2021

Community Heat Pump Systems Utilizing Oil-Free Compressor Technology

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ABSTRACT

The goal to decarbonize buildings is quickly driving growth in the adoption of heat pumps to replace fossil fuel-based heating equipment. The trend is significantly driven by the integration of renewables in the electric grid, also replacing fossil fuel-based sources, to in-turn drive decarbonization. The impact of this change is greater if also changing out end-use fossil fuel-based heating equipment to electric-driven.

With the trend to heat pumps, there is a critical choice on both the scale and corresponding heat source. The heat pumps can be implemented with ambient air as the heat source or with other higher temperature/efficiency sources such as geothermal, process or district cooling heat recovery. Nevertheless, these sources are not always available in close proximity to the heat load. This raises the opportunity for larger-scale heating systems, serving multiple loads and with the corresponding opportunity to integrate one or more potential higher-temperature heat recovery heat sources. A related critical factor with the growth of heat pumps is resiliency. The term has historically mainly been associated with critical facilities and the ability to withstand critical events. Now it's evolving because of that same integration of renewables into the power grid and their inconsistent availability. Now resiliency has more to do with preparing for this periodic unavailability – Ensuring that demand is met when supply is not necessarily available.

This paper will present a concept for a community heating and cooling system utilizing oil-free turbo compressor technology, to address the electrification of heating while also taking advantage of multiple higher-temperature heat sources. The technology and heat sources ensure the most efficient system possible, resulting in minimum operating costs and maximum decarbonization, while the community configuration and multiple sources ensure resiliency, consistently meeting the demand requirements.

1. INTRODUCTION

Buildings consume 70 percent of electricity generated in the U.S. according to the Energy Information Agency (EIA). Moreover, approximately 61 percent of this electricity was generated by carbon-based fossil fuels in 2019, 38 percent from natural gas and 23 percent from coal (IEA, 2020). The result is that buildings are a major contributor to fossil fuel-based greenhouse gas emissions. This is changing with the growth of renewable power generation integrated into the electric grid. Over the last several years, renewables have grown from 13 percent of overall power generation in 2013 to 17 percent in 2019, as shown in Figure 1. The IEA in 2020 reported that 90 percent of all global new electric power generation came from renewables. The growth is accelerating with the higher volumes of solar and wind technologies and as the corresponding costs decrease. According to ACEEE, wind power is now lower cost than those same fossil fuel sources and solar is rapidly approaching parity with the most cost-effective forms, as indicated in Figure 2. The building electric consumption figures include only the electrical equipment utilized today, missing the equipment currently fueled by other sources. The source of heating in buildings is currently mainly onsite burning of fossil fuels, including by furnaces and boilers. The shift now is to electric-driven heat pumps to replace those onsite fossil fuel-based sources. As heat pumps replace those boilers and furnaces, the corresponding carbon emissions reduction increases. As the corresponding sources of that electrical power also switch from fossil fuel-fired sources to renewables, the resulting decarbonization again increases. Said another way, the decarbonization potential of switching the power grid to renewables increases if other emissions sources such as heating are also switched over to utilizing electric power. This switch from boilers to heat pumps (for example) also increases the electric grid load. These increases are generally seen during winter periods though, which corresponds with the former '*valleys*' (low periods) of electricity demand. This is a significant benefit from the utility perspective, leveling overall demand and increasing revenue without driving new peaks and the resulting need for additional generation capacity. Therefore, electric utilities are being tasked with this electrification of heating – It increases their topline revenue without a significant corresponding increase in their infrastructure costs. This is also why we see the growth in utility electrification programs and corresponding heat pump incentives.

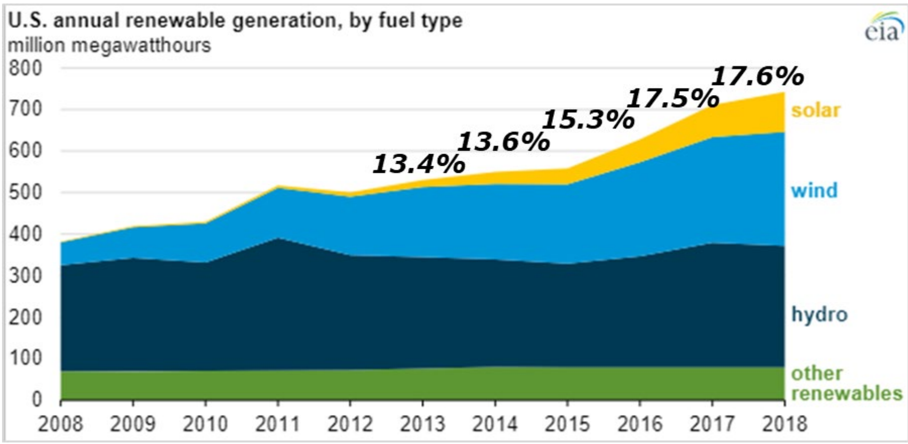

Figure 1: U.S. Annual Renewable Generation, by fuel type. Source U.S. EIA (2019)

