Air Source Heat Pump's Transformative Potential

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ABSTRACT

This paper presents the case that air source heat pumps may be as technologically essential to efficiency, utility grid management and climate goals as photovoltaics, LEDs, and electric vehicles. The current state of the technology belies its potential. Just as PVs, LEDs and battery technologies took decades to achieve important breakthroughs, heat pumps are similarly undergoing some critical evolutionary step-changes in their capabilities. As fully mature technologies, with manufacturing economies of scale, necessary trade skills, standards, policies and demand management control integration, heat pumps can profoundly transform our energy system.

This paper presents the basis for this thinking, technology improvements, core barriers, an update on promising efforts by energy efficiency organizations and utilities in North America. The paper presents a call to action on specific additional steps that are needed for strategic alignment of energy efficiency and greenhouse gas reduction driven efforts to remove critical barriers. The authors hope this paper spurs healthy debate and collaboration.

Introduction

Air-source heat pump (ASHP) technology uses a refrigeration cycle to concentrate and move low grade heat from ambient air. Recent advances in air source heat pump technologies create dramatic new opportunities to reduce cost, improve comfort, and expand ASHP value in utility grid resiliency and greenhouse gas reduction.

For this paper, we are distinguishing conventional heat pumps from the emergent new ASHP. This new class of inverter-driven distributed-intelligence-equipped heat pumps is referred to herein as "iASHPs". What makes this class of heat pumps different than the old "chew toy" of past decades is that they are notably more efficient, can operate well in cold climates, and can be more responsive to utility grid stability needs. It is the authors' belief that the synthesis of new technologies and standards of practice with full economies of scale will enable iASHPs to harvest ambient energy at a lower life cycle cost than many other resources.

Even at a market mature state, iASHPs will not likely be viable in climates where outdoor ambient air temperatures remain below 5F for extended periods of time – where backup heating becomes essential.

The US currently uses roughly 11 Quads for residential and commercial space and water heating (EIA 2018). The majority of this energy is provided by either fossil fuel-driven systems or electric resistance heating. As discussed later in this paper, meeting this load with iASHPs would reduce space and water heating energy use by more than 50% and can reduce total US energy consumption by approximately 8% (8.1 Quads). Displacing only the electric resistance

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[1] While all authors contributed to this paper, not all authors agree with every point made in this paper.

heating applications would reduce US energy consumption by about 2.1% (Nadel 2016). The net impact on greenhouse gas emissions is similarly reduced as the electric system that provides power for these iASHPs shifts toward lower carbon sources.

Achieving the market potential for iASHP is neither simple nor likely to occur without market intervention to advance product maturity, standards of practice maturity, and production economies of scale. This is a classic "chicken and egg" problem that plagues many technologies. At its current state, the conventional ASHP doesn't provide a strong enough value proposition in heating climates. To realize full market maturity may require substantial coordinated effort between utilities, manufacturers, and government.

Transformative Trajectories

Four Important Technologies

Air source heat pumps are one of several essential technologies which have emerged in the past 20 years that will dramatically reduce total energy use and related environmental impact. Example essential technologies are: LED lighting, new renewables[2], and electric vehicles. Combined, these technologies provide cornerstone services in an industrialized society providing heating, cooling, lighting, transportation, and environmentally sustainable energy. Table 1 shows a comparison of energy needed to provide these services currently (pre-transformation) and for both the technical potential (100% change) and achievable potential. The achievable potential represents a future state of substantial market maturity in performance, standards of practice, and economies of scale.

Table 1: Technical and Achievable Potential Comparison

Application	Source Energy Use (Quads)			Achievable Savings
	Current Use	100% Adoption	Achievable Adoption	
Residential and Commercial Lighting	3	1	1	2
iASHPs for Space and Water Heating	11	3	7	4
Light Vehicle Transportation	15	3	11	5
Photovoltaics	-0.2	-9	-5	5
Total Energy (Quads)	30	-1	15	**15**

Source: Authors' calculations, based on EIA 2018 Energy Outlook data. The Achievable figures assume 50% market penetration by 2050, except for lighting where 100% is assumed.

