Mini-split Mania

A Report on the Cost and Performance Characteristics

of Ductless Mini-split Heat Pumps

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FOREWORD

The new era of high performance ductless mini-split heat pumps is revolutionizing building conditioning industry. Personalized comfort with exceptional energy efficiency from extreme cold to hot and humid conditions are readily handled with today's mini-split heat pumps.

The cover photo shows the 1 ton mini-split heat pump installed in the 2100sqft Equinox House in Urbana Illinois. Equinox House is a zero plus energy house constructed in 2010. An infrared beacon (CERV-IR) in the photo foreground allows CERV smart ventilation systems to control any number of mini-split heat pumps in a seamless manner. Smart ventilation coupled with high performance mini-split heat pumps results in exceptional air quality, comfort, and energy efficiency.

This report presents information on ductless mini-split heat pumps that may surprise you. For example, installing two mini-splits where one would handle house loads increases efficiency as well as providing redundancy and improved comfort control. Another surprise is that a manufacturer's low capacity mini-split models are often identical machines. So why are the cost and yellow tag performance between "identical" machines different?

Build Equinox is involved in a wide range of home projects around North America, and we hope sharing our knowledge on a variety of home technologies will be a benefit to our growing CERV community. It is time to move beyond energy, designing homes with exceptional indoor environments that improve our health, comfort and well-being!

Executive Summary

The following cost and performance characteristics are discussed in this report:

1) Two one ton, ductless mini-split heat pumps operating at partial load are more efficient than a single ductless mini-split operating at the combined load
2) A manufacturer's low capacity mini-split units are often identical machines, differing by control algorithms, "yellow" tag rating and price
3) Human productivity decreases by 1% per degree F of temperature outside of their personal comfort range for a cost significantly exceeding the energy cost for comfort
4) Fixed cost for one popular low temperature mini-split series ranges from $730 to $1175 with a variable cost range of $575/ton to $730/ton for their low, medium and high performance model series
5) Similar fixed and variable cost trends are found for other manufacturers' low temperature, ductless mini-split heat pump models
6) Today's inverter drive (variable speed), two-stage compressors with variable speed fans incorporated into ductless mini-split heat pumps operate at higher efficiencies during partial load conditions

Introduction

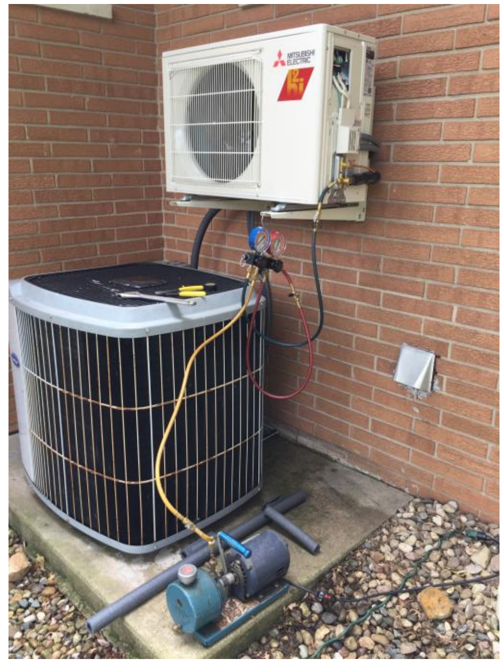

Figure 1 A 1 ton "mini" being added to a home with central AC for zone control and improved efficiency at partial loads.

Figure 1 shows the addition of a 1 ton ductless mini-split to a home's central conditioning system. The home's owner reports that the mini-split has improved their home's comfort and efficiency.

Figure 2 shows two ductless mini-split heat pumps at Equinox House. [Equinox House], a zero-plus solar powered home in central Illinois, has been conditioned for the past 8 years with a single 1 ton ductless, mini-split heat pump. A second ductless mini-split heat pump was added last fall to demonstrate the new CERV2's ability to control multiple distributed conditioning systems (stay tuned for future articles!).

Over the past 10 years, high efficiency mini-split heat pumps have grown in popularity. We are seeing mini-split heat pumps in many projects. Some homes, similar to Equinox House, only use mini-split heat pumps for conditioning. Other homes use them in combination with other systems for additional conditioning flexibility and redundancy.

Let's assume you are working on a project and are considering using ductless mini-split heat pumps. You've worked hard to design a high performance home that only requires 1 ton (12,000Btu/h) of heating and/or cooling capacity and are considering using a ductless mini-split. Should you:

1) choose a single 1ton mini-split heat pump?
2) choose two 1/2ton mini-split heat pumps?
3) choose two 1ton mini-split heat pumps?

The answer isn't so straightforward. The first two answers make sense. The third answer seems unreasonable because everyone knows overcapacity is inefficient. Or is it?

Answer 1) is least expensive in upfront cost, but distribution of heating and cooling from a single mini-split requires a relatively simple home (open floor plan) without significant spatial and temporal comfort load variations as well as occupants with comfort condition tolerance.

We pay a significant price in human productivity when we're uncomfortable. We lose one percent in human productivity for every degree (F) outside of our personal comfort range [1].

Answer 2) is reasonable because although the upfront cost is more expensive, a home can be "zoned" for better comfort control. An additional benefit is that two "half ton" mini-split heat pumps operate more efficiently than a single one ton mini-split! One high quality mini-split manufacturer (see Figure 3) lists a SEER value of 33.1 for their half ton, ductless mini-split, and a SEER value of 26.1 for their one ton unit, for an efficiency increase of 27%! There are few opportunities in today's high performance homes with this type of energy performance gain.