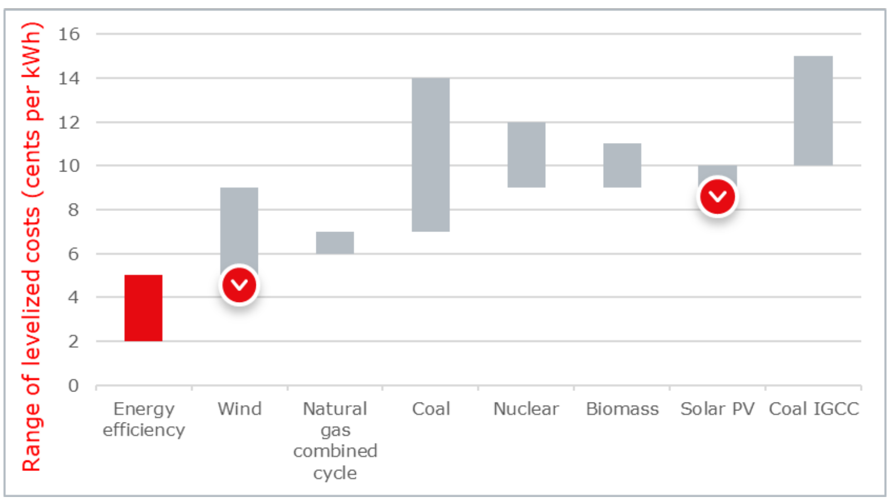

Figure 2: Levelized costs of electricity resource options. Source: ACEEE (2014)

2. ENERGY EFFICIENCY AND DEMAND/RESPONSE

The decarbonization of heating comes from the heat pump efficiency compared to fossil fuel-fired sources in addition to the renewable integration in the power grid. As an example, an electric-driven air-source heat pump replacing a fossil fuel-fired boiler operates at an approximate 3.5 COP, or 3.5 kW of heat for every kW of electricity input vs the maximum 1 COP of that boiler, as shown in Figure 3. Additionally, those same heat pumps tend to get significantly more efficient during part load/lift (differential temperature) operation, as opposed to the fossil fuel-fired sources, which may get slightly more efficient if they are the condensing-type. This all increases the decarbonization potential of electric heat pumps replacing fossil fuel-fired sources.

Starting with a baseline of 100 percent electricity coming from fossil fuel-fired sources, it is critical to account for the efficiency of that electric power generation. As mentioned earlier, the highest percentage today comes from

natural gas and the majority of these are combined cycle plants, with power generation efficiency of approximately 45 percent. It is critical to also account for the 5-10 percent transmission and distribution losses, getting that electric power to the end-use point.
Even with 100 percent of the electrical power generation coming from fossil fuel-fired sources and accounting for the generation efficiency and distribution losses, there is the corresponding potential, strictly based on the heat pump efficiency advantage, for an approximate 60 percent carbon emissions reduction. This is the heat pump decarbonization baseline. Then, as the electric grid changes over to renewables, that carbon emissions reduction benefit increases approximately 3 percent for every 10 percent increase in renewables incorporation.

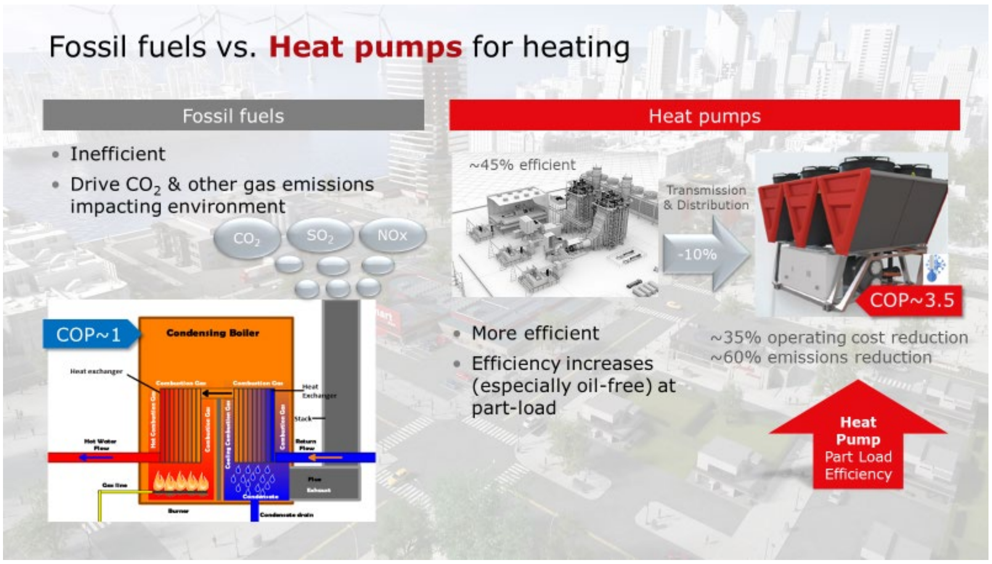

Figure 3: Electrification of heating and heat pump benefit drivers. Source: Company (2020)