Table 1 shows the approximate savings potential of iASHP is larger than LED lighting and comparable to that of electric vehicles and photovoltaics. These calculations assume the future iASHP systems have a seasonal COP of 2.2 for water heating and 3.0 for space heating sourced from an electrical grid with 50% average renewable generation content. The technical

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[2] This includes PV, Wind, bio-energy, geothermal and small hydro.

potential values[3] represents the unlikely situation where 100% of the available applications are converted to heat pumps, whereas the achievable potential[4] represents the authors' estimate of what is possible to achieve by 2050. While the basis of these values assumes an electric powered heat pump, it is noteworthy that iASHP systems could be energy equivalent if driven by on-site gas driven heat pumps with COP values of 1.4 or higher, though not as low a global warming impact without the substantial emergence of renewable energy based natural gas.

Market Transformations Require Robust Markets

The vapor compression cycle has been used for moving heat since the first refrigeration systems were developed in the 1830's, and the concept of a reversible heat pump cycle was first described by Lord Kelvin in 1853. Commercial applications for space conditioning began in 1945 (Finn Geotherm 2018). While the vapor compression cycle is widely used today for refrigeration and cooling, it remains relegated to smaller markets for heating air or water largely because alternatives such as coal, oil, gas, and electric resistance heating are often cost competitive and can operate effectively in cold climates.

New technologies need a large enough market to transition to a state of market maturity. Without a starting point, they can indefinitely remain under-capitalized, under-utilized and un-refined, and never achieve market maturity. As an example, photovoltaics (PV) remained a niche technology for remote applications for 50 years until the major market intervention of the German feed-in tariff (FIT) that began in 2004. When the FIT was first introduced the photovoltaic system cost was greater than 15 times current costs, it lacked standards of practice, trade skills, utility grid interconnectivity, finance-ability, consumer awareness, aesthetics and faced many other barriers to widespread adoption. Photovoltaics would likely have remained a niche technology had not a significant PV market opportunity been established, through which technology was able to mature. Today PV power in the US has a levelized cost of energy of about 15 cents per kWh and is on path to reach 5 cents per kWh by 2030 (Fu 2017).

Similarly, LED lighting did not begin its path to market maturity until a robust market emerged. When light emitting diodes (LEDs) were first produced in 1950s, they were heralded as a future replacement to incandescent lighting. They remained a niche product for signal indication and small power applications until their relevance to portable computers, cell phones, and computers provided the economies of scale needed to mature the total market. LEDs as a light source capable of displacing fluorescent and incandescent lights may not have advanced without the successful early stage markets like exit signs and traffic lights and the substantial market that emerged for the computer and TV markets. Such early and adjacent markets are common market transformation drivers that enable technologies to mature and reach adequate economies of scale to be cost-effective replacements to incumbent technologies.

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[3] Technical Potential Assumptions: The lighting baseline estimate is adjusted to pre LED conditions (based on NEEA's 2011 building stock assessment values, with end state efficacy estimates of 100 lumens per Watt (lm/W) for residential lighting and 150 lm/W for commercial. Light vehicle transportation is based 75% conversion to electric vehicles with an MPGe rating of 120, and 25% with a fleet average of 23.2 MPG. The photovoltaic "savings" are based on a projected 1000 GWp (GW peak) of installed capacity under a solar resource of 1400 kWh/Wp (peak Watt of solar capacity)PVWATTS – St Louis.

