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The Fastest Possible Way to Decarbonize Our Building Heat Loads

Discussions amongst energy efficiency advocates for the buildings in which we live and work often turn to the question of whether it would be wise to decarbonize water and space heating by going "all-electric". The urgency is fueled by the fact that, particularly in residential buildings, heating represents on average about 2/3 of all energy consumed in the home. That number is greater if you live in cool/cold climates (~60% of the US population, all of Canada, and most of Europe). One strategy for decarbonization of heating loads is to switch (in all climates) away from gas, propane, or oil-fired appliances, to electric heat pumps, which, combined with adding a lot more wind and solar to the electric grid, would result in zero-carbon heating. That sounds great at first glance, but deeper analysis, particularly for cool/cold climates, reveals that it would actually yield more, not less carbon in the short and medium term and be economically impractical. Fortunately, there is a better solution for reducing building heat carbon emissions quickly, using an alternative technology, that also sets the stage for economically viable long-term decarbonization.

The alternative, Thermally Driven Heat Pumps (TDHPs), can deliver the lowest carbon footprint AND the lowest operating cost to US homeowners in cool and cold climates where heating matters the most. Electric Heat Pumps (EHPs) can and still should play a role in building heat for milder climates which are cooling, not heating, dominated. Both heat-pump technologies are highly energy efficient and represent the next wave of HVAC technology to advance the cause of decarbonization. But outcomes differ by climate zone, and thus, have complementary strengths and weakness.

EHPs use the Vapor Compression Cycle, familiar for those who have studied how air-conditioners or refrigerators work. In the four-step process, the heavy lifting is done at the compression stage, usually mechanically driven via an electric motor. On the other hand, TDHPs of the type being designed by SMTI, use the Absorption Cycle. It has a similar four-step process, but the key difference is in the compression stage, which is driven with heat, not electro-mechanically. The input fuel can be anything that provides heat, such as traditional natural gas, propane, or heating oil. It can also include renewable fuel sources (discussed in-depth later). As heat pumps, either EHPs or TDHPs can technically be used for either heating and/or cooling. But their performance and economic characteristics are different, particularly in different climates. The most common configuration for purposes of this discussion is "air-sourced", meaning that in heating mode both heat pumps are connected to and draw heat from surrounding air. However, TDHPs using the Absorption Cycle retain their energy efficiency to provide building heat to a much greater degree as the outside air temperature gets colder.

Which technology allows faster decarbonization of heating?

This is a discussion of a comparative study examining the question of which technology will best facilitate the fastest pathway in the US to permanently reduce carbon emissions for building heat. The issues involved are complex and, as always, the technical considerations must be balanced with the economic impacts at both the micro (i.e. household) and macro levels.

Study Methodology

The study used widely respected and publicly available energy modeling tools to compare widespread adoption of both TDHPs and EHPs for single family home heating. The process examined both Green House Gas (GHG) emissions and annual operating costs (utility bills) to the homeowner. Not surprisingly, the location of the home impacts these considerations due to differing local energy prices, the local electrical grid carbon content, and the various climates that dictate the amount of energy required to keep a home comfortable throughout the year. The local cost of energy is tracked by the Energy Information Administration (US-DOE). The carbon content of the local electric grid is reported by eGrid, a program of the US Environmental Protection Agency (EPA), where the latest data (2016) available was used.

For energy performance modeling, the National Renewable Energy Laboratory (NREL) publishes and maintains Energy Plus, which predicts the amount of energy required for various building configurations. It uses hourly weather data to enable this analysis for most locations in the world, and extensively throughout the US. The program contains performance profiles for EHPs, but not TDHPs, which are still pre-commercial. However, based on extensive testing of numerous of SMTI's TDHP prototypes in both lab and field installations, the Gas Technology Institute (GTI) has developed performance profiles based on actual test data. GTI has developed an adaptation of NREL's Energy Plus which contains an integration of all its existing performance profiles, plus those found for TDHPs. The system, Energy Performance Analysis Tool (EPAT - http://epat.gastechnology.org/) integrates an area's weather patterns and the local specification for electricity carbon content ("carbon equivalent" as determined by eGrid 2016).

