days. With wholesale prices pegged to their cap of $9/kWh, that's $6500 worth of electricity in just 3 days. While the winter peak demand from the heat pump alone is comparable to the same piece of equipment running during a summer peak, the backup electric resistance heating demand is typically much higher.

Current estimates of heat pump impacts are frequently underestimating the impact of full electrification. ISO-NE's most recent CELT report includes forecasts of winter peak impacts. However, their forecasts are based on estimates of per home impacts, (ISO-NE 2021) that are likely much too low. Their estimates show resulting impacts per home for full electrification being approximately 4 kW, while the actual impacts per fully-electrified household in New England are likely to be 10 kW or more during extreme cold snaps.

Reduced Resiliency for Fully Electrified Homes

When we fully electrify, we've made people more dependent on electricity for health/safety – this increases the value at risk during extreme events – see Texas for what happens to people depending on electricity for heat and otherwise ill-prepared with backup heat. At least 200 people died during the Texas cold snap, most of them from a lack of heat in their homes.(Houston Public Media, 2021) While this can also happen in a heat pump home with fossil backup, during rolling blackouts, a home with fossil heat delivers more heat per unit of electricity and typically has higher capacity (e.g. 60-100 kBtu, matched to cooling airflow) compared to 41 kBtu for a typical 12 kW electric resistance heating strip set.

Future Grid Performance During Extreme Cold

While states and utilities have set aspirational goals of 100% renewables by a certain point in time (e.g. 2035-2050), the actual economics of doing so are debatable. While experts disagree on the feasibility of a 100% renewable grid at this time, they do agree that the marginal costs of each incremental amount of supply being met by renewables goes up dramatically as the fraction nears 100%.

At this time, it seems likely that carbon-free electricity gets pushed to 90 to 98% of total electricity production, with the last part driven in part by extreme cold conditions being met with current natural gas generation or similar technologies, the same way that they do now. In this scenario, capacity costs are comparable to now, but generation during extreme cold conditions has comparable carbon emissions to now. Under this scenario, a heat pump operating at extreme cold conditions with a COP of 2 or lower hooked up to a 40% efficient grid (total gas to delivered electricity) will have higher carbon emissions than an 80% efficient gas furnace or boiler. Electric resistance backup heat operating in these conditions will have double the carbon emissions per unit of heat delivered when compared to an 80% efficient gas furnace or boiler.

In either case, running of electric resistance heat for backup needs to be minimized. **In most climates, meeting the full load during extreme conditions with electric resistance backup heat should be a minimal part of a decarbonized built environment. Otherwise, significant additional generation, transmission, and distribution capacity will be required to be built. Given the expected usage of this generation capacity, it will likely be fossil-fired.**

Cold Snap Technical Solution Strategies

The authors have identified nine technical solutions strategies to the extreme cold problem identified above that either reduce the load, meet the load with electricity, or meet the load using non-electric heat sources. These strategies (and others) have various pros and cons that will have varying impacts, depending on the climate and utility context under consideration. While it's hard to say which of these strategies will ultimately get employed at scale (or whether some other strategy omitted from this list might actually be employed instead), it's likely that some combination of these strategies will get used.

Strategy 1. The default full electrification: **Add electric resistance heat and then worry about the capacity needs later.** This is where most utilities are going now, where load gets added and the grid needs to be built out to accommodate this increased load, with full electrification.

Extreme cold performance and carbon efficiency: At extreme temperatures, large amounts of electric resistance heat are required. As per the discussion in the Future Grid Performance During Extreme Cold section above, this is either extremely costly to supply the needed electricity capacity or comes with significantly lower carbon efficiency than a gas furnace.

Pros: In new construction, this is the lowest cost option where we are now on the marginal capacity cost curve. Allows for the possibility of full electrification, eliminating gas fixed charges for the home. If all homes in an area did this, the gas distribution system could be disconnected.