[4] Achievable potential: iASHP = 75% of possible applications, LED lighting = same as technical potential, light vehicle transportation includes only impact of EVs (internal combustion engine efficiency held constant so

What is Possible

Current Technology & Market

The term heat pump is a generic term used to describe a vapor compression cycle that moves heat from one location to another. However, the term is commonly used only for systems in which refrigerant flow can be reversed so that it can move heat in either direction. Air conditioners or refrigerators are heat pumps that are only used for cooling and they lack the reversing valve necessary for bi-directional heat movement. For simplicity, this paper will refer to all types of vapor compression equipment used for heating air and/or water as heat pumps. It is not specific about what is the underlying energy source used to drive the heat pump. Electrically driven motors are common, but at scale and with adequate maturation, natural gas driven motors, or absorption cycle systems may be equally viable.

All these products are part of a generic family for which the core technology is the same. Advances in this core technology benefit all types of heat pumps and refrigeration systems. Just as the LEDs for lighting benefited from market development of LEDs in computers, heat pumps used for water heating can benefit from development of heat pumps used for space conditioning.

Most residential and commercial heat pumps and air conditioners use well established constant-speed compressors with simple analog controls. This technology has limited capability as it is often not capable of serving heating needs when ambient temperatures become cold (below freezing) and requires some form of back-up heating. Space conditioning with these systems consists of three primary components: the outdoor compressor/evaporator, the indoor forced air fan-coil, and a backup heat source such as an electric resistance heating coil (see figure 1).

Figure 1 – Heat pump examples: heat pump water heater, mini-split HP, and central forced air HP

The potential market for iASHPs is much larger than the market currently served by conventional ASHPs. This is primarily because of their ability to provide heating in cold climates. The future market (annual sales) potentially includes the displacement of 3.1 million warm air gas and oil fired furnaces, 2.6 million residential central heat pumps, 5.2 million central air conditioners 8 million single room air conditioners, and packaged terminal heat air conditioners (AHRI 2018), and 9 million water heaters (Ryan 2010).

Heat Pump Enabling Technologies

The following sections describes four enabling technologies that define the future iASHP. These technologies are currently ready for market adoption and are already used in some heat pump applications (e.g. mini-split heat pumps, non-HVAC applications, etc.). Complete integration of these technologies, development of trade skills, and market acceptance however will likely happen slowly if at all, without some form or active market intervention.

Variable Frequency Drive and Cold Climate Technology. A major performance improvement to the heat pump is the variable frequency drive (aka “inverter driven”) which adjusts the speed of the compressor and the related heat exchanger fans for enhanced performance. By electronically adjusting the speed of the motors, it is now possible to operate the compression motor at much lower speed, dramatically increasing performance at low loads. Low load performance is also improved because the heat exchangers are more effective under low speed conditions. Variable frequency drives are also key to several manufacturers developing cold climate heat pumps which are capable of maintaining full capacity at 5 degrees Fahrenheit through a combination of driving the compressor at higher speeds and careful refrigerant management techniques. This combination results in reduced backup heating hours, lower peak demand and a 10-20% seasonal performance increase (Energy& Resource Solutions, 2014).

Another potential benefit of using a variable frequency drive is that the power electronics within the heat pump can potentially draw power from the utility grid in a way that enhances the utility power distribution system. Inverter drives are capable of providing a small amount of VAR (volt-ampere reactive) support, low voltage ride-through and curtailment when the utility grid becomes stressed. This feature of an inverter is already in use by photovoltaic inverters in Germany and being tested in US markets like Hawaii (NREL 2016, Nelson 2016).

Distributed Intelligence. Advanced micro processing and machine level learning present a new opportunity for residential and commercial heating and cooling systems. New low-cost artificial intelligence (AI) deployed at the microprocessor level are already being deployed in cellular phones and are expected to “trickle down to all [mobile] devices” (The Verge, 2018). HVAC systems will be capable of gathering data about consumer preferences, occupancy, and weather to develop a physics based model of how the total system (house, building, storage) behave. Placing AI within the heat pump has the advantage of enabling the heat pump manufacturer to integrate operational information about the compressor(s), fan(s), pump(s) and heat exchangers that is not possible at the home energy management or thermostat system level. Locating the AI at the machine level creates a “distributed intelligence” where only minimal high level data is needed for system optimization.