The analysis focused on emissions and economic performance across various locations throughout the continental United States. For comparative consistency, the home's parameters were kept the same across all locations (2,700-square foot single family detached home with four occupants, average building envelope), eliminating any effects from other factors, allowing for direct comparison of five heating technologies.

Technology Considered	**Energy Efficiency Rating**	**Notes**
Traditional Furnace	AFUE[1] = 80%	The minimum fuel efficiency permitted in the US (it is 92% in Canada)
Traditional Furnace	AFUE = 96%	A commonly installed high-efficiency option available in the market
Standard Electric Heat Pump	HSPF[2] = 9.0	An Energy-star qualified rating in standard EHPs
Cold Climate Electric Heat Pump	HSPF = 13.0	Highest efficiency available in a unitary EHP product[3]
Thermally-Driven Heat Pump	AFUE = 140%	On-market soon; prototype performance verified by 3rd parties

Since the TDHP is designed as a cool/cold climate heating product, the 14 locations studied were a cross section of areas that mostly had more than 4,000 Heating Degree Days per year (approximately the northern half the US). Sizing of each heating unit was optimized for building design and the location's weather (as would be done in an ACCA Manual J calculation, the standard for HVAC installation contractors).

To generate valid comparisons in a mass fuel-switching deployment scenario for electric heat pump technology, the study assumes the electric grid's "non-baseline" (aka marginal) carbon emissions for each region. The power generated in each region has a total carbon content influenced by a varied mixture of relatively carbon-intensive sources (e.g. coal, gas) and low/zero-carbon sources (e.g. nuclear, hydro, wind, solar). Any near-term electrical load growth required to serve new winter heating loads with EHPs would most likely be fueled by a region's marginal and more carbon-intensive sources. This would remain true until new zero-carbon electricity sources are added that can cover the marginal demand of EHPs during the winter night hours when building heat is most prevalent. Thus, the non-baseline rate is more appropriate to use as a marginal carbon cost for these calculations. While certainly expected to grow, the pace of future solar and wind expansion is a subject more fully addressed later in this article.

[1] AFUE: Annual Fuel Utilization Efficiency is the standard by which the Dept of Energy rates the energy efficiency of gas-fired heating appliances. On a seasonal basis, it represents the average ratio of heat energy output (to the home) vs. the required heat input (from natural gas).
[2] HSPF: Heating Seasonal Performance Factor similar to AFUE, but is the standard applied to vapor-compression based appliances when they provide heat. It is a ratio of heat energy supplied (in BTU) to energy required (watt-hours) as a seasonal average.
[3] Ductless mini-splits, which can be as high as HSPF 15, were not considered as they are impractical and costly for whole-house heating.