As the power grid incorporates a higher percentage of renewable energy, the other growing factor is resiliency. This term has historically mainly been in the context of critical facilities (data centers, hospitals, etc.) with constant operation and the ability to continue to operate in the event of power losses and extreme events such as hurricanes. In its latest evolution, the resiliency term also now refers to accounting for the periodic renewable generation unavailability. As the percentage of power coming from renewables grows, so does the power availability (resiliency) risk from those periods when wind and solar resources are not available due to being intermittent in nature, creating a supply & demand disconnect.
There are several solutions available for this disconnect and resiliency risk, including both supply-side and demand-side storage, enabling '*ride-through*' in those unavailability periods. Energy storage takes various forms, including batteries, pumped hydro, hydrogen and thermal storage. The most cost-effective form of energy storage today is thermal storage. While the energy storage cost of batteries will continue to come down, thermal storages is still in the range of about 1–10 percent of the applied cost of battery storage, and we expect that difference will continue for a while. The different storage forms though are optimized solutions for different 'disconnect' periods and the solutions will end up being a mix depending on the supply/demand specific application dynamics. The general industry long-term storage direction for this disconnect duration seems to be:

1. Short duration (<~4 hours) – Thermal storage
2. Medium duration (~4-8 hours & transport) – Battery storage or similar (e.g., redox flow battery storage)
3. Long duration (>8 hours & transport) – Hydrogen or similar

Another related recent term and trend is "*Grid-interactive Efficient Buildings*" (GEB), which is about enabling buildings to provide flexibility in energy use and grid operation. GEB requires efficiency, load shift, shed and modulation to quickly react on the demand side to deficiencies on the supply side (US DOE, 2020). These building are also shifting to the concept of separate, sensible and latent load cooling – which can increase efficiency and reduce resulting energy use by taking advantage of the higher cooling temperature and more efficient resulting efficiency of sensible-only cooling and the flexibility to modulate separately to the varying sensible and latent loads. The overlap with the trend to electrification and heat pumps is critical, as those same demand side solutions are then expected to leverage these same efficiency and flexibility solutions, as summarized in Table 1.

Table 1: Grid-interactive Efficient Building (GEB) HVAC technologies and associated goal benefit potential. Source: DOE Building Technologies (2020).

	Technologies (Capability Legend: NA, Low, Med, High)	Efficiency	Load Shed	Load Shift	Modulate	Overall Potential
HVAC	HVAC#1: Smart Thermostats	Low	Med	High	Low	High
	HVAC#2: Separate Sensible and Latent Space Conditioning	High	Med	Med	NA	High
	HVAC#3: Liquid Desiccant Thermal Energy Storage	Med	Med	High	NA	High
	HVAC#4: Controls for HVAC Equipment w/ Embedded T-stats	NA	Low	High	Low	Med
	HVAC#5: Hybrid Evaporative Precooling	High	Low	Low	NA	Low
	HVAC#6: Dual-Fuel HVAC	NA	High	NA	NA	Low
Cross Cutting	CC#1. Thermal Energy Storage (TES)	Low	Low	High	Low	High
	CC#2. Modulating Capacity Vapor Compression	High	Med	Med	Med	Med
	CC#3. Non-vapor Compression (NVC) Systems and Materials	High	Med	High	Med	High

3. THE ROLE OF DISTRICT ENERGY SYSTEMS

Missing from most of the conversations thus far on electrification, heat pumps and grid-interactive efficient buildings has been the potential of district or community energy systems to address all these goals. District & community energy systems have built-in redundancy, storage, modulation flexibility and resiliency. A district energy system takes advantage of the built-in thermal flywheel effect, creates the option for recovering heat from different sources in the system, and turns down generation sources that are built into the system as needed based on demand. Critically in terms of resiliency and electrification infrastructure costs, it centralizes the electrical load increase to locations which can manage the increase, vs. strapping it to individual buildings and removes the associated heat pump capital investment from those buildings.