A home energy management system, thermostat, or remote sensors could provide information about room temperatures and occupant set-point schedules. Internet connectivity could provide near-future weather and utility price information. The combination of these high level data is sufficient for an AI equipped iASHP to learn how increase comfort, and minimize energy cost over time.

A future residential iASHP could for example combine information from weather forecasts, near-term utility pricing along with occupant history to pre-cool or pre-heat spaces for optimal homeowner comfort at minimal cost. Such a device could provide automatic commissioning, minimize utility costs, be responsive to utility needs (through price signal information). It could also potentially provide a service technician with operational maintenance data in advance of system failures.

Advanced Heat Exchangers. The performance of heat exchangers used in residential and commercial heating and cooling systems is well below what is currently technologically possible. Improvements to the air to refrigerant heat exchanger can increase the heat exchanger heat transfer coefficient (HTC) leading to improvements to both operating efficiency and broader operating temperature ranges (Chapp 1998). One such example are micro-channel heat exchangers, which until recently were only common in automotive radiators but are now beginning to appear in some mini-split and VRF systems. Mass production of advanced heat exchangers will enable an iASHP to heat reliably when it is cold outside without backup heating and/or provide better cooling or moisture extraction when it is hot outside. Potential energy savings of 0.7 to 1.1 quads is possible by the increasing the condensing unit's heat transfer coefficient in U.S. market heat pumps (Westphalen 2006). Work currently funded by the US DOE Office of Energy Efficiency and Renewable Energy seeks to use advanced heat exchangers to reduce the amount of refrigerant, and material needed while increasing performance by 20% (US DOE 2016)

New Refrigerants. The phase-out of HFC refrigerants will likely result in a switch to hydroflouroolefins (HFOs) or HFO/HFC blends, hydrocarbons (HCs), or other "natural" refrigerants like CO_2 or ammonia. This transition will not be easy, but if integrated well can result in better performance, safety, and enhanced utility grid resiliency. HFC refrigerants such as diflouroethane (R32) and hydrocarbons such as isobutane (R600) or propane (R290) offer lower cost and often improved performance, but present challenges because of their flammability. R32 is slightly flammable (an A2 refrigerant) though it is extensively used now in mini-split systems throughout Asia. Another likely replacement is R744 (CO_2), which offers produces higher COP values under large changes in temperature with enabling it to operate cold climates while delivering very high temperature (190 F) output temperatures.

Hydronic Systems and Thermal Storage. The combination of new refrigerants coupled with hydronic systems could improve seasonal COP by 10-12% over current R410a systems (Konghuayrob , 2016). While current hydronic systems are often more expensive to install, future standards of practice may eliminate this as added cost is not intrinsic to hydronic versus refrigerant systems. In addition to improved performance, are four additional benefits of moving to hydronic systems.

1. The trades needed to install hydronic HVAC equipment do not need a refrigeration certification. The outdoor iASHP unit can be a packaged assembly that provides hot and chilled water, with only hydronic, control wiring, and power connections.
2. The system becomes far more independent of the interior conditions and a system can be placed in defrost mode without delivering cold air to the indoors. In addition, the higher heat capacity of water and energy stored in the system can enable very rapid defrost cycles, reducing loss of capacity impacts in cold ambient conditions.
3. A single system can be tasked with both domestic water heating and hot and chilled water for space conditioning, thus *potentially* lowering overall system cost.

4. Hydronic systems can be easily used to store energy. A low-cost 50-gallon storage tank, for example, can provide 4-7 kWh of useable storage without negatively affecting occupant needs (Eustis 2016).

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Benefits of iASHP

Lower Costs. A mature iASHP market should result in lower total energy cost (to the economy) through, lower operating costs from greater energy efficiency and the potential benefits to electric utility through the demand management capabilities of an iASHP. The initial incremental cost of the technologies will likely decrease over time as soft costs and non-reoccurring engineering and manufacturing costs become negligible at market maturity[5].