Short-term Results

Carbon Dioxide (and equivalents) Emissions

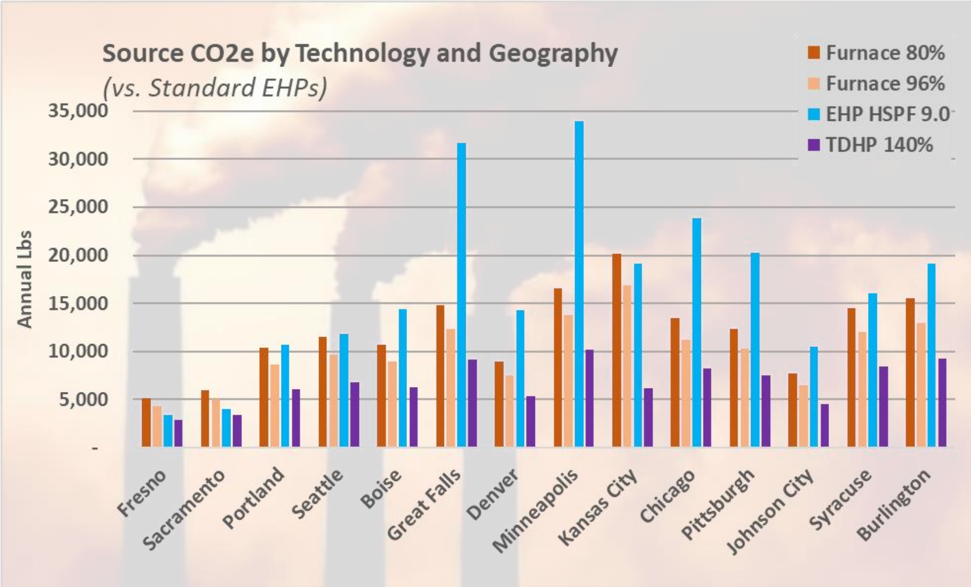


Figure 1: Source CO2e by Technology and Geography

The analysis shows that a TDHP has the lowest net carbon footprint of any building heating technology, even in California. Besides TDHPs having the lowest carbon footprint, it should also be noted that at current grid-carbon levels, most places would see increased carbon emissions from building heat if an all-electric solution were rapidly adopted at scale.

Figure 1 compares annual carbon emissions using EnergyStar^{TM} EHPs with a seasonal energy efficiency factor (HSPF) of 9.0. While HSPF 9.0 is a relatively strong level of energy efficiency, this type of EHP product probably would not normally be installed in the coldest climates without backup, according to manufacturer recommendations and typical contractor practices. Therefore, the newest variation with the highest available unitary product efficiency, the "cold climate" EHP or CCEHP (HPSF = 13.0), was also compared for subset of 7 of the coldest cities in the study (Figure 2). While the relative performance improved somewhat, the overall result of TDHP superiority for CO_2 emissions remained unchanged for these cities.

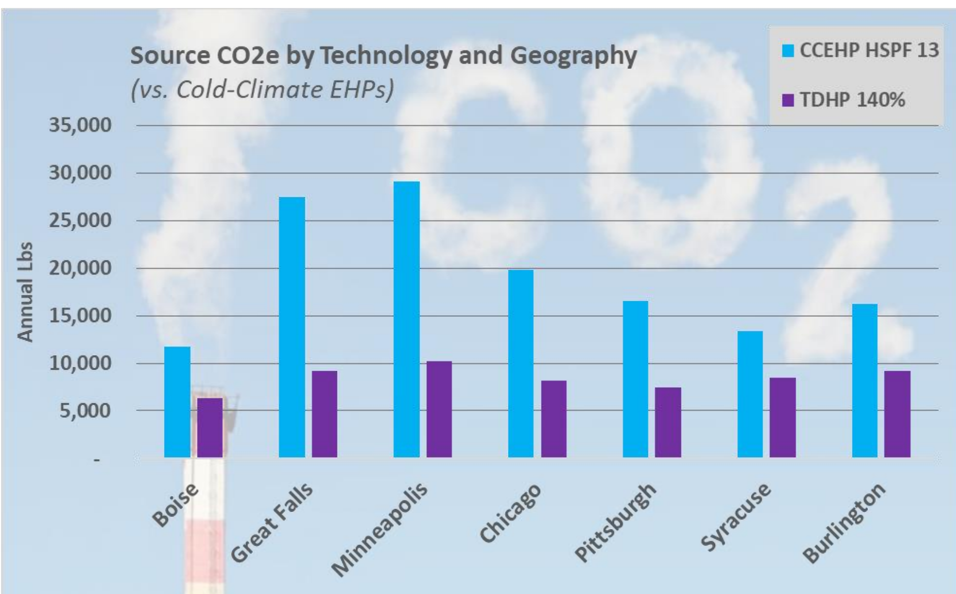


Figure 2: Source CO2e by Technology (CCEHPs) and Geography

These charts demonstrate that the local grid's non-baseline CO_2 content is among the most important factors when comparing carbon emissions from different heating technologies. As can be seen, many states in the middle of the country do not have as clean a grid as places such as California.