Figure 2 A ¾ ton mini-split has been added to the original 1 ton mini-split in Equinox House. The new unit has been installed to demonstrate the CERV2's ability to control distributed mini-splits with our CERV-IR (CERV-Infrared) technology. Other than minor differences in looks with an 8 year age difference, the two minis are identical. The two minis give us an efficiency boost over the single mini in summer and winter!

Answer 3) is not so obvious because in yesterday's world of "bang-bang" (on/off) capacity control, a significant efficiency loss occurs with oversized systems. In today's world of variable speed (inverter) capacity control, the opposite occurs. Two 1 ton mini-split heat pumps operating at half capacity have higher combined efficiency than a single 1 ton heat pump operating at capacity! In fact, two 1 ton mini-split heat pumps operating at half load can have the same efficiency as the two ½ ton mini-splits operating at full load. What?

Here's the interesting part. Several manufacturers' small tonnage mini-splits are all the same machine! A close examination of a manufacturer's line of low capacity mini-split heat pumps (eg, ½ ton or 6000Btu/h; ¾ ton or 9000Btu/h; 1 ton or 12,000Btu/h; 1 ¼ ton or 15,000Btu/h nominal capacities) reveals they are identical machines with the same nuts, bolts, sensors, and circuit boards. The three units shown in Figure 3 have identical dimensions, electrical specifications, refrigerant charge, and installation instructions, but different prices and yellow tag efficiencies.

We address four topics in this report:

1) The value of comfort
2) Ductless, ducted, multi-head and VRF heat pumps
3) Low capacity, low temperature mini-split cost and performance
4) Increased efficiency of heat pumps at partial capacity

The Value of Comfort

Comfort is complex. Everyone has their own comfort preferences, and as we all know, one size does not fit all. Although we can define an "average" comfort range, it is no more useful than defining average weather. If you think designing for average is a good idea, build a house with doorways based on average human height (5'7" for the US [2]) rather than today's "3 sigma" 6ft 8 inch doorway height in the US.

We are now in an age where we can have individualized indoor environmental quality. One of our CERV homes has three 1 ton mini-splits…..her space, his space, and their 5 dogs' space. Distributed throughout a home, workplace, school or other indoor space, one should be able to control their indoor environment's air quality and comfort.

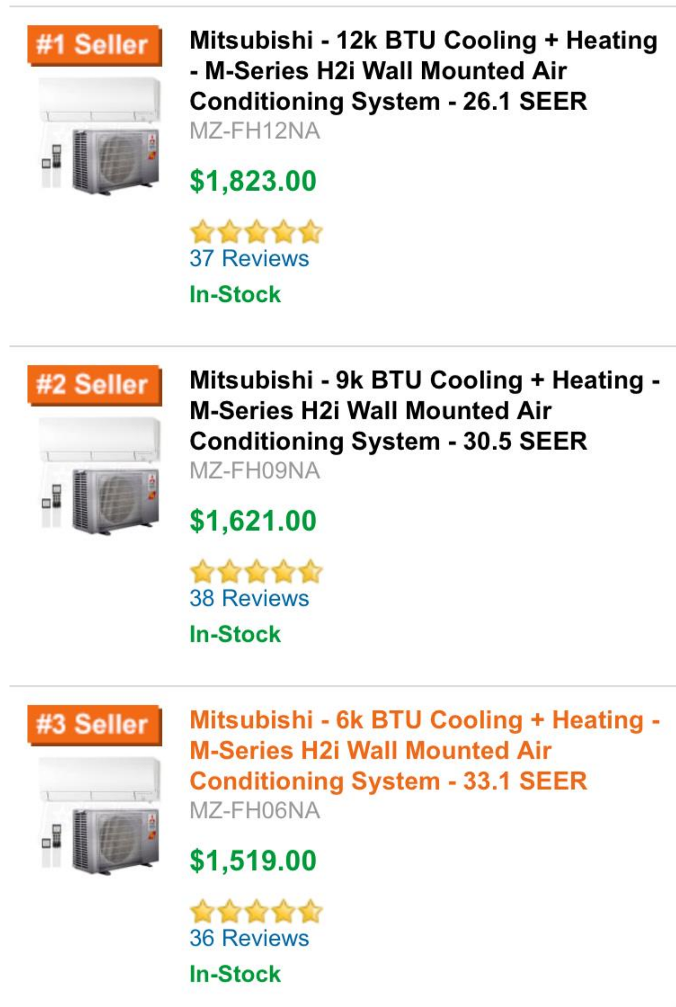

Figure 3 These three ductless mini-splits by mini-split technology pioneer Mitsubishi are all the same unit. Height, width, amount of refrigerant, installation instructions…..everything is identical except the cost.

Buildings, both residences and other, may be the only products in which significant customer dissatisfaction is the norm. A study [3] of 215 buildings with 34,000 survey respondents found that only 26% of the buildings had less than 20% occupant air quality dissatisfaction, and only 11% of the buildings had less than 20% comfort dissatisfaction. In other words, almost 90% of the buildings surveyed failed to have less than 20% occupant dissatisfaction. Any other business with such large levels of customer dissatisfaction would not last long in the marketplace. Note that the remaining building occupants are not necessarily "satisfied".

