I used to think that electric heating could never be justified—for any reason. As energy guru Amory Lovins said in the 1970s, using electricity for heating was “like cutting butter with a chain saw.” It just didn’t make sense to use such a high grade of energy for such a low-grade energy need.

But since then, electric heat pumps have become widely available. This has changed my mind and I find myself recommending electric heat all the time. In fact, a new house that my wife and I are planning in southern Vermont will have electric heat—from a heat pump. Let’s find out what heat pumps are, and why they make sense.

**Electric Heating Basics**

What I thought about as electric heat in the 1970s, when Lovins’ preaching was ringing in my ears, was electric-resistance baseboard heating. With electric-resistance heat, electric current is converted directly into heat. Special “resistance wire” is used that resists the flow of electrons, producing heat in the process. Electric-resistance heat is most commonly delivered through baseboard “radiators,” but it can also be delivered through radiant ceiling panels, fan-driven convection heaters, and radiant-floor systems.

Electric-resistance heating is 100% efficient—each kilowatt-hour (kWh) of electric energy is converted into a kWh of heat. However, that only considers the conversion efficiency in the unit—and does not factor in the utility transmission losses or the efficiency of the source (see “Improving Source & Site Efficiency” sidebar).

Instead of using electricity directly to produce heat, the electrical energy can be used to move heat from one place...
to another—like from outdoors to indoors. That’s the basic principle of a heat pump: it extracts heat from the outdoor air (air-source heat pump) or from the ground (ground-source heat pump) and delivers that heat inside the building.

The idea of moving heat from a cooler to a warmer place is counterintuitive, but it’s exactly what your refrigerator does. Peter Temple, an architecture professor Keene State College, refers to this concept as “pumping heat uphill.” While electric resistance is 100% efficient at converting electricity into heat, a heat pump can deliver (move) two to four units of heat for every unit of electricity it consumes.

Every substance that is at a temperature above absolute zero (about 460°F, where all molecular motion stops) contains heat energy. Cooler objects have less heat energy (energy of motion of the molecules) than warmer objects. But even air molecules at 0°F have enough heat so that we can extract some, and leave the air just a little cooler than it was before.

A heat pump’s coefficient of performance (COP) is the ratio of energy delivered compared to the operating energy. A heat pump with a COP of 1 delivers 1 unit of heat for each unit of electricity consumed—no better than electric-resistance heating. A COP of 2 provides twice as much heat from the electricity consumed. That can be thought of as 200% efficiency—though it really isn’t a measure of efficiency, since the electricity is used for moving, rather than generating, the heat. Some heat pumps, in some situations, can have a COP as high as 5 or 6.

Understanding Heat Pumps

Heat pumps work by altering a refrigerant between its liquid and vapor phases in a closed loop. This phase change process releases and absorbs heat, enabling the heat pump to move heat from one place to another—even if the heat source is colder than the heat sink. This refrigerant cycle or vapor-compression cycle is the principle behind nearly all air conditioners, heat pumps, and your kitchen refrigerator.

There are four main components to a heat pump—compressor, condenser, expansion valve, and evaporator, plus heat exchangers to deliver heated or chilled air to the living space. Gaseous refrigerant is mechanically squeezed in the compressor—a process that also raises its temperature. This hot vapor then enters the condenser, where the hot vapor cools and condenses into a liquid state. A heat exchanger in this part of the heat pump transfers heat to the surrounding air (because that air is cooler than the refrigerant), and that heated air is delivered to the house.

Next, the condensed liquid refrigerant flows through an expansion valve, where it experiences a sudden pressure drop. This further cools the refrigerant, which at this point is mostly liquid. From there, this liquid refrigerant flows into the evaporator, where it evaporates into a vapor, a phase change that requires absorption of a large amount of heat. The heat exchanger uses air to warm that vapor and, in the process, chills the air.