NOx Pollution

Regions concerned about air quality must pay attention the production of NOx, which is released by burning of fuels for power generation and heating. These substances lead to creation of fine particulates and ground-level ozone which cause adverse health and environmental effects (e.g. asthma, smog, acid rain). This has historically been a major issue in California (which now has strict regulatory standards), but many other cities also have growing concerns. Like the CO_2 story, TDHPs also offer the lowest or among the lowest level of NOx emissions across all building heat technologies (Figure 3).

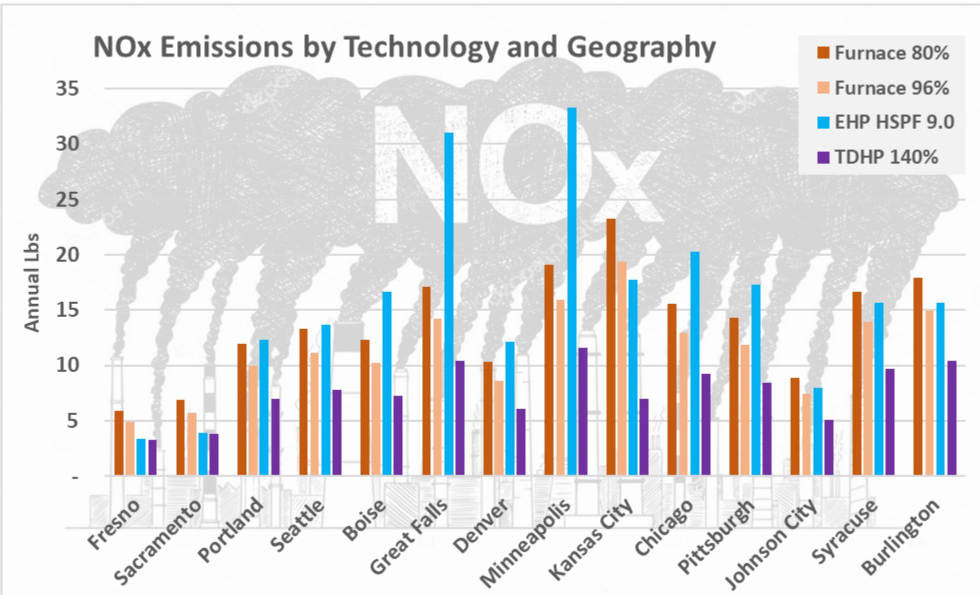


Figure 3: NOx emissions by Technology & Geography

Annual Operating Costs

As previously noted, the economic question will make a difference in homeowners' willingness to adopt new technology. The installation cost of TDHPs and EHPs is roughly similar at equivalent capacities; thus, operating costs are the key driver of the total economic impact to consumers. The study methodology enabled cross-regional comparison of annual operating costs for the basic technology configurations (Figure 4).