Only a 2F temperature variance from an occupant's preferred thermal comfort range causes a 2% drop in productivity (see Figure 4), with a cost much greater than the cost of a better quality comfort conditioning system. For example, a building occupant with an annual salary of $50,000 would cost a company $1000 per year with a 2% productivity decrease due to a 2F discomfort. Adding a mini-split heat pump to each employee space on top of an expensive, ineffective centralized conditioning and ventilation system would pay for itself in improved productivity within 5 years. Even better, don't install centralized systems in large buildings. Instead, install smaller distributed fresh air ventilation systems and comfort conditioning systems.

The new world of multiple, distributed mini-splits (and their commercial cousins, Variable Refrigerant Flow, or VRF systems) allows spaces within buildings to maintain localized occupant comfort preferences. Our focus at Build Equinox is on residential indoor environmental quality. Although one might argue that one's work salary is independent of the home environment, we argue the opposite. Low productivity at home due to poor environmental quality at home does impact one's productivity at work. Poor sleep quality at home due to poor air quality and discomfort certainly affects one's work. Poor decisions at home, or reduced home productivity can cause employees to "catch up" at work which is also a cost to employers. And, perhaps most significantly, children living in homes with poor air quality and comfort imposes a cost on society due to lowered "productivity" in learning. The bottom line is that discomfort has a significant cost, and with today's heat pump technologies, excellent indoor environmental quality can be installed cost effectively in homes in all climate zones.

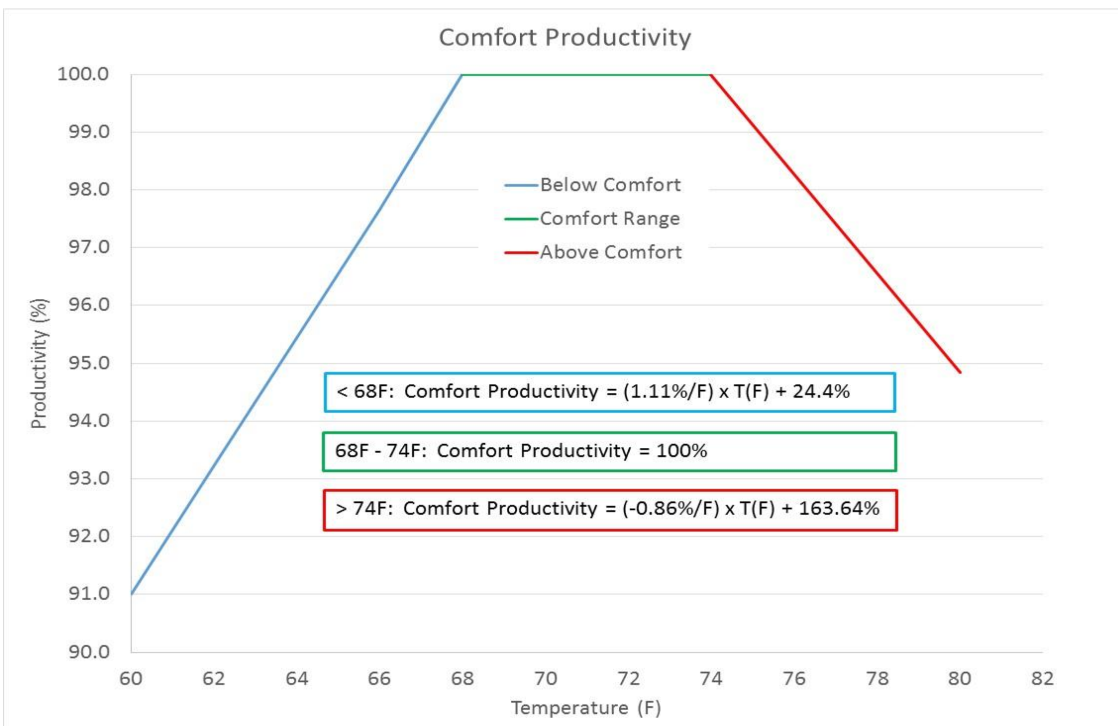

Figure 4 Simplified comfort productivity chart from trends in Fisk, et al [1]. Above and below one's preferred comfort temperature causes 1% productivity drop for every degree outside of one's preferred comfort band.

Ductless, ducted, multi-head and VRF heat pumps

This report is specific to single head, ductless mini-split heat pumps. There are some shared characteristics with related technologies, but there are also some significant differences one needs to be aware of to achieve the energy and cost benefits we discuss in this report. The new world of high performance air-to-air heat pumps consists of a variety of technologies, and we need to define things more specifically.

Figure 3 shows some examples of single head, ductless mini-split heat pumps. A single outdoor heat exchanger unit is coupled to a single indoor heat exchanger unit. For “mini-split” heat pumps, the indoor unit is powered and controlled by the outdoor unit. Ductless indoor units are extremely quite and the fans have very high airflow efficiency because the heat exchanger and fan are integrated into a synergistic configuration, resulting in 10 to 30cfm per Watt [3].

Single head mini-split heat pumps may be ordered with “ducted” indoor units, allowing the conditioning unit to be hidden. Ducted units also have the potential to circulate and distribute conditioned air to multiple spaces. Unfortunately, ducted units have poorer energy efficiency than ductless units because of decreased heat exchanger size and increased fan power. Ducted units cost more than ductless, and installation costs are greater as well. For example, from one online wholesale site, a 1ton ductless version of Mitsubishi’s GH series (operation down to -4F) costs $2360 with a SEER (Seasonal Energy Efficiency Rating) of 16.0 in comparison with the ducted version costing $1632 with a SEER of 23.1. Paying more for the unit and its installation, while losing 40% efficiency is not economical, but aesthetic value and personal preferences are important and need consideration.