“The key idea,” says Temple, “is that we have a loop and there are two phase changes every time the refrigerant goes around that loop.” Heat is absorbed on one side of the loop (evaporation) and dissipated on the other (condensation).
Every heat pump has a heat source and a heat sink, and these can be swapped. In the winter, the heat source is the outside air (air-source heat pump, ASHP) or the ground (ground-source heat pump, GSHP), and the heat sink is the house that is being heated. In the summer, that is reversed, with the house air being the heat source and either the outdoor air or ground being the heat sink. The same coils are used, but in one season they serve as evaporator coils and in the other season they serve as condenser coils. A heat pump’s reversibility is one of its key benefits.

Imagine removing the door on your refrigerator. In the winter, you position the refrigerator in a doorway, with its opening facing the outside. In this configuration, the refrigerator works like a heat pump to heat your house—extracting heat from the outside air and transferring that heat to the room through the coils on its back. In the summer, you turn the refrigerator around and fit it back into the doorway so that its cool interior now faces the room. Now it works like a heat pump to cool your house.

A real heat pump doesn’t have to be physically moved, but uses valves to accomplish the same effects—the condenser becomes the evaporator and the evaporator becomes the condenser.

Confused? Don’t worry. The refrigerant cycle is complex and not very intuitive. But it works—as it has since Willis Carrier first perfected its use in 1900. In a heat pump, the components are elegantly housed in a box located inside the home or in separate indoor and outdoor units. The user doesn’t see those thermodynamic processes happening, but can just enjoy the results.
GROUND-SOURCE HEAT PUMPS

Ground-source heat pumps have been a darling of the green building movement—and for pretty good reason. Temperatures underground remain much more constant year-round than air temperatures. This makes the ground a better heat source in winter and a better heat sink in summer, boosting the efficiency of a GSHP compared to an ASHP.

Most GSHPs are closed-loop systems, in which long coils of plastic tubing (usually polyethylene) are buried in horizontal trenches or vertical bore holes. This tubing serves as a primary heat exchanger, transferring heat between the ground and an antifreeze (glycol) solution, which is brought to the heat pump where another exchange of heat with the refrigerant happens.

A specialized type of closed-loop heat pump uses the coil of tubing sunk in a body of water. The heat transfer to and from the water is very rapid, so the coil doesn’t need to be as long. However, this type of system is uncommon, since most homes don’t sit next to usable water sources.

Open-loop GSHPs are also referred to as groundwater or surface-water heat pumps, depending on the water source. Water is pumped from the ground or a body of water, circulated through the heat pump, where heat is either extracted from it or added to it, then returned to the source. If the water is extracted from a well (most common), it is usually returned to the ground through a separate injection well. Open-loop heat pumps present a greater risk of contaminating either the aquifer (groundwater) or the surface water from which the water is drawn, and are prohibited in some states.

Ground-source heat pumps extract heat from the earth using a well, several bore holes, or loops laid in shallow trenches.
The WaterFurnace 502W12 hydronic heat pump is capable of delivering 150°F water, and is suitable for baseboard radiator systems, underfloor and overfloor radiant applications, and fan-coils that transfer heat to a forced-air heating system.

Rather than circulating an antifreeze solution through the ground, direct-exchange (DX) GSHPs circulate the refrigerant directly. These heat pumps are simpler and more efficient because they don’t use a secondary heat exchanger in the heat pump cabinet to transfer heat between the ground-contact antifreeze and refrigerant loops. But DX heat pumps require copper tubing, which is more expensive than polyethylene. They require a lot more refrigerant, and the copper may corrode and eventually leak.

Some GSHP manufacturers claim COPs as high as 6 for their systems under certain conditions, and COPs of more than 3 are common. High COP claims may be exaggerated for real systems in the field—the performance of GSHPs drops as the heat-exchanger loop warms or cools the soil over time.

GSHP Performance
One of the only long-term studies of GSHP performance is a field study of 83 heat pump installations in the United Kingdom by The Energy Saving Trust, with support from government agencies, utility companies, and manufacturers. Published in 2010, the study examined 54 GSHP installations and 29 air-source heat pump installations.

Only a handful of the GSHPs (13%) performed at a COP of 3 or higher. About the same number had measured COPs of less than 2. The largest number performed with COPs in the 2.2 to 2.4 range—below the expected performance of GSHPs.

One of the problems appears to be poor installation or lack of commissioning (inspecting, testing, and tweaking the installation after completion). Operation was another problem, with some homeowners telling researchers that they did not understand the operating instructions.