GHG Reduction. Conventional air source heat pumps have an on-site heating efficiency roughly 3 times that of the combustion driven heating, but currently have comparable overall greenhouse gas (GHG) emissions when transmission, distribution, generation, and refrigerant losses are included. However, this is not true when viewed from a future state where ASHP technology has matured, refrigerants have changed, and utilities have shifted substantially to renewable energy sources.

To understand the full relative greenhouse gas emissions from a future state iASHP we calculated the total global warming impact of providing 1 million BTU of heat to a space from several heat sources. The results of this analysis are shown in Figure 2. The analysis included all transmission losses, generation efficiencies, seasonal operating efficiencies of the heating systems, electric power draw standby, distribution (fans and pumps), and gas leakage values.

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[5] Conversations under NDAs with manufacturer product engineer and university research scientists.

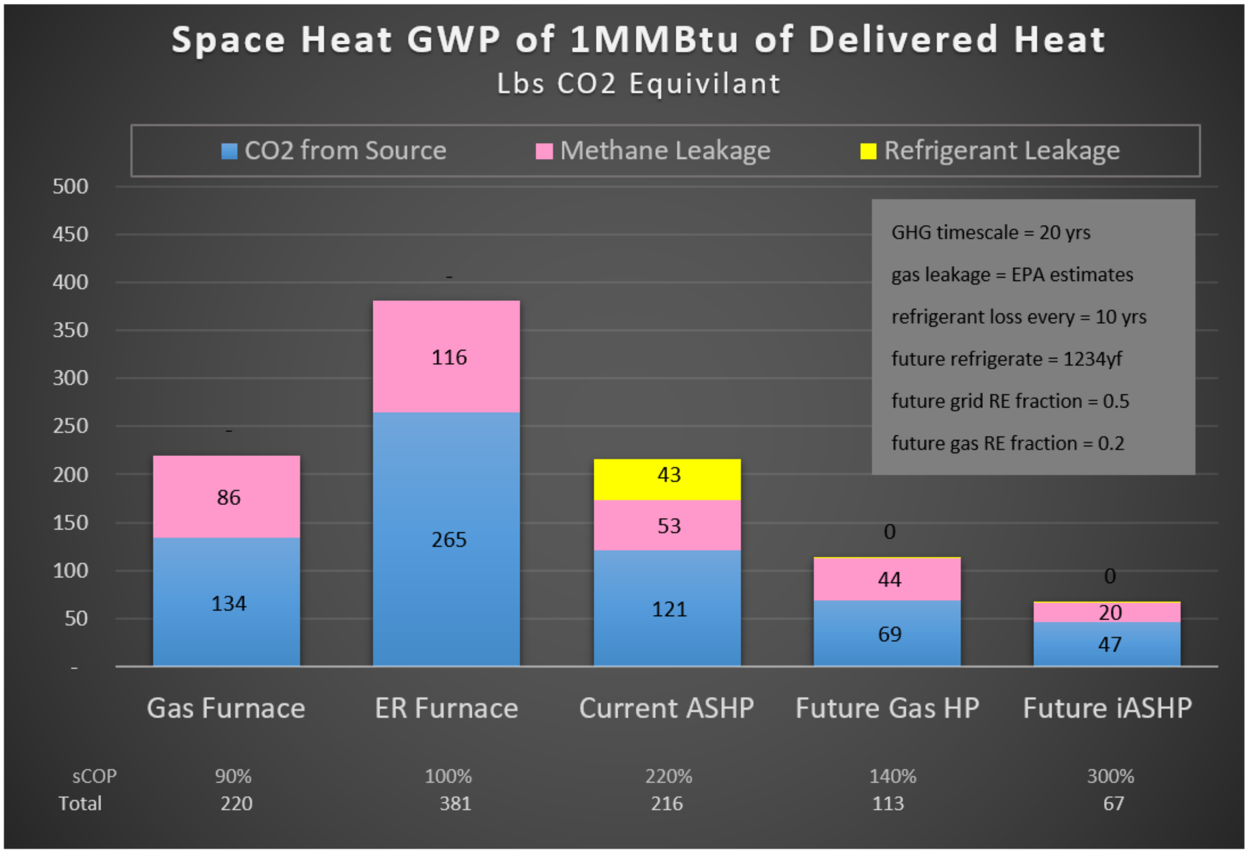

Figure 2 – global warming impact comparison of 5 different heat sources
Source: Author's calculations using data from many sources; key assumptions discussed in the text.