Cons: Adds tremendously to winter peak loads, on the order of 10 kW per home. At the margin, this has limited incremental grid costs, but if we fully electrify most homes, this creates a big problem, with big costs. As an example, for ISO-NE, current summer peak is ~25 GW and current winter peak is ~20 GW. Electrifying 4 million homes at 10 kW each means 40 GW of added winter load, which gives a new winter peak of 60 GW. The same math applies to most grids in the United States. At a nominal avoided cost of capacity of $100/kW-year, each fully electrified house costs $1000/year in additional capacity costs. **The present value of the additional capacity required is frequently the single largest cost or benefit component in a full-electrification scenario with winter capacity impacts included.**

Strategy 2. The fossil hybrid: Leave gas equipment in place for now; size HPs according to ACs. This is the lowest cost means of achieving significant building decarbonization. This is the solution most favored by HVAC contractors at this time.

Extreme cold performance and carbon efficiency: At extreme temperatures, a gas furnace or boiler maintains capacity just like it does now. Carbon efficiency is the same as now, or could be improved with high efficiency furnaces and boilers.

Pros: Extremely low cost, focused on swapping ACs into HPs. A replace on burnout of an air conditioner or new installation of an air conditioner in place of a heat pump has an incremental cost of $200-$1000[3] and requires no additional ductwork modification. Does not impose significant additional winter peak loads on the grid.

Cons: Only displaces 50-90% of loads max, depending on the climate. In warmer climates (e.g. climate zones 3 and 4), a heat pump sized for cooling will be capable of meeting all heating loads down to 10 to 15 degrees, which will cover 90% of heating loads or more. In colder climates, the air conditioner will be sized smaller and the loads will only be met to 15 to 25 degrees; combined with these climates having more of their heating loads at colder temperatures, the fraction of the load being met with the heat pump drops off. A large reduction in throughput of the gas system means fixed costs will dominate gas infrastructure expenses and gas costs will increase in this scenario. While this is listed as a con, this increasing price of natural gas could have the add-on effect of making heat pumps more cost-effective relative to gas.

Strategy 3: Cold climate heat pumps sized closer to extreme condition loads. This is the approach favored by heating electrification advocates. If a cold climate heat pump can be sized to meet the whole load, then a home can be fully electrified.

Extreme cold performance and carbon efficiency: This depends on the definition of extreme cold. At 0 degrees, the cold climate heat pump should perform well. At -15 and below, current technology will not work at all – this area is ripe for further research and development to make heat pumps that will continued

[3] While the incremental cost of a heat pump over an air conditioner piece of equipment may only be $200 or less, heat pumps installed with furnaces or boilers require some additional control wiring.

to run at much colder temperatures. For climates that never get below 0, this solution should work. Carbon efficiency is worse than a gas furnace. A heat pump running at a COP of 1.8 at -10, running off electricity generated by a natural gas power plant with 40% efficiency results in more gas consumed than a furnace operating in the same conditions.

Pros: Decarbonizes more of the heating load than hybrid systems.

Cons: This is potentially very expensive, depending on the climate. It requires both a cold climate heat pump and more heating capacity than would typically be designed for. Does not work in climates with record temperatures below -13.

Strategy 4: Hybrid with gas in place, but add extra heat pump capacity. In this case, for a ducted system, the heat pump is sized as large as possible for the existing ductwork. Once that is filled, or also in the case of boiler-based systems with no cooling or smaller cooling systems, you can add ductless heat pump capacity to increase heat pump capacity. This additional heat pump capacity will not be used very much compared to the first heat pump.

Extreme cold performance and carbon efficiency: At extreme temperatures, a gas furnace or boiler maintains capacity just like it does now. This system with the additional heat pump capacity meets the load under more conditions than solution 2, offering incremental carbon efficiency improvements, especially in cold climates that would have small existing air conditioners.

Pros: Decarbonizes more of the heating load than solution 2, while continuing to avoid adding winter peak demands to the grid. Having two (or more heat pumps) may allow for greater performance optimization with capacity modulation.

Cons: More expensive than solution 2, both in up front capital costs and in operating costs. Each incremental piece of heat pump capacity has lower utilization, with resulting higher levelized cost of heat.

Strategy 5: Heat with biomass during extreme cold snaps (e.g. wood stove or pellet stove). While adding an extra backup heating system seems unlikely for many people, in parts of the country with less reliable electricity and more frequent extreme weather (e.g. Northern New England), a large fraction of homes have wood backup heat that they can use when the power goes out. Some of these homes go years between using their backup heat systems (if they go years without experiencing a significant power outage).