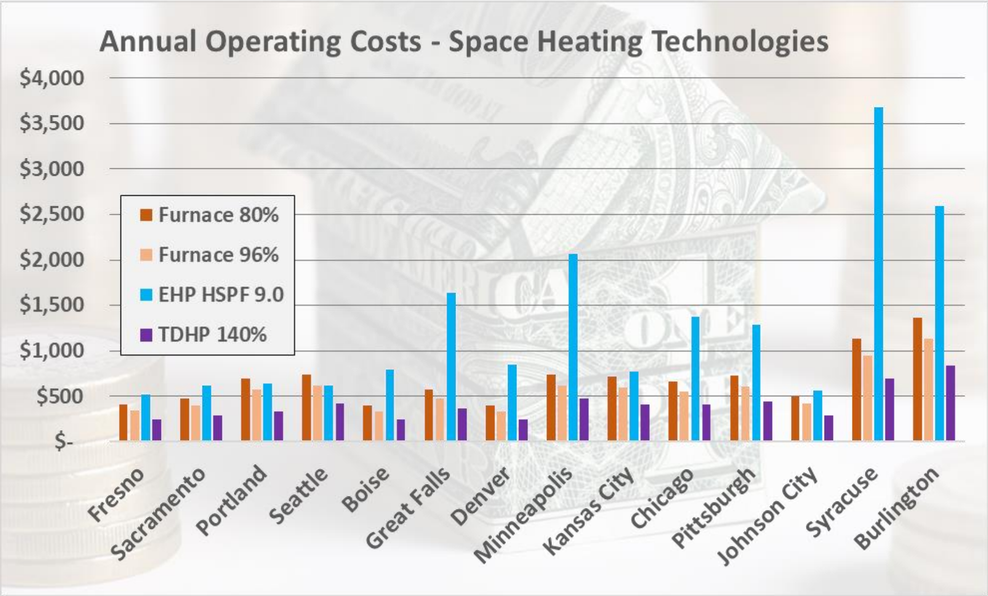


Figure 4: Space-heating Annual Operating Costs by Technology and Geography

Again, to ensure the newest electric heat pump technology (the CCEHP) is considered in cities where it would most likely to be manufacturer recommended, a comparison was run including this technology (Figure 5).

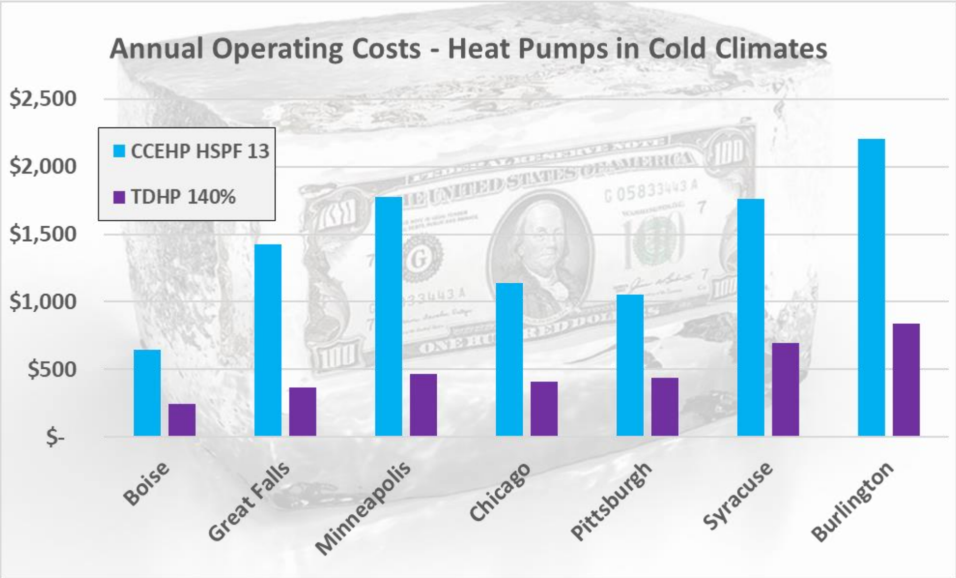


Figure 5: Annual Operating Costs for TDHPs vs CCEHPs

For economic performance, the local cost of energy plays the largest role. Because natural gas is typically one-third to one-fourth the cost of electricity per unit of energy, even gas furnaces have lower operating costs than the EHP option in all but two locations. The relationship between prices of these two energy sources is not expected to change significantly in the next decade, according to the US Energy Information Administration.

In all locations, TDHPs were demonstrated to have the lowest operating cost of any other option. EHPs, in most cases, contrary to what one might expect, would actually increase the operating cost compared to what a homeowner would pay who is currently heating with gas. Further, the total installation costs of TDHPs and EHPs are somewhat comparable without fuel-switching. In some cases, particularly where there is no existing air-conditioner in the home, a fuel-switching scenario from gas to electric heating could also require upgrades to the home's electrical system, adding significantly to the EHP cost. Thus, without large subsidies, the conversion of a gas furnace to an EHP system often would not make financial sense from the homeowner's perspective and would require economically inefficient subsidies to motivate any type of change. The availability of a TDHP to a gas-heated homeowner creates a much more economically attractive option.