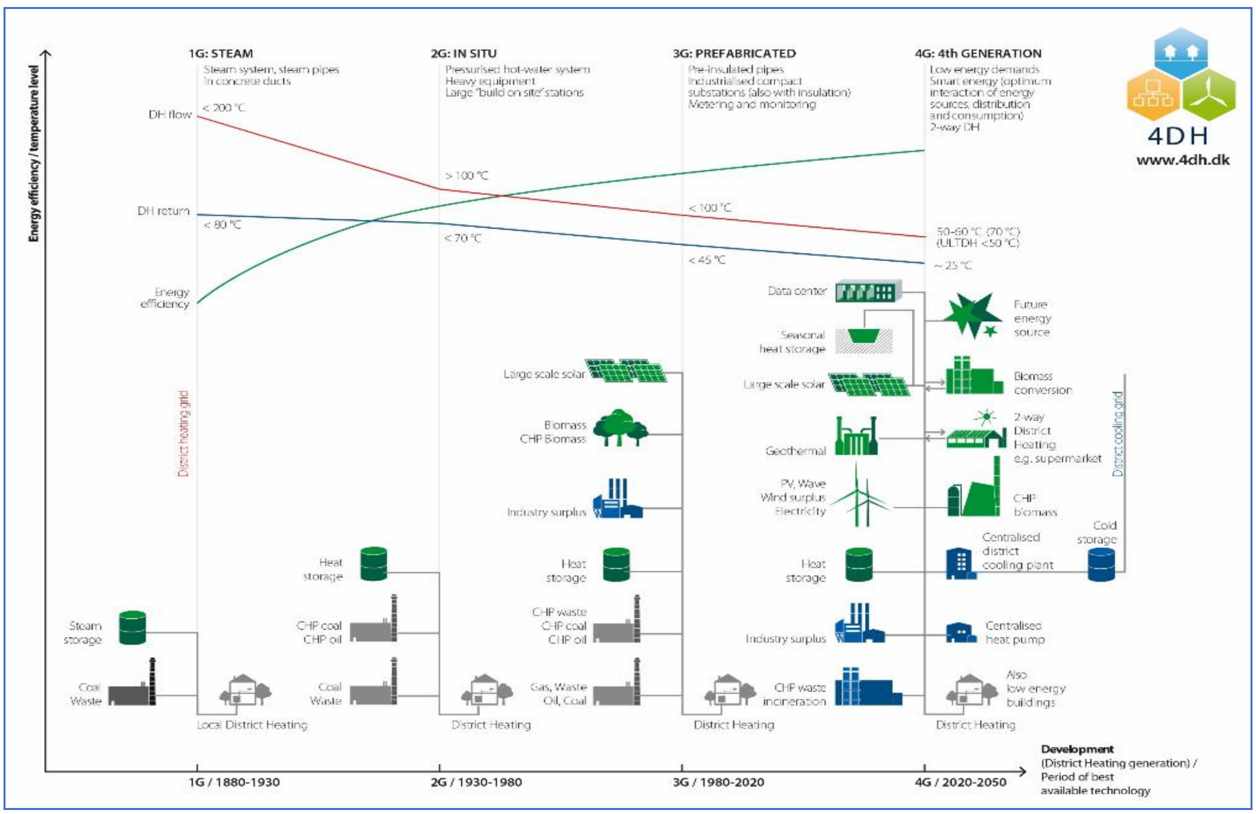

Figure 4: District heating technology evolution (source: 4DH research centre, www.4dh.eu)

In recent years, district energy—especially district heating—systems have seen a significant evolution, particularly in integrating in and planning out heat recovery and electrification of those systems. Critical in this is the evolution of district heating systems over the last several years and specifically Europe the 4th generation. District heating was 1st invented in the US in the Edison days, but then evolved in Europe and each new generation lowers the heating operating temperatures. Figure 4 shows this evolution to the latest 4th generation district heating system and corresponding 55-65 °C heat supply temperatures, down from >100 °C in earlier generations.

Fossil fuel-sourced heating operates at approximately the same efficiency at low or high heat supply temperatures. But for a heat pump, it is critical to reduce the heat supply temperature it to in-turn provide a lower operating cost and resulting payback vs the boiler or furnace it is replacing. Every vapor compression heat pump gets 1-1.5 percent more efficient for each 1 K reduction in the differential temperature that it must achieve, which is driven by both the heat source and supply temperature. Europe's district heating evolution also provides a great benchmark for the usage of different heat recovery heat sources utilized in heat pumps. To this end, Figure 5 reports the heat source temperatures and heat pump volumes associated with different application sources of heat pumps applied to European district heating through 2017. It shows that wastewater is by far the most common source, but higher temperature sources including industrial, geothermal and flue gas are also common.