Figure 2 shows that total GHG emissions of current ASHPs and gas furnaces are very similar, with 220 and 216 lbs CO_2/MMBtu respectively. Future Gas ASHP and iASHP have much lower total equivalent GHG emissions, 113 and 67 lbs CO_2/MMBtu respectively. Thus the projected source based GHG of the future state iASHP is 70% less than current total emissions from either current gas furnace or ASHP space heating[6].

The assumed seasonal coefficient of performance (sCOP) for the gas ASHP is 1.5 which is based on current lab-tested (but not yet commercially available) technology. The assumed iASHP sCOP is 3.0 which is based on field validated performance for currently available inverter-driven cold-climate mini-split heat pumps (NEEP 2017). The assumed natural gas leakage rates are based on EPA estimates of 1.4%. The current source of electricity is natural gas burned in combined cycle gas turbine with a fuel rate of 7,652 Btuh/kWh and a transmission loss of 6% with a 20% renewable energy contribution resulting in GHG emissions of 0.72 lbs of CO_2 per kWh. The future source of electricity produces 0.31lbs of CO_2 per kWh (equivalent to Gas CCT with a 65% RE contribution). The current ASHP refrigerant is R410a with a 20-year global warming potential (GWP) of 4340 and the future iASHP assumes the use of a natural refrigerant with an assumed GWP of 4. All cases assume the refrigerant leaks out once every seven years. The natural gas leakage is divided by extraction, transmission and distribution values depending on where it was burned. The effective global warming impact of refrigerant and natural gas

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[6] Does not include GHG emissions of manufacturing, transport, sales and installation of the heating system itself.

leakage was based on the 20-year impact rather than the 100-year impact as it is in this time scale that climate change needs to be addressed.

Barriers, Challenges and Opportunities

While ASHPs have established healthy markets in some regions of the United States, most regions have very low market penetration. For example, heat pumps are used in 20% of homes in the South Census Region, which is double the nationwide percentage (EIA 2017). Several key market barriers exist today that have impeded the mass adoption of ASHPs in all regions and maturation of the technology for heating. While barriers could vary by climate or market, a number of barriers are common to all.

Market Barriers

Recent strategy and market assessment work provides excellent descriptions of the primary market barriers to advancement of air source heat pumps (NYSERDA 2017; Hopkins 2017; Lee 2018; Conzemius 2016). The primary market barriers are as follows:

- Limited awareness of the technology (consumer and installer)
- Limited confidence in the technology (consumer and installer)
- High initial installed cost
- Performance challenges, especially at low ambient temperature
- Policymaker support, especially around fuel-switching
- Potential new winter peaks
- Current performance metrics do not adequately differentiate systems optimized for different climates

The primary challenge iASHPs face is reaching product economies of scale and technology maturity, before the product is sufficiently mature, and production has increased sufficiently to drive out initial non-recurring product and production capacity costs. This classic “chicken and egg” problem is best overcome by pursuing all near term cost effective opportunities where minimal initial investment can be used to leverage larger economies of scale.

Near Term Market Opportunities

Near term opportunities increase market scale and product maturity include:

- Ratepayer funded energy efficiency programs
- GHG reduction policies and programs
- New requirements on HVAC refrigerants
- Leveraged niche market opportunities
- Availability of affordable communication technologies to enable dynamic operation
- Growing value stream for more flexible loads
- Zoneability of many ASHP technologies to improve comfort and control

Current Market Transformation Efforts

Market transformation for iASHPs is not relegated to just utilities, DOE and a few manufacturers who are investing in new technologies. There are many activities currently underway that are laying a foundation to transform the market. Table 2 presents several organizations actively working on this and the key barriers they are addressing.