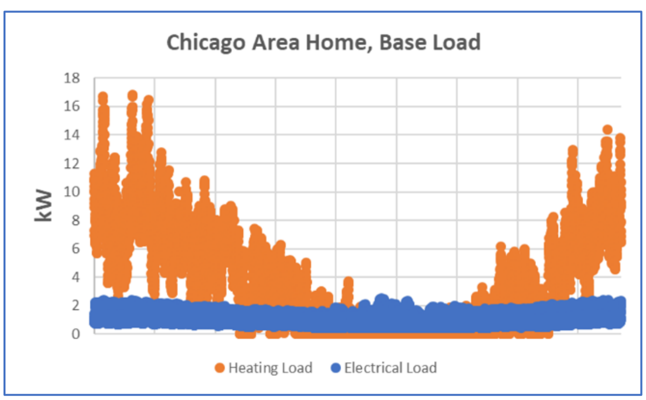
Comparing Emissions and Assuming Future Renewable Electricity Increases

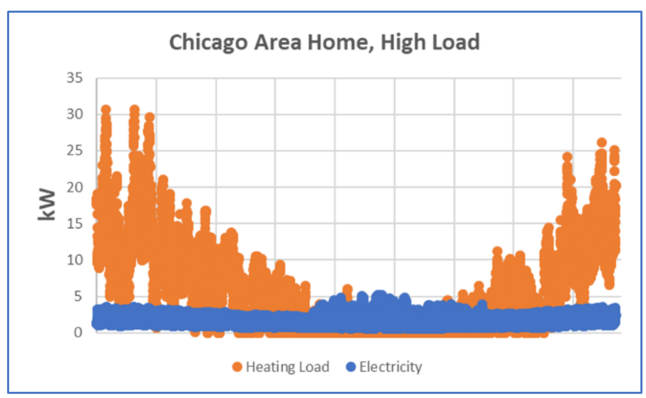
The current study demonstrates that TDHPs presently have the lowest-carbon and lowest-cost impact for any residential building heat technology that is on, or close to being on the market. At this point, some may ask, "What happens over time as electricity gets greener?" One perspective is that ever-increasing amounts of wind and solar electricity will make the grid greener, negating the carbon advantages of TDHPs and back to a position favoring EHPs. This perspective carries an obvious and simple intuitive appeal, but it also depends on several assumptions which, upon further consideration, undermine the expectation that EHPs would eventually dominate the market.

Converting the grid will be expensive

The prospect of converting electrical transport and distribution systems poses a daunting challenge to the all-electrification solution, particularly when it comes to providing for heating loads. The utility grid (wires, poles, transformers, etc.) must be built for peak, not average, loads. Thus, carrying winter heating loads (which dwarf summer loads in cool/cold climates) via electricity, regardless of the generation source, would require a massive expansion of the infrastructure that delivers this power to us. The farther north you go, the more massive this requirement. Additionally, this is all without considering the grid build-out requirements to electrify transportation, which will add further cost.

Figures 6 & 7 illustrate this problem by way of modeling the hourly heating load and electrical energy requirement (lighting, cooling, electronics, etc.), using DOE's EnergyPlus, for a pair of theoretical homes in Chicago – an area known for both hot summers and cold winters. Comparing these loads on the same basis (average hourly kilowatts) across an entire year, these charts illustrate the highly desperate heating load vs current electric power requirement for typical homes. Whether the required grid expansion is 3X or 5X or (likely) more, the cost would be prohibitive, regardless of where such a move is contemplated.





Figures 6 &7: Comparing Electrical EHP Required in Summer & Winter (Chicago)

New Generation Assets Will Be Priced Much Higher

The previous point addresses only the wires needed to carry electrical energy and does not address the need to build new renewable generation assets themselves. Solar and wind power prices have dropped significantly over the past decade, bringing them into solid economic competition with coal and nuclear, and even some gas-fired plants. Generally, lower renewable prices are a positive development, but one cannot apply these prices to the winter building heat question and make the same assumptions. Today, wind and solar plants are priced with the assumption that their energy is needed year-round. Since winter heating loads are much more massive, serving that type of load means building new renewable electricity generation assets (wind and solar) that would be used only about half of the year. Half the usual use of a resource could mean twice the price per kilowatt-hour, and that does not include lower solar efficiencies during winter months.