Multi-head mini-splits have become popular because multiple indoor “heads” connected to a single outdoor unit can be distributed throughout a house. Our experience shows installation costs for two “single head” mini-split units is not significantly different from the cost of a 2 head multi-head mini-split. Refrigerant leaks in multi-head units are more problematic to find, and a single leak brings down both indoor units, in contrast to the redundancy that two or more independent units offer.

Purchase is similar between two individual units and a multi-head unit. Mitsubishi’s 1 ton hyperheat is advertised at $1914 while a two head hyper heat with 2 tons of nominal capacity costs $4800 from the same online site. As with the ducted unit, multi-head units lose efficiency. Multi-head units lose efficiency because a single outdoor unit tries to meet the demand of two indoor units. For the Mitsubishi hyperheat, the SEER rating drops from 26.1 for the single head unit to 19.0 for multi-head units, for a 40% drop in efficiency. Finally, one loses flexibility with multi-head systems. All indoor units must be in the same mode (heating or cooling). Many homes require multi-mode operation for a variety of reasons. With single head mini-splits, each region can operate as one desires.

Variable Refrigerant Flow (VRF) heat pumps are the commercial cousins of the multi-head mini-split heat pump. Low temperature versions of VRF systems are available, as well as “three pipe” versions that allow indoor heads to simultaneously be in heating or cooling mode. As with mini-split multi-head units, these units do not achieve the energy efficiency of a single head, ductless mini-split heat pump. Some manufacturers’ VRF systems look identical to multi-head mini-splits, and most likely, the indoor units and outdoor units are probably identical in physical. The main difference being that a manufacturers’ “commercial” reps handle VRFs while their “residential” reps handle mini-splits. A physical difference among some manufacturers is that mini-split units power the indoor units while a separate power source is used to power a VRF’s indoor unit. As with multi-head mini-splits, one loses redundancy with VRFs and a refrigerant leak indoors can result in a substantial amount of refrigerant released in a confined space.

The bottom line is that single head, ductless mini-split heat pumps outperform their close relatives by a substantial margin with today’s technologies. Additionally, the value of redundancy with multiple single head mini-splits may seem like a luxury until that extremely cold or extremely hot, humid day occurs, and one is relegated to paying overtime repairperson costs to fix the problem.

Low Capacity, Low Temperature Mini-split Cost and Performance

We receive a lot of questions from architects, builders and homeowners regarding the cost of installed mini-split heat pump systems. A manufacturer's line of low capacity mini-split heat pump models are often identical machines with only minor differences. The primary difference are the computer control algorithms that impact the "nominal" capacity and the performance numbers on the "yellow tag". So why does a 1/2 ton (6000Btu/h) heat pump cost less than the "same" unit rated at 1 ton (12,000Btu/h), as shown in Figure 3? We'll try to answer that question in this section.

Figure 5 shows the cost trends for three model series of ductless mini-split heat pump models. The Mitsubishi "FH" model (aka "Hyper Heat") is one of the original low temperature heat pumps. Mitsubishi's "GL" and "HM" model series are lower cost (with operation down to -4F rather than the Hyper Heat's -13F). Linear trendlines with cost relations are marked on the plot for each model.

The trendline relations in Figure 5 provide insight into each heat pump model. Although we don't know the exact manufacturing details of the three models, the "intercept" value of the cost relation tells us the "fixed" cost for building these heat pumps. The FH model has a fixed cost of $1175 in comparison to fixed costs of $928 and $728 for the GL and HM models, respectively. The fixed cost difference as one moves from the low cost HM model to the high end FH series is approximately $450. The fixed cost variation might be due to a higher quality compressor with higher efficiency. "Inverter" drive (speed controlled) compressors and two-stage compressors, for example, have increased efficiency and cost more than standard single stage, fixed speed compressors. Also, improved sensors along with more advanced computer controls would increase a model's fixed cost.

The trendline "slope" (cost per capacity) characteristics of each heat pump model series in Figure 5 is the variable cost for increasing the capacity of each model series. The variable cost changes from $576/ton to $704/ton to $732/ton for the HM to GL to FH model series, respectively. Increased heat exchanger areas and heat exchanger enhancements (eg, high performance fin surfaces) for outdoor and indoor heat exchangers are primary reasons for variable cost increases.

Figure 6 shows efficiency trends versus unit cost per capacity. The "SEER" (Seasonal Energy Efficiency Rating) cooling rating is used, however, a similar trend will be found if the HSPF (Heating Seasonal Performance Factor) heating season performance factor is used. Remember, the FH series are identical units, as are the GL series models and the HM series models. If I would like to have a SEER level great than 30, I will need to spend $2500 per ton or more. Note that the increasing cost per capacity trend is due to both the increasing cost of higher efficiency components and the derating of a unit's capacity.

Figure 7 shows that market forces dictate a mini-split heat pump cost variation of $600 to $800 per ton with a fixed cost variation of $500 to $1200. Figure 7 shows remarkable consistency among manufacturers' ductless mini-split units. Except for two model series (Mitsubishi FH "High" and Daikin XL), the cost versus capacity trends (slopes) for the models are very similar. The "High" and "Low" designations within a particular model series (eg, the Mitsubishi FH series) is a break where a unit's specifications indicate that the model is significantly different (eg, unit dimensions and weight). The break between series models is often between 1 ton and 1 ½ ton models. The fixed cost variation among the units may be component quality as discussed previously, but may also be due to a "feature" such as wireless control.