Table 2 – Active ASHP Market Transformation Efforts

Region/Organization	Technology Research & Development	Test Procedures and Metrics	Installer Training	Consumer Education / Awareness	Cost Reduction or Financing	Increased Production	Policy/ Admin Rules
Canada (EnerCAN, CSA)		X	X	X	X		X
US DOE	X						X
Cities (CNCA[7])							X
NGOs (ACEEE, NRDC)							
EPRI	X	X					
California (CEC, CPUC)	X				X		X
NEEP and Partners		X	X	X	X		
NEEA and Partners		X	X	X	X		

The efforts identified in Table 2, are not well coordinated and in particular lack the large market drivers that enable manufacturers to invest in sufficient production scale and product development and refinement. This suggests that leveraging niche market opportunities where scale and product maturity can be increased is most likely to succeed with minimal investment. Example niche market opportunities with particularly strong potential include:

1) The replacement of electric resistance heating in moderate climates, with replacement of electric furnaces a particularly attractive opportunity.
2) Conversion of central air conditioners to iASHPs.
3) Displacement of oil/propane heating systems, particularly in homes lacking central air conditioning.
4) Efficient new buildings where money can be saved by not installing gas service.

The moderate climates of the Pacific Northwest provide a unique market opportunity for iASHP advancement for three reasons. First, climate in this region is not severe enough to prevent current inverter-driven mini-split heat pumps from providing near 100% displacement of space heating. Second, electricity rates are at or below national average rates. Third, the regional electrical grid is increasingly constrained by capacity and could benefit from the demand response capabilities of a more “alonetic”[8] technology (Eustis 2016). This provides an opportunity to develop scale and manufacturing capacity for a cold climate-focused iASHP.

Homes in much of the Southeastern United States have central air conditioning systems, often with electric resistance heating. Much of the time the system operates in cooling with little need for heating. This market can be a unique opportunity to upgrade the central cooling systems to a central iASHPs when the equipment needs replacement. The additional cost of conversion to

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[7] Carbon Neutral Cities Alliance

[8] a term coined by Conrad Eustic (Portland General Electric) used describe an electric device capable of beneficially support operation of the electric utility grid.

an inverter driven heat pump (capable of meeting both heating and cooling needs) is often cost effective in homes with electric furnaces (Nadel 2016). Thus, homes in this market may provide an opportunity to develop scale and capability for cooling focused iASHPs.

Conclusion – A Call to Action

Most HVAC systems have a useful life between 15 and 20 years. This means that are potentially 50 million opportunities for heat pumps to be installed between now and 2050. At market maturity the iASHP could provide three important benefits:

1) Lower cost per delivered unit of heating.
2) Utility grid management and resiliency benefits provided by the inverter drive, storage, and load shifting
3) Lower total system carbon emissions

The technologies needed to achieve these benefits are known and available (inverter-driven, variable speed drives; advanced heat exchangers; and distributed intelligence capabilities) but have not been integrated into the full range of heat pump applications. These technologies remain scattered across many different products and market niches, not at manufacturing economies of scale, and without strong market drivers. Manufacturers will **not** likely invest in product development without seeing a clear opportunity for future competitive advantage and profit. It is therefore incumbent on other market actors to provide a clear roadmap that outlines future market opportunities by providing:

1. Clear performance metrics and performance targets
2. Rewards for achieving those performance targets
3. Monitoring to make sure that performance in the field is consistent with these targets
4. Support for installer training
5. Support for end-user awareness

Achieving this end state begins with coordination of various ongoing efforts across North America. The market transformation effort would benefit from a high level market transformation strategy to which all market actors are committed. This will help drive the product development and manufacturing investments needed to reach the necessary economies of scale and product maturity.

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