Increasing Wind and Solar Requires Energy Storage at a Massive Grid-Scale

As solar and wind power assume greater shares of the total generation mix, their intermittent generation nature creates larger issues with a mismatch between their generation profiles and society's energy demand profile. This is true for both a daily (e.g. the "solar duck-curve") and for a seasonal basis (much more energy is generated in summer vs. winter). The most commonly used solution today is to add more natural gas plants (as "peakers"), but this is ultimately not consistent with a decarbonized economy. Another possibility is putting utility-scale energy storage technologies to work. For winter heating loads, we could theoretically generate all that energy during the summer, but this would require a massive "seasonal-energy-shift" using technologies that are well beyond the capabilities of today's better-known and rapidly evolving chemical battery class (e.g. Tesla, lithium ion, etc.). Those are good solutions for managing the problem of hour-ahead or day-ahead storage needs. However, the massive scale of storing heating energy for buildings loads is a very different problem requiring energy quantities and time-lengths that are orders of magnitude beyond anything in the current chemical battery class.

A useful graphic to visualize this issue was developed by the Fraunhofer Institute in Germany (Figure 8), which currently faces one of the world's largest energy storage problems due to massive solar capacities on their grid. During some hours of the day, the spot-prices of solar and wind electricity currently turn negative, meaning the utility takes money from the renewable energy generator to use their power. This also currently happens in some places in the US. Without grid-scale storage, such a backwards economic situation would only get worse as nations and states evolve towards 100% solar and wind generation for electricity. Figure 8 shows hydrogen and renewable natural gas (labeled H2 and SNG on the chart) as the technologies most feasible for this level of energy storage. "Excess" power on the grid is converted to hydrogen via technologies such as electrolysis, making hydrogen an energy storage medium. There is some discussion about whether it is best to store it as hydrogen or take it another step to methane. The later course is both fully renewable and a net-zero-carbon natural gas solution. This makes it clear that gas pipelines will remain relevant and evolve to carry some mixture of renewable energy as more solar and wind come online. TDHPs can operate on either or a mix of both hydrogen and methane to provide space and water heat for buildings. This maximizes the value of any renewable because TDHPs use it more efficiently than any current technology.

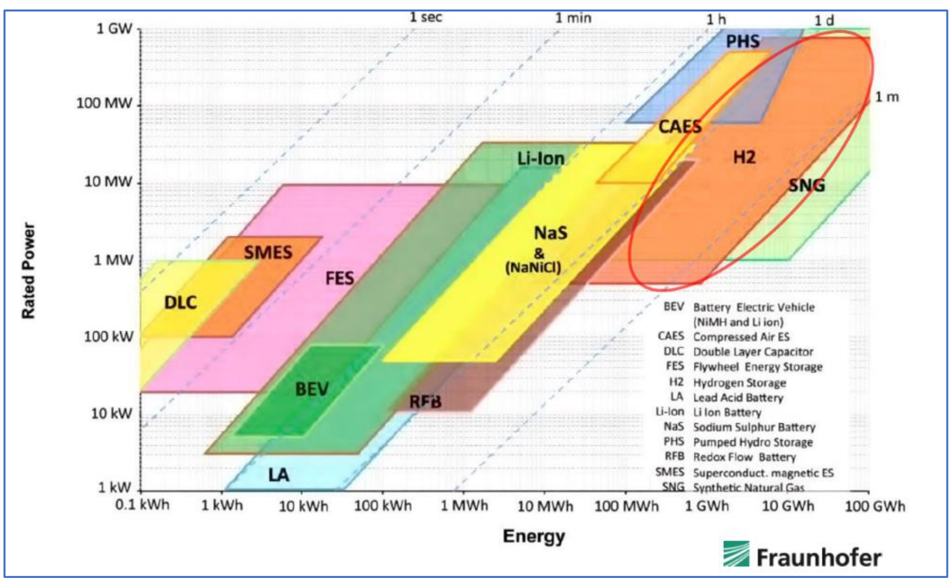


Figure 6: Survey of Energy Storage Technologies

What About Renewable Gas?