Extreme cold performance and carbon efficiency: The carbon efficiency depends on the fuel used, how it's grown, manufactured, etc. In theory, the fuel can be carbon-free, but at a minimum, for forest-based fuels, use of the forest for fuel may preclude some of its utility for producing other things that sequester carbon. Heating systems that are natural draft, without makeup air, increase heating loads somewhat due to the increased infiltration from air going up the chimney.

Pros: Always works if you have available fuel. Some of these systems can also run during a grid failure, increasing resilience (which is attractive to homeowners).

Cons: Additional costs, homeowner inconvenience. If homeowners thought of them as backup heating systems only used a few days per year, they may be more accepting of the inconvenience.

Strategy 6: Reduce loads through envelope retrofits and extremely efficient codes. Once a potential winter peak demand benefit is added to an envelope retrofit, the overall cost-effectiveness of the retrofit may be significant. Homes built with sufficient envelope insulation and mass may be capable of reducing heating loads to near zero. However, more commonly, this will be used in concert with one of the other solutions.

Extreme cold performance and carbon efficiency: Envelope improvements always reduce the load, in all conditions, including during extreme cold. This makes the home more resilient to power outages and reduces loads. There is no fuel consumed and there are no carbon emissions.

Pros: Works all the time. Lasts a very long time, works with all technologies. When installed in conjunction with new heating and cooling system, reduces the cost of equipment by allowing it to be smaller.

Cons: Likely does not eliminate the entire load, so requires an additional load.

Strategy 7: Install additional heat pump capacity with advanced heat pump controls. Controls can be optimized to run the heat pump as much as possible, preheating buildings when the heat pump can run and when it has sufficient capacity so that it can then be turned off during shorter duration extreme cold temperatures.

Extreme cold performance and carbon efficiency: Does not actually change the heat pump performance, but by preheating the house (to the extent possible), may make it possible to get through a short period of time when the heat pump cannot run due to extreme cold temperatures.

Pros: Controls upgrades have low incremental costs.

Cons: If the controls don't work right, could result in extreme failure, frozen pipes, high bills for consumers, etc.

Strategy 8. Reduce loads in new construction through extremely high efficiency envelopes and limit electric resistance backup size. Even at HERS ratings at new Net Zero code levels, homes will need to increase heat pump size or add supplemental fuel to meet the load. By limiting the size of the electric resistance backup, utility peak demand impacts can be limited during times of extreme cold. This prevents the oversizing of electric resistance backup heating elements in homes with high efficiency envelopes. In the absence of intervention, we'd expect HVAC contractor to continue to install 12 kW electric resistance backup strips to avoid callbacks, since the incremental cost of installing them over 6 kW electric resistance strips is limited to the increased wire and circuit size.

Extreme cold performance and carbon efficiency: In this case, all carbon emissions are eliminated and the utility peak impacts are significantly reduced, but not eliminated.

Pros: The high efficiency envelope delivers savings all the time and winter peak demand impacts are reduced from the default option. This solution also carries all of the other benefits of the all-electric home, including reduced gas fixed charges, etc.

Cons: The winter peak demands are still increased relative to a home with a gas furnace backup.

Strategy 9. New and improved heat pump technologies that are not impacted as much by the cold. All of these technologies need work. These are listed in rough order of how close to mass market

1. **Ground source heat pumps or other water-to-air configurations.** Ground source heat pumps are here and ready but pricey. With winter peak impacts added and additional incentives available, they might fly, but current pricing is for a boutique product, not a mainstream product. Applicability is highly site-specific at this point; requires installation of a ground loop. A small solar water heater could also serve as the heat source for a water-to-air heat pump.
2. **Other thermal storage systems using the earth,** explicitly pumping heat into a section of earth in the summer. Carries all of the same drawbacks of ground source heat pumps.
3. **Experimental desiccant storage systems.** These use a higher thermal storage density medium instead of earth or water, meaning they could be squeezed into more sites.
4. **Adding active thermal storage on the high or low side of the heat pump**, e.g. something like the prototype DREAM system featured in the 2007 CU Solar Decathlon entry. The system featured ice storage on the low side of a water-to-water heat pump that was melted using low cost solar thermal (PV-thermal). A reversible phase change material system is the same idea.