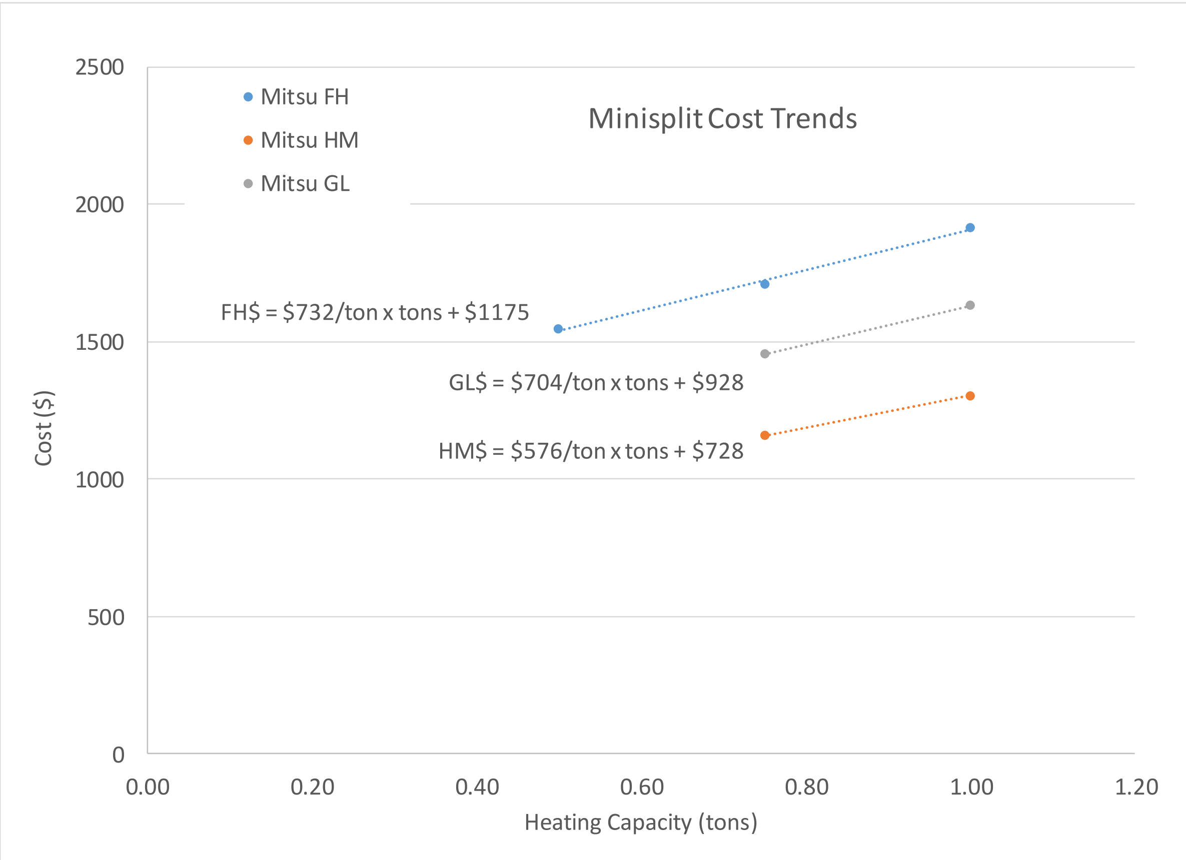

Figure 5 Cost versus heating capacity trends for Mitsubishi's FH, GL and HM mini-split heat pump models. The popular FH ("Hyper Heat") has the highest efficiency and lowest operating temperature (-13F). The GL series is intermediate in performance with a low temperature operation limit of -4F. The HM series is the lowest performing model series. Note that the GL and HM currently have two nominal capacities (3/4 ton and 1 ton) while the FH now offers three nominal capacity units (1/2 ton, 3/4 ton, and 1 ton).

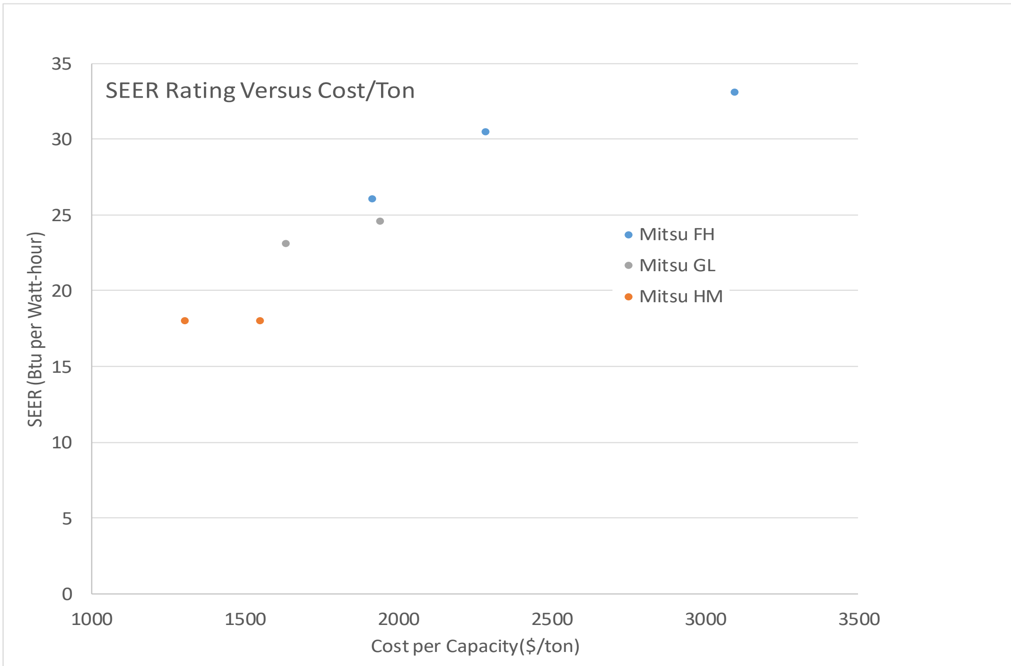

Figure 6 SEER (Seasonal Energy Efficiency Ratio) performance value versus cost per capacity for Mitsubishi FH, GL and HM ductless mini-split heat pump models.