There are uses for renewable hydrogen and methane other than simply as a storage medium for excess solar and wind power. Due to the attention that renewable electricity receives, there has been lower awareness of progress developing renewable gases (RNG) and fuels from bio and waste stream sources (landfills, agriculture, algae, etc.). These technologies are getting more cost-effective and further enhance the relevance of existing gas pipelines, gradually changing their mission from delivering a non-renewable, net-carbon additive product to one delivering fully renewable and net zero-carbon energy. With RNG in the pipe, the same energy-density advantages cited above would still apply, making it completely unnecessary to perform a massive build-out of the electrical grid for winter heating energy delivery.

The scope of this study does not permit a full review of RNG technology potential. However, gas utilities are rapidly developing this capacity on several fronts, and several already offer consumers the option of switching to RNG for their homes at a modest price premium. Southern California Gas recently announced that it will provide 20% RG in its pipelines by 2030. Fortis BC (British Columbia) and CenterPoint Energy (Minnesota) already offer (or are proposing to offer) RNG tariffs to their customers, similar to renewable electricity tariffs. A study for SoCal Gas by Navigant showed that they could achieve the same building decarbonization goals as all electrification at lower cost using less than 20% RNG in their system.[4]

How Fast Will People Change Their Heating Equipment?

Being one of the more expensive costs to owning a home, it should be noted that people typically replace HVAC equipment only once every 20 years or so. Without massive and economically burdensome subsidies, it is unlikely consumers will do it at a faster pace. This lends perspective to timeline considerations when evaluating gas and electric solutions. A mass-scale all-electrification of building heat loads solution may assume all the electrification challenges cited above will eventually be solved. However, the results of the present study demonstrate that carbon emissions would actually increase with that solution, particularly in the short-run, and likely in the longer term. Additionally, the all-electrification solution also does not consider either the existence of TDHPs, nor progress in the renewable gas front creating a much less expensive and faster way to achieve building heat decarbonization. Wholesale change-over of the existing stock of HVAC equipment in buildings to new technologies is at least a 20-year project, likely longer.

Conclusion

With TDHPs poised to enter the market soon, current conditions make it clear that at mass scale they would immediately make a major impact reducing residential building heat load carbon emissions – and provide significantly lower operating costs in the areas where this matters most. There are appropriate uses in different locations for both TDHPs and EHPs – and heat pumps in general are clearly the wave of the future. At this stage, attempting to regulate by picking specific technologies, or even the best energy carrier (electricity vs. gas), is unlikely to lead to the desired outcome of significant and rapid decarbonization. Where incentives are used, they should be calibrated to the level of decarbonization achieved without necessarily requiring homeowners to fuel-switch their HVAC equipment. Finally, giving home and building-owners choices, along with the right market signals for the desired outcome, will most rapidly achieve the goal of decarbonizing residential building heat loads

About SMTI

SMTI was created to develop and advance Thermally Driven Heat Pumps by taking a fresh approach to a well-established thermodynamic cycle and position it for its most economically beneficial uses. Headquartered in Johnson City, Tennessee, the company's goal is the overall development and marketing of the TDHP technology category. Its business model is to manufacture the heart of the gas absorption cycle – a "Thermal Compressor" – and sell it to the existing manufacturers in the HVAC industry. They in turn, will add customized componentry and controls, using their existing factories and expertise, and release it as their own product into their normal distribution channels. This approach makes it easy for manufacturers to bring a new high-efficiency product category to market rapidly with minimal risk, and at a much lower cost than if they were to attempt the R&D by themselves. To date, SMTI has raised more than $12 million to develop the basic technology and, with 3rd-party-verified field-tests of prototypes, establish the basic performance metrics, costs, and capabilities of modern TDHPs. As of early 2019, SMTI is currently working internationally with several major manufacturers on advanced product development projects, which will put TDHPs in the market capable of replacing today's traditional furnaces, boilers, and hot water heaters. For more information, visit: ***www.StoneMountainTechnologies.com***.

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[4] https://www.socalgas.com/1443741887279/SoCalGas_Renewable_Gas_Final-Report.pdf