Strategy 10. Add transmission and/or storage in other places in the grid. If we continue on a path using solution 1, electric resistance backup heat, then we will have to find grid-based solutions to meet the new heating load. While none of these appear to be able to handle the entirety of the increase, there are a variety of storage solutions being deployed. The size of the storage problem is approximately 700 kWh, based on a 10 kW average electric resistance load over 3 days, but that could be reduced using some of the solutions above. Solutions include:

a. **Home-sited battery storage** (not very cost-effective, currently ~$1,000/kWh).
b. **Electric vehicle managed charging** (very cost effective) – for cars with big batteries, incent people not to charge for days at a time during extreme peaks, much longer duration DR than traditional DR, well-suited for 2-3 day peaks. For a car with a 300-mile range being driven an average of 30 miles per day, people could go a week without charging. This shifts about 80 kWh up to a week.
c. **Increased use of hydro systems for seasonal storage.** While this already gets used in various power systems, in places with the existing infrastructure (western US, etc.), or the potential for additional hydro development (Quebec/Labrador), low-utilization hydro turbines could be installed to run a few weeks per year at increased output, with water held back for this use. This option is well-suited to hydro systems with large storage relative to throughput. Also requires more transmission. Increased output would result in artificial winter floods, which may be seen as beneficial or detrimental, depending on the perspective.
d. **Build more transmission lines to transport electricity from hot climates to cold climates.** Some have advocated for building more transmission to move electricity from places with excess renewables to places experiencing a storage. While this would clearly help, some polar vortexes are so widespread that they cause extreme cold across most of the homes in the United States at the same time, e.g. from Texas to Georgia and everywhere north of that at the same time.

Building Electrification Extreme Cold Weather Policy Problems

Many states and the Federal government have raised the stakes by committing expanding efforts towards promotion of heat pumps. While there are several other policy problems, the authors have focused on the extreme cold weather blind spot.

Problem 1: We don't currently value winter peak impacts of full electrification Winter peak avoided costs used most places are currently 0. While this is true now, it will not be true in a full electrification scenario in most places. Additional research is needed to improve estimates of winter peak demand increases associated with full electrification and incorporate them into cost-effectiveness frameworks.

Problem 2: Flat costs of electricity do not reflect actual grid economics now or in the future. When we remove the backup heating option from the home as it would be in a fully electrified home, we shift the burden of backup to the utility. We expect our utilities to be able to keep power available especially at times of extreme weather. To do so they must construct and maintain adequate capacity that will be used quite infrequently. If they do not have this capacity available, there will be outages that have their own costs. Because most residential customers pay only a per kWh charge, all of their collective use is charged the same price even though it costs the utility more to supply your heat pump than it does your refrigerator.

The recent shortage of power in Texas is an excellent case study to understand the dynamics between four components: weather, a device such as a heat pump that uses more electricity as temperatures become more extreme, utility supply, and electricity pricing. The extremely cold weather combined with electric resistance heating created a demand for electricity that the Texas grid could not supply. Shortages raised the prices of the available power. When people were exposed to full wholesale cost variability in Texas, some of them spent $10,000 + in one week heating their homes. We recognize there may be flaws in the variable wholesale pricing used in Texas, a chief one being that customers didn't have a real time indicator of the higher pricing and only found out about it when they got their bills. The real message is that supplying peak loads has costs that are not reflected in the cost-effective testing now being done. We need to compare the home with a gas heater as backup to the full electric home with the utility cost of supplying that backup. This also needs more research.

Problem 3: Building code objectives still focus primarily on reducing annual energy consumption and on current energy costs (with great success), which may not be reflective of future energy costs. Because buildings last a very long time, these objectives may not produce an optimal building for 2040 or 2070.