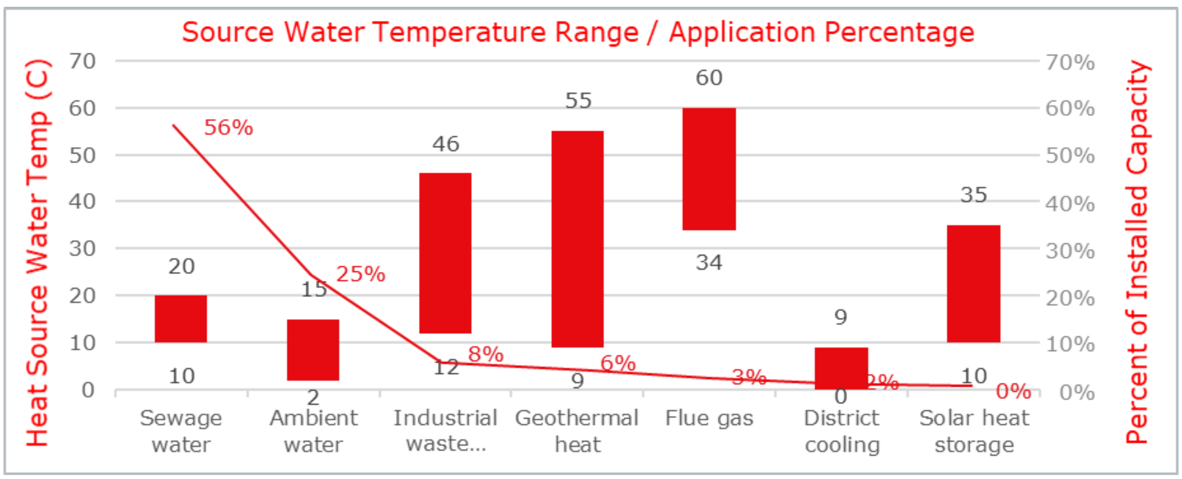

Figure 5: European district heating heat pump application and heat source temperature. Source: Heat Roadmap Europe (2017)

Adding heat pumps, and specifically water-to-water heat pumps utilizing heat recovery, is a fantastic solution for both electrification and the ultimate goal of decarbonization. Examining the different district energy solutions available today, we see that smaller-capacity heat recovery sources are becoming much more prevalent as opposed to more of the centralized utility-driven generation. The corresponding energy source is moving from large centralized generation using lower temperature heat sources such as ambient air and surface water to decentralized higher temperature heat recovery sources, frequently based on '*symbiosis*' applications, where the recovered heat is from the cooling of a facility or process. As mentioned, the main driver for this focus on the distributed higher-temperature heat sources is the resulting compressor work reduction and heat pump efficiency, but also to avoid driving new winter period electrical load peaks. Optimally, these water-water heat pumps are applied on critical facilities, with year-around cooling loads, resulting heat recovery and onsite backup power generation for additional resiliency. For instance, a data center is a perfect application opportunity example, because it provides multiple corresponding heat source benefits, including:

1. Year-around and consistent heat load and resulting heat recovery.
2. Higher temperature cooling and resulting heat recovery temperatures / higher heat pump efficiency.
3. Critical facility onsite backup power generation, for demand response scenarios and combined facility cooling / community heat.

Looked at from the community heating system perspective, this is one of the most efficient, highest operating hours, lowest operating cost and lowest emissions potential baseload heat sources. This factor of course increases with the corresponding increase in the percent of power for that data center coming from renewables. A conceptualized district energy solution is illustrated in Figure 6.

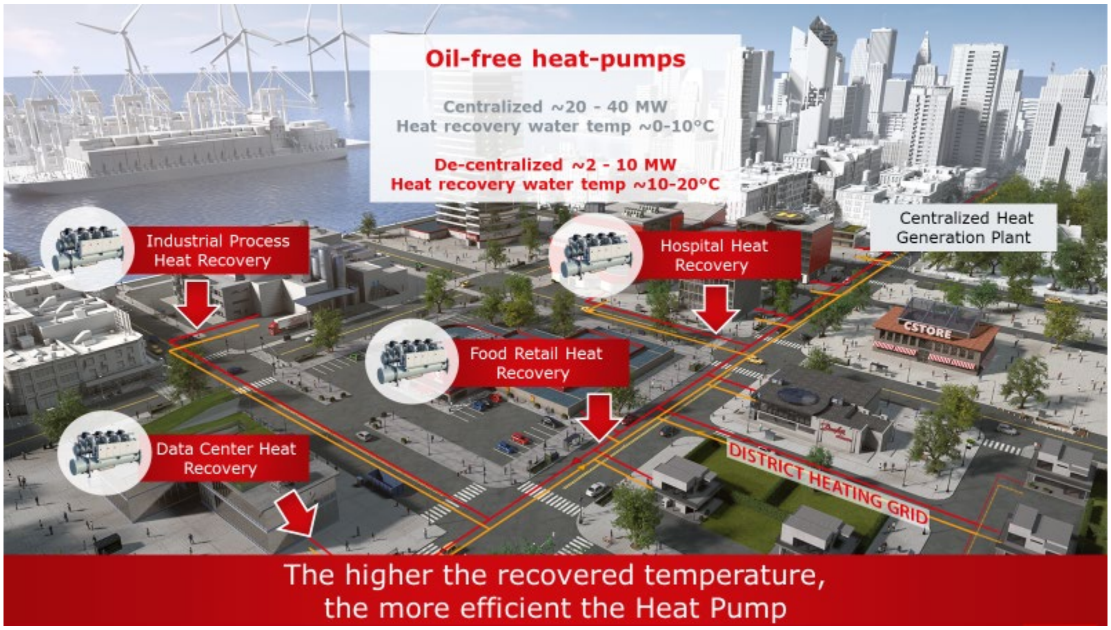

Figure 6: District energy integration of heat recovery heat pumps, applied to symbiosis cooling and heat recovery systems. Source: Company (2020)

4. COMPRESSION TECHNOLOGIES FOR COMMUNITY-BASED HEATING SYSTEMS

There are two main compression technologies for HVAC systems: dynamic and positive displacement. Dynamic compression adds kinetic energy to the refrigerant, while positive displacement harnesses potential energy by "squeezing" it and reducing the area. Oil-free turbo compressors fit into the first (dynamic) category. There are also a variety of bearing types. Historically, oil-based bearings were used in both dynamic and positive displacement compression technologies. Today, there are several oil-free options, including magnetic, ceramic and gas bearings. Among newer compression technologies, magnetic bearings provide flexibility in terms of capacity, reliability, and efficiency.
Because oil-free compressors minimize physical size through high-/variable-speed operation, they are ideal for retrofit applications where a smaller footprint is beneficial for physical heat pump size and/or multiple compressor combinations on a single unit.