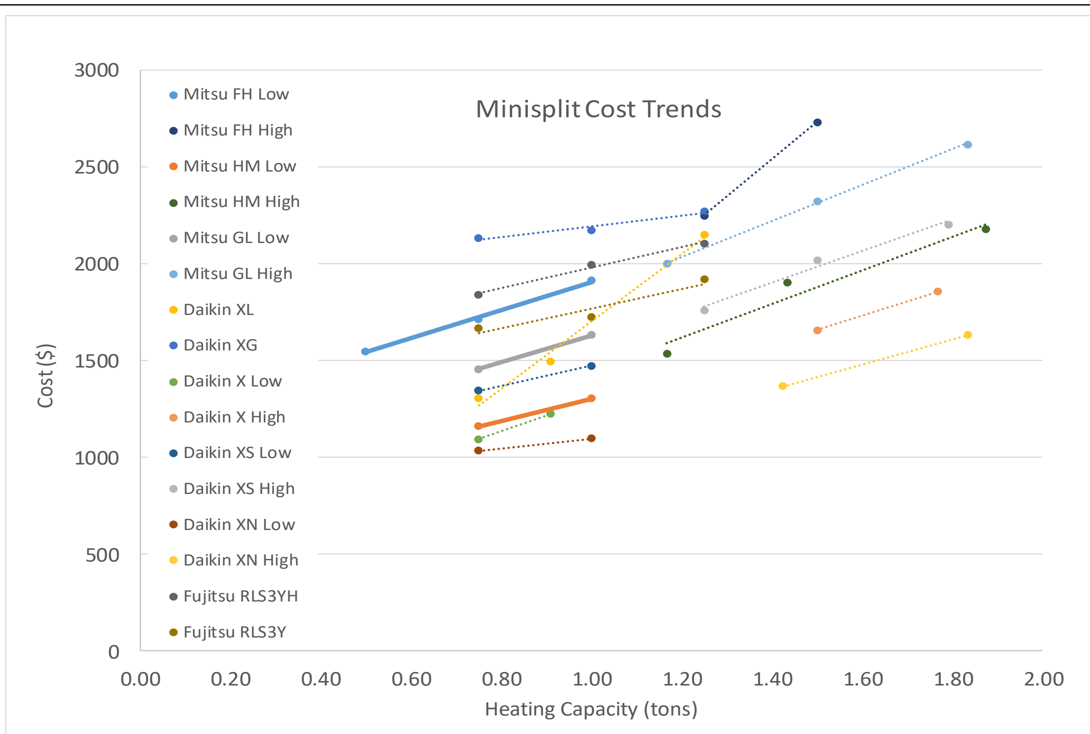

Figure 7 Ductless mini-split heat pump trends for three manufacturers. Trendlines are drawn among "identical" models of differing capacity. The three Mitsubishi series solid trendlines agree with most other manufacturer model capacity cost trends.

Increased Efficiency of Heat Pumps at Partial Capacity

Chapter 6 of Natural Capitalism [4] from the Rocky Mountain Institute popularized the phrase "tunneling through the cost barrier". Natural Capitalism's authors list three basic engineering concepts for tunneling through to new cost efficient solutions:

1) The whole system should be optimized
2) All measurable benefits should be counted (eg, include the value of health, productivity and comfort….not just energy)
3) The right steps should be taken at the right time and in the right sequence

Too often, home designers ignore the first two steps and skip to the third step. For example, house insulation levels are often chosen without any regard to the house comfort conditioning system. Optimal insulation thickness depends on the type of house comfort conditioning system! A house using electric resistance heat requires a different amount of insulation than a house with a heat pump. As discussed in Natural Capitalism, once one goes down the path of pre-conceived ideas, economic optimization is destroyed. The appendix contains a house design example that illustrates this effect.

When seeking economically optimized solutions, one relies on component manufacturers to economically optimize the products they are selling. Competition drives heat pump manufacturers to achieve the best performance at the best cost. Manufacturers strive to have one of the best "yellow tag" ratings at a reasonable price for the unit's nominal heating and cooling capacity.

In this section, we want to provide a conceptual framework for understanding why a heat pump has higher efficiency when it is operated at heating and cooling capacities below the nominal capacity rating. That is, we wish to answer the question as to why choosing two heat pumps is more efficient than one!

Three primary factors determine the optimal design of a heat pump:

1) The Second Law of Thermodynamics (2ndLoT)
2) Heat exchanger heat transfer characteristics
3) Cost of heat exchangers

The 2ndLoT is often thought of as a cruel ruse played on engineering students in thermodynamics courses. Nothing could be further from the truth because the 2ndLoT provides a framework for understanding the performance limit of any process. In our case, the 2ndLoT defines how much compressor power is needed for "pumping" heat. If one wishes to pump heat from the inside of a house to the outside during summer, a hot day requires more compressor power than a warm day. Likewise, if one would like to pump heat from a bitter cold outside to the inside of a house, more compressor power is needed than on a cool day.