Problem 4. The policies have committed to supporting current heat pump technologies without waiting for evaluation results. Most of the data on heat pump performance comes from the manufacturers and not from field tests of performance. One metering study done for 2015-16 winters in MA shows a steep decline in COP for units from above 3.0 at 40° to around 2.0 at 10°, (Cadmus 2016). These results are now seven years old and need updating. Programs are scrambling to get metering studies in the field to determine actual efficiencies across all potential weather conditions. One study also reporting in this conference metered the performance of low-income homes and a multifamily building where heat pumps were installed to replace electric resistance heating in Michigan, (Popli et. Al. 2022). The study found that "compared to baseboard electric heaters, mini-split cold climate heat pumps were found to reduce the average heating season energy consumption of MF and SF homes in Michigan by 36% and 7%, respectively." These savings figures are quite surprising as they are well below the values expected. A third study conducted in British Columbia (RDH 2021) showed significant issues with ductless cold climate heat pumps in a small sample of homes, with low airflow contributing to measured efficiency coming in much lower than rated. The BC study pointed to a systematic rating bias in rating units without louvers and then installing them with louvers.

The results are an example of the complexities of programs that seek to use heat pumps to address climate change. Studies in MA and CT have found that a large percentage of units incentivized by the program end up being used exclusively for air-conditioning. MA now promotes integrated controls that will run the heat pump as the primary heater until the temperature drops below a switch-over setpoint, art which time the backup fossil-fuel heater kicks in. A recent evaluation indicates that contractors are reluctant to use low switch-over settings, fearing that doing so would generate high bill complaints.

Policy Prescriptions

In light of the fact that states have already committed to expanding heat pumps, we offer the following policy recommendations.

Stop with the emphasis on 100% electrification in cold climates, until we get a 2050 technical solution worked out, rather than defaulting to a grid with double the capacity we have now. In the near term, partial displacement is much more cost-effective and simpler to achieve. It might still be OK to pursue 100% electrification in new buildings, since it's easier to build a new building to require extremely efficient envelope (2021 IECC has less than half the heating loads of buildings from the 1990s, let alone the 1960s).

Rather than just increasing incentives on the current systems, use more of the funds to develop and demonstrate better technologies. Continue to invest in R&D on heat pumps, with a focus on even colder climate performance than current cold climate heat pumps. In Northern climates, existing homes and even new homes that are not super-efficient will need a heat pump capable of running at -30 and carrying significant capacity down to -20, which is a step beyond current cold climate heat pumps. While some commercial variable refrigerant flow equipment is already capable of operating at these temperatures, residential equipment is not available at this time.

Water-to-air or water-to-water heat pumps are more suited to supply heat when outdoor temperatures drop. Ground source heat pumps are such a technology, but other sources of warm water are available. In Europe, solar water heaters-assisted heat pumps use the solar collectors to heat up water as the input source. (Redko, 2020) The 2007 University of Colorado Solar Decathlon house featured a water-to-water heat pump with ice storage on the low temperature side, being fed by a combination of air-to-water heat exchangers and PV-thermal solar thermal collection. Other variants on this idea should be explored further as an alternative to ground loops.

If we are serious about full electrification, put additional emphasis on weatherization. As the Michigan example shows, installing heat pumps in current homes can result in disappointing results. Conversely, there are numerous anecdotal cases of new super-efficient homes in Northern climates where a small heat pump heats the whole home. The issues discussed in this paper are lessened in a well-insulated home versus a less well insulated home. To reach full electrification will require significant efficiency upgrades in buildings. Utility programs need to tie all-electric conversions more closely to energy efficiency upgrades. Connecticut has a requirement that homes get an audit before they get conversion incentives. That should be the minimum step, with incentives increased when shell improvements are made. Both Connecticut and Massachusetts have new renovation and additions programs. Studies in both states, show the energy savings opportunities have more than 15 the savings potential compared to what is available from new construction. Both programs are experiencing a low demand and need a way to boost interest. If full electrification is the goal, these two programs need a tighter connection.

Make codes and standards improvements to drive higher heat pump and heat pump water heater adoption.

- Consider codes to require all CACs be capable of heat pump heating – true incremental cost should be less than $200/heat pump for like size and efficiency in new construction. Costs for retrofits are a little bit higher to cover new control wiring and thermostats.
- Consider code requirements to drive significantly better envelopes.
- Consider changing codes to focus more on saving energy during times of constraint, by weighting savings by future time value of energy savings.
- Consider requiring electric water heat with heat pump water heaters in new construction.
- Require new construction to be electrification-ready, similar to what California has done.
- For all-electric new homes, require high performance envelopes and restrict the size of backup electric resistance heat to reduce winter peak demands**.** Building all-electric homes with reduced winter peak demands gives utilities a chance to see how all-electric homes perform when optimally designed. This "sandbox" will allow people to capture information on long term performance of all-electric homes before pursuing the more difficult step of going from 80% electric heating to 100% electric heating for existing homes with poor envelopes.