Additionally, since these same compressors have no mechanical contact in either the compression or bearing support system, oil-free machines are quieter, lower maintenance and maintain performance over their lifetime. The two primary sources of noise coming out of heat pumps are the mechanical contact in both the compression process and the bearing support system. Since a magnetic bearing-based oil-free turbo compressor has neither of these, the primary noise is then the significantly lower level of the refrigerant flowing through the system and the 'hum' of the variable speed. The result is a compressor with noise level on average 8 dB lower than an equivalent capacity screw compressor. This is a critical factor for installations next to critical spaces, outdoor or retrofit in tight mechanical room spaces, where the added cost of expensive attenuation can be avoided.

Those same mechanical contact factors are beneficial to maintaining long-term performance. As HVAC installations have become instrumented to track their performance, there is a growing recognition in the industry that the performance of these systems degrades over time. Wearing down of mechanical bearing and compression contact, along with oil included in the system getting into the heat exchangers and degrading that performance, are the primary sources of this heat pump performance degradation over time. Since an oil-free turbo compressor has neither one of those factors, then the performance should be maintained. The oiled vs. oil-free difference is obvious, but the compression difference can be verified. This has been accomplished per the below summary showing the results of re-testing six compressors after ten years of operation. The comparison shows that the performance of the compressors all had zero-to-negligible degradation, with one 'outlier' at three percent.

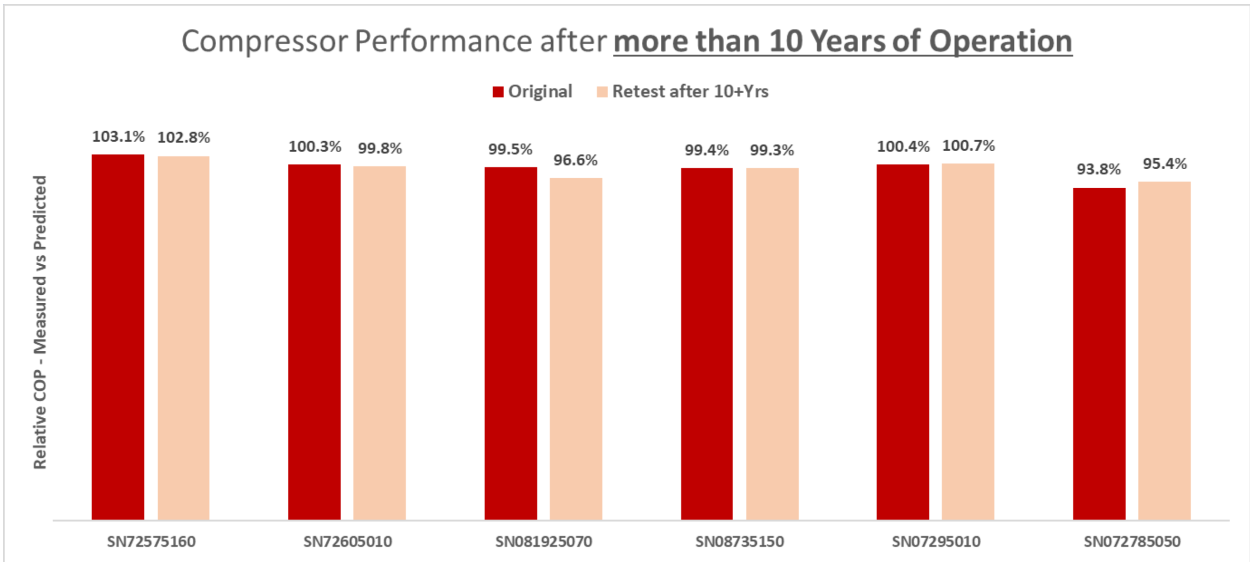

Figure 7: Performance of dynamic, oil-free, variable speed compressors re-tested after ten years operation. Source: Company (2021)

For heat pumps, this factor is critical to ensure that the payback vs the fossil fuel-source heating alternatives is accurate, since the majority of these life-cycle cost evaluations today do not incorporate a performance degradation factor, leading to potentially wrong conclusions, unless utilizing oil-free turbo compressor-based heat pumps.