Heat exchangers are required for transferring heat between the heat pump and its surroundings. During summer conditions, the indoor mini-split heat exchanger (evaporator) must be colder than indoor air for heat to flow from the inside house air into the refrigerant boiling in the heat exchanger. Likewise, the outdoor heat exchanger must be hotter than the outside air temperature to exhaust heat from the heat pump to the outside air. Winter time heating occurs in the opposite manner.

A small heat exchanger requires a larger temperature difference between the heat pump and the surrounding air than a larger heat exchanger for moving the same amount of heat. For example, a heat exchanger twice the size of another heat exchanger reduces the temperature difference between the heat exchanger and the surrounding air in half. This heat exchanger characteristic directly impacts the heat pump efficiency by reducing the overall temperature difference that heat is pumped against.

Heat exchanger cost provides information to determine the optimal design of the heat pump. Reaching the 2ndLoT maximum heat pump efficiency limit requires infinitely large indoor and outdoor heat exchangers. Infinite heat exchangers cost an infinite amount of money (just like an infinite amount of wall insulation). Tiny heat exchangers require a lot of energy because the reduce heat pump efficiency with large temperature differences. An economic optimum for a heat pump generally exists in which the sum of lifetime energy cost plus the heat exchanger costs are minimized.

The analyses for determining the most economical heat pump design is easier described than demonstrated because the combined mathematical relations are cumbersome and require extensive analyses. For example, what should the manufacturer choose for outdoor and indoor conditions? If the unit will only be sold in Florida, the manufacturer should use climatic conditions typical for that region. Most manufacturers would like their product to have a broad geographical distribution potential, which requires optimizing over a broad range of conditions. As discussed previously, the lower cost Mitsubishi heat pumps should not be used in regions that experience weather below -4F. For those regions with winter weather temperatures greater than -4F, any of the Mitsubishi units in Figure 5 could be selected. Note that one would optimize each design configuration with each heat pump model to compare the optimal configurations (Step 1 from Natural Capitalism).

Figure 8 shows a simulation surface of Life Cycle Cost (LCC) for a heat pump based on the 2ndLoT, heat exchanger modeling, and economic costs typical of heat pump heat exchangers. The LCC increases rapidly with heat exchangers smaller and larger than those of the economic optimum. For the heat pump modeled in Figure 8, the minimum (optimum) lifecycle cost is $7000, with $4300 of energy cost and $2700 for installed heat pump cost. This optimal heat pump uses 700W of electrical power and has a COP value of 5.0 (EER = 17). The ambient conditions assumed are 104F (outside) and 68F (inside).

Most comfort conditioning systems only operate at a fraction of their “design day” capacity. If the heat pump modeled in Figure 8 is operated at half of its design capacity, the heat exchangers are twice as large as needed for its nominal heating and cooling capacity ratings. Doubling the heat exchanger size per capacity, as previously discussed, reduces the temperature difference between the heat pump and the surrounding air causing an increase in efficiency. For the heat pump modeled in Figure 8, the COP increases to 6.0 (EER = 20.4) from 5.0 for an efficiency increase of 20%. Note that an electric resistance heater has the poorest heating efficiency of any heat pump with a COP of 1, and, of course, it has no ability to cool (cooling COP = 0). For those who would like a more in depth look at this effect, Winkler’s [5] investigation of two 1 ton mini-split heat pumps contains detailed data over a range of heating and cooling capacities.

Returning to our introductory discussion, is it better to install a single ductless heat pump that meets a home’s comfort conditioning capacity needs, or to install two heat pumps that can better distribute comfort while also achieving higher energy efficiency? The answer will be revealed by conducting economic analyses of the single heat pump and dual heat pump cases, and comparing those results.

If the single heat pump case has a lower life cycle cost because the dual heat pump energy savings are less than the extra heat pump cost, the dual heat pump may still be a desirable option based on improved comfort distribution (and its associated value) and the value of redundancy (if a unit breaks during extreme weather, rather than calling an emergency repair person, one can wait). This is the essence of Natural Capitalism’s Step 2, casting a broader definition around the value and cost of an entire design. That is, one should think beyond energy and place value on our health and comfort.