Recalculate cost-effectiveness using both GHG costs, but also the full cost of backup in a future heavily electrified grid, whatever the source. Calculating BC on current savings ignores both the market transformational impacts and the lost opportunities. This will shift the priority to improving the thermal efficiency of the building. In new buildings and renovations, addressing windows and insulation are more cost-effective and not doing them are almost permanent lost opportunities. If we know that we will need to replace these in 25 years to decommission residential gas delivery, then we need to change the short-term perspective of the BC calculations.

The Future Role of Heat Pumps

Encouraging all-electric homes that impose large peaking demands on utilities is not the environmental-friendly solution that greenhouse gas policy is seeking. Shifting large peak loads to utilities is very likely to mean a continued reliance on gas to meet those demands. Under current prices, this shift seems cost-effective from the building owner's perspective, but that is because current pricing is not capturing these peaking costs to the utility system. Full-electrification needs to consider the whole societal costs of supplying energy to that building.

Until such time as homes are made super-efficient and renewable energy sources are cheap, plentiful, and available in ways that can handle extreme weather events, it may be greener to use strategies that use a minimum amount of gas to meet the coldest days' loads. We recognize that by using these gas products, we may postpone or eliminate the possibility of closing down gas distribution systems and realizing the significant savings in GHG that result from eliminating leaking. In the near and mid-term, addressing gas leaks directly is likely to be far more fruitful in most neighborhoods where gas is now a fixture.

Heat pumps are destined to be an important component in an electric future but promoting them on their own right now may backfire, as it did in the 70s with the first iteration of heat pumps. We need to find out more about their performance and how best to operate them as part of a whole home system. We need to work to educate contractors and users on their correct uses and limitations, recognizing that word of high costs and cold homes could once again doom this technology as it did in the 70s. We need to research and develop systems and operating strategies that overcome the limitations inherent in the current designs. Most importantly, we need to encourage their installation into homes that have first maximized energy-efficiency.

References

Cadmus 2016, Ductless Heat Pump Impact Evaluation, https://ma-eeac.org/wp-content/uploads/Ductless-Mini-Split-Heat-Pump-Impact-Evaluation.pdf

CNBC 2021, "Texas electricity firm files for bankruptcy citing $1.8 billion in claims from grid operator", https://www.cnbc.com/2021/03/01/texas-electricity-firm-files-for-bankruptcy-citing-1point8-billion-in-claims-from-grid-operator.html

DNV 2019, R1617 Connecticut Residential Ductless Heat Pumps Market Characterization Study – Final Report; Microsoft Word - R1617 DHP Report 201906-20 FINAL.docx (energizect.com)

Gold, R., 2021, "Status Report on Electrification Policy: Where to Next?", in *Current Sustainable/Renewable Energy Reports* 8.

Guidehouse 2021, Energy Optimzation Fuel Displacement Impact and Process Study, https://ma-eeac.org/wp-content/uploads/MA20R24-B-EOEval_Fuel-Displacement-Report_2021-10-13_Final.pdf

Houston Public Media 2021, "Texas Winter Storm Death Toll Goes up to 210, Including 43 Deaths in Harris County", https://www.houstonpublicmedia.org/articles/news/energy-environment/2021/07/14/403191/texas-winter-storm-death-toll-goes-up-to-210-including-43-deaths-in-harris-county/

ISO-NE 2021; Final 2021 Heating Electrification Forecast. https://www.iso-ne.com/static-assets/documents/2021/04/final_2021_heat_elec_forecast.pdf

Popli, S. et al., 2022; "Energy Savings through Cold Climate Heat Pumps at Income Qualified Residential and Multi-family Homes in Mid-West",Sahil Popli, Chris Newton, Caroline Berman, Cherish Smith, International Energy Program Evaluation Conference, San Diego, 2022

RDH 2021. https://www.rdh.com/wp-content/uploads/2021/01/BC-Cold-Climate-Heat-Pump-Study-Final-Report.pdf

Redko, A. et al., 2020. *Low Temperature Energy Systems with Applications of Renewable Energy*.