5. NEXT PHASE OF REFRIGERANTS AND TURBOCOMPRESSORS

These evolving dynamic, variable speed, oil-free vapor compression technologies utilizing new HFO refrigerants can potentially further reduce refrigerant CO_2 emissions, as reduced pressure and density can lead to lower global warming potential (GWP) with minimized flammability. The coming years will likely bring lower-pressure and lower-density refrigerants, and supporting technologies optimized for their use. Figure 7 illustrates this dynamic, that to accomplish the goal of achieving lower GWP while also minimizing flammability requires moving to lower density. As the refrigerant selection moves to lower density that also leads to technologies optimized to moving a high volume of these lower pressure, large molecule fluids where turbo compressor technologies play a major role in ensuring needed capacities.

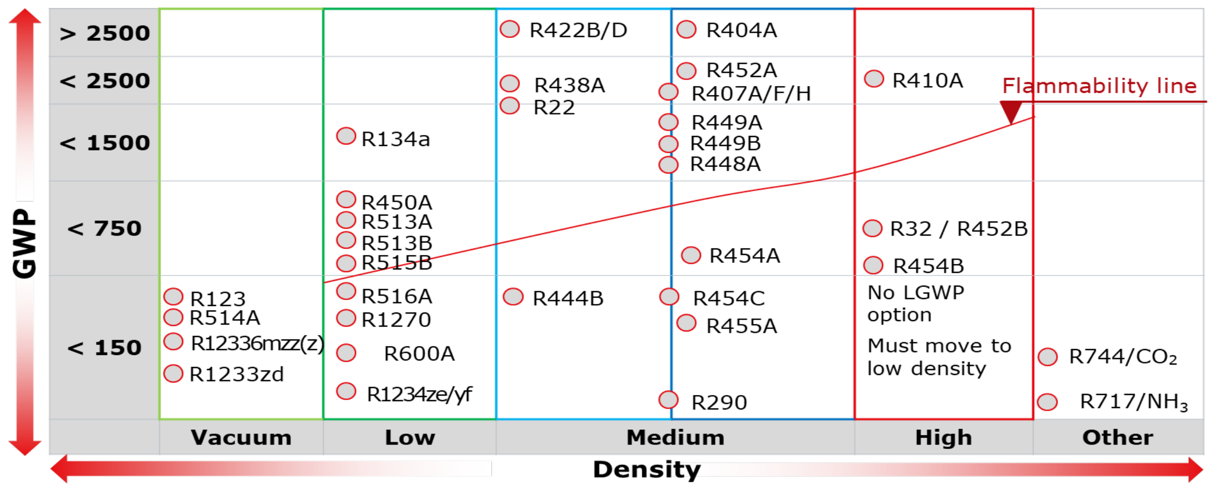

Figure 8: Tradeoffs between GWP and volumetric capacity as well as flammability of low-GWP refrigerants and their blends. Source: Company (2020)

It is critical to optimize these dynamic centrifugal compressors to their target application operating temperatures. There are three basic oil-free turbo compressor technology optimizations on the market today, as summarized in Figure 8:

- Standard lift optimization for lower lift or lower differential operating temperatures, which support water-cooled, evaporative-cooled and hybrid chillers.
- Medium lift optimization for air-cooled chillers, water-cooled chillers in more challenging environments and water-to-water heat pumps with lower required heating temperatures and/or higher cooling/heat-source temperatures.
- High lift optimization – the most recent innovation for oil-free turbo compressors – is on the mechanical design of the compressor, along with the aerodynamic compression process. It supports the most challenging applications, including very high ambient air-cooled chillers, water-to-water heat pumps with higher heating and/or lower cooling/heat source temperatures, air-to-water heat pumps in milder climates, medium-temp process cooling and thermal storage applications.

The optimal solution for a specific application frequently includes more than one of these optimizations. Specifically, for larger-capacity heat recovery applications in community / district heating / micro-thermal grid applications, the optimal performance solution is frequently a combination of the Medium and High-lift optimized compressor designs. This depends especially on the heat recovery source temperature and the district heating return water temperature. The latter return temperature factor is driven by demand-side flow and heat transfer technologies utilized. On the demand side it is critical for the district heating system to use variable speed flow, two-way pressure independent control valves and efficient heat transfer stations. This in-turn enables lower return water temperatures and implementation of this more efficient hybrid compressor optimization heat pump solution.