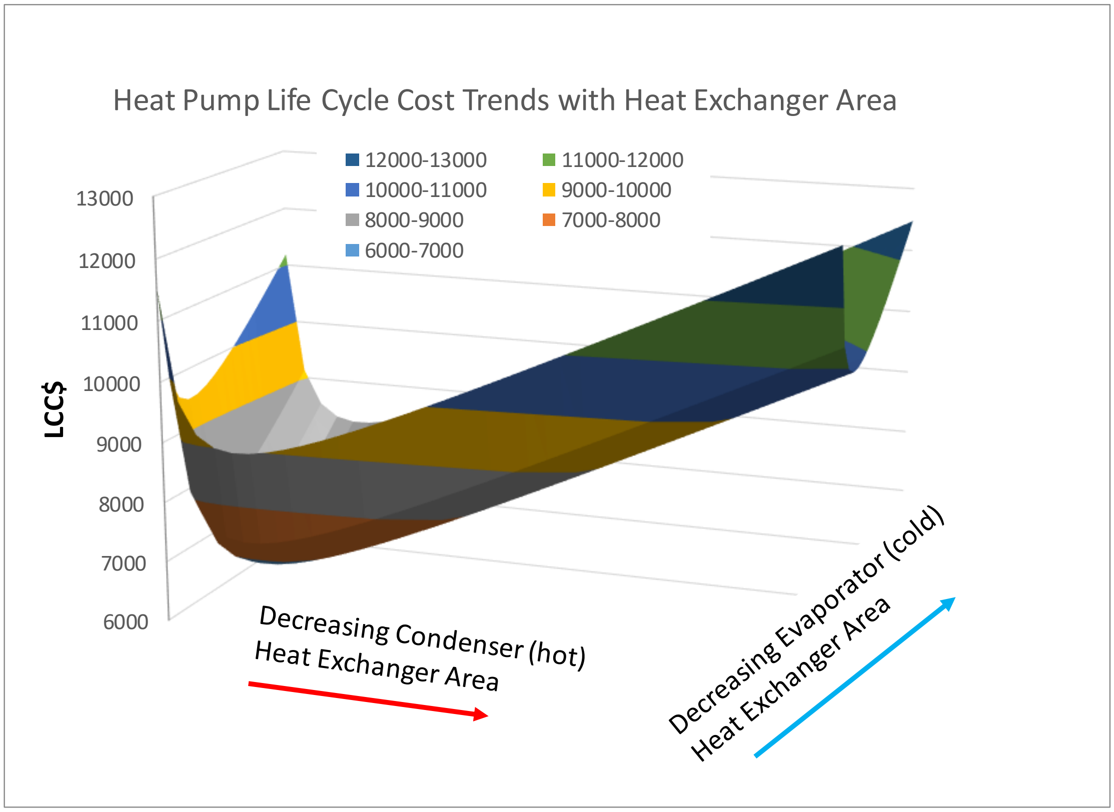

Figure 8 Life Cycle Cost surface for a mini-split heat pump based on condenser (hot) and evaporator (cold) heat exchanger areas. An outdoor air temperature of 104F (40C) and indoor temperature of 68F (20C) have been assumed. Small heat exchangers rapidly increase lifetime energy cost while excessively large heat exchangers increase heat pump cost.

References

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Appendix

Example: Economic Comparison of Insulation Thickness with Different Heating Systems

We present a simple example to demonstrate the economic relationship between insulation thickness and house heating system. We compare two identical homes. One home has a heat pump with a COP (Coefficient of Performance) of 3 and 6 inch thick insulation in the walls and roof. The second home has 12 inch thick insulation and is heated with an electric resistance heater (COP = 1). Figure 1A shows schematics of the two homes.

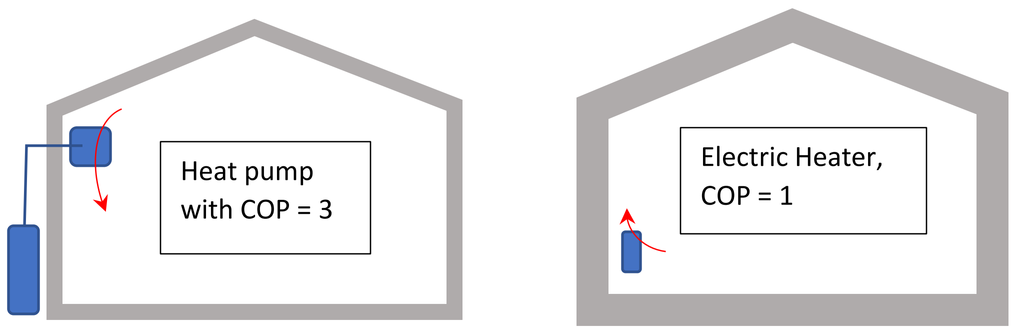

Figure 1A Two identical homes. One home has half the insulation thickness of the other and is conditioned with a heat pump having a COP = 3. The second home uses an electric heater (COP = 1) for heat.

The homes are in a region with a 6000 degreeF-day winter season. Combined wall and roof area of both homes is 3000sqft. Insulation costs $3 per cubic ft with an R-value of 3.5 per inch are assumed, resulting in an insulation cost of $4500 for the heat pump house and $9000 for the electric heater house.

The annual heating load for the heat pump house is 6000kWh (~20,000,000Btu) and 3000kWh (~10,000,000Btu) for the electric heater house. The electric heater house requires 3000kWh of electrical energy while the heat pump house uses 2000kWh of electricity. Assuming an electric utility rate of 12cents per kWh, the electric heater house has a utility bill of $360 per year and the heat pump house has a utility bill of $200 per year.

We will assume no cost for the electric heater (eg, a 1500W heater can be purchased for $20) and an installed cost of $2500 for the heat pump, with assumed lifetimes of 10 years for the heater and heat pump (note: contrary to common belief, heat pumps generally outlive electric resistance heaters).

The Life Cycle Cost (LCC) for the electric heater house is $12,600 ($9000 for insulation and $3600 for 10 years of energy). The heat pump house has an LCC of $9400 ($4500 for insulation, $2500 for the heat pump, and $2400 for electricity). The LCC of the electric heater house is 34% greater than the heat pump house LCC, and the energy consumption of the electric heater house is 50% greater than the heat pump house! For sure, a home owner can find something useful for the $3200 savings. Perhaps purchase 1500Watts of solar PV or take the family on a vacation!

This example is a simple comparison of the economic and energy efficiency interrelation between insulation and comfort conditioning system efficiency. They are intimately tied together and must be considered simultaneously during initial design activities. Each design configuration needs to be optimized before comparison of configuration choices, however, that requires a closer examination of many other factors (occupancy, ventilation system, windows, water heater efficiency, climate, solar PV system cost, etc) in addition to insulation and comfort conditioning systems. Our free-to-use ZEROs (Zero Energy Residential Optimization software) has been developed with residential economic optimization in mind. Try it out!