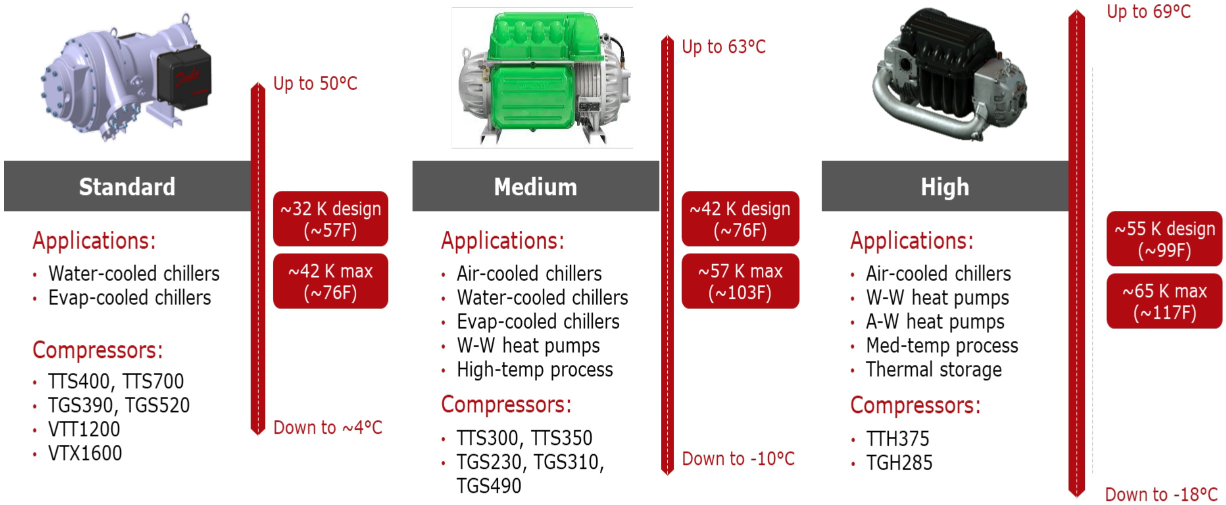

Figure 9: Oil-free turbo compressor optimizations for different operating temperatures. Source: Company (2020)

All vapor compressors have two sets of forces in the compression process: the radial (side-to-side) motion of the shaft driving the compression process and the axial (back-and-forth) motion. While previous oil-free turbo compressor designs had both stages of compression on one end of the compressor, new high-lift optimization technology moves the second stage of compression to the opposite end, which balances those axial forces. The two compression stages pulling back against each other enables a higher differential temperature capability, while maintaining no mechanical contact and the associated benefits. The most recent version of this vapor compression technology can now provide those same technology benefits formerly relegated mainly to comfort cooling chillers applied in milder climates, now to the hottest environments, provide cooling at lower temperatures – including thermal storage – or provide heating with heat pumps. What were once unattainable applications for magnetic-bearing-based compressors is no longer the case, thanks to this evolving technology that enables operation in more challenging applications.

Oil-free design allows engineers to combine a variety of technology to optimize based on real-world conditions. For example, where cooling is required for industrial manufacturing, this technology can provide cooling and then recover the heat through a symbiosis heat pump, which boosts the temperature to supply the district heating system. When the industrial process is not operating, a parallel geothermal ground-source loop can also supply heat to the district heating system via that same heat pump. This dual cycle system can enable full-time supply as the baseload of a district heating system, maximizing operating hours and helping buildings recoup the first cost investment in less than three years. An example of such system is shown in Figure 9.

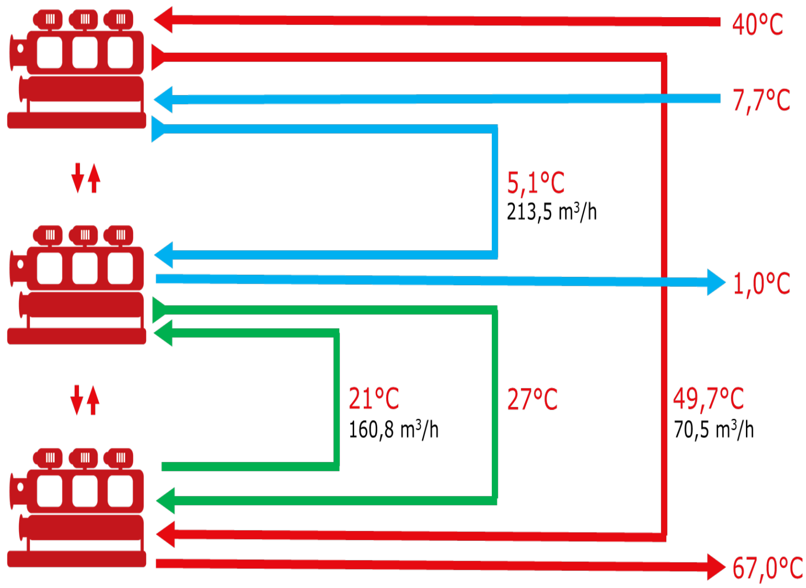

Figure 10: Example heat pump system architecture and operating temperatures for process cooling and heat recovery to community/district heating system. Source: Company (2020)

6. CONCLUSIONS

An evolving portfolio of magnetic bearing, variable speed dynamic vapor compression technology can support an expanding array of applications with a variety of compressor combinations to maximize operational efficiency, minimize operating costs. All of this while lowering CO_2 emissions via both the electrification of heating and utilizing the most efficient heat pump technology solution, which maintains that performance over time and optimal versions of that technology per the operating requirements.

NOMENCLATURE

Acronyms

GWP	Global Warming Potential
HFO	Hydrofluoroolefin

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ACKNOWLEDGEMENT

Acknowledging Eddie Rodriguez for the chart in Figure 7 and Leping Zhang for contribution of the system architecture shown in Figure 10