GSHPs also alter the ground temperature, causing a drop in performance. “You end up cooling the ground a lot in the winter and warming it up a lot in the summer,” says Temple. In climates such as New England, where heating loads dominate, cooling of the ground from GSHPs may accumulate over multiple years—dropping the GSHP performance from year to year. In cooling-dominated climates, a similar drop in performance may occur over time as the ground warms up from year to year. More testing is needed to understand these seasonal and year-to-year performance issues with GSHPs.
AIR-SOURCE HEAT PUMPS

Air-source heat pumps have long been popular in some parts of the United States. Until recently, they only made sense in milder climates where winter temperatures rarely drop below about 40°F.

Unlike their ground-source cousins, ASHPs have separate indoor and outdoor units where different parts of the vapor-compression refrigerant cycle take place. But like GSHPs, they can be switched from heating mode to cooling mode seasonally.

ASHPs rely on the outside air as the heat source in winter and as the heat sink in summer. When outside temperatures are low, it’s harder to extract heat from the air, and efficiency drops. In fact, at temperatures below 30°F, most older U.S. ASHPs would automatically switch to electric-resistance heating, so the benefit of the refrigerant cycle was lost.

The outdoor unit of a minisplit air-source heat pump can be small and inconspicuous. The refrigerant lines going to the inside minisplit unit are protected inside of the shown chase.

In the past 10 to 15 years, there has been a revolution with ASHPs, as Japanese companies have brought variable-refrigerant-flow (VRF) or “minisplit” heat pumps into the U.S. market. Most VRF heat pumps can operate down to 0°F (or even lower) without significant loss in performance. In southwestern New Hampshire, for example, these systems have been successfully heating houses without any other heat source, even with outside temperatures as low as -18°F.

VRF heat pumps vary the flow of refrigerant in ways that significantly boost performance, while the older, standard heat pumps operate at a constant flow—either on or off. VRFs also benefit from improved refrigerants and sophisticated electronic controls.

The indoor unit can be wall- (most common), floor-, or ceiling-mounted. Small-diameter refrigerant lines connect the indoor and outdoor units. They are relatively easy to install and elegant in their simplicity. They cost a lot less than GSHP systems, because trenching or well drilling isn’t required, nor are long lengths of tubing.

ASHP Performance.

The best VRF ASHPs operate with COPs that are close to those of GSHPs, and their performance doesn’t change over time due to long-term changes in ground temperatures.

Costs of both GSHPs and VRF ASHPs vary widely depending on available installers and system popularity, but the pricing differences can be dramatic. It is not unusual for GSHP installations to cost $25,000 to $35,000, while $10,000 to $15,000 is more common for the VRF units. With simple installations in places where a lot are installed, VRF heat pump installations can cost as little as $5,000.
Heat Pump Water Heating
Both ground- and air-source heat pumps can be configured to heat water along with space heating and air conditioning. In the summer operation mode, water heating can be almost free—as a byproduct of the cooling cycle. In this mode, heat is extracted from the indoor air, but instead of simply dumping it into the ground or outside air, a “desuperheater” diverts the waste heat for water heating. Only a few heat pumps incorporate water heating, but this will become increasingly common as heat pump advances continue.

Heat Pumps & Photovoltaic Power
If we can reduce space-heating loads—through high levels of insulation, well-insulated windows, and airtight construction—and provide some heat with passive solar design, then it makes sense to provide the small amount of needed heat with solar electricity. And it makes sense to use heat pumps, rather than electric-resistance heat, since heat pumps are far more efficient.

PV systems can allow achieving net-zero-energy use in homes. With the heating loads low enough and using a heat pump to deliver more heat from each kWh, a simple rooftop or ground-mounted PV system with net metering should be able to satisfy those needs. For example, a well-built, well-insulated, and well-sealed 1,500-square-foot house in southern New Hampshire, for example, could require about 9,500 Btu per square foot per year for heating, or about 14.25 million Btu per year. That converts to about 4,175 kWh, which in New England could be supplied by a 3.5 kW PV array.

COMPARING FUEL COSTS
Comparing the economics of a heat pump to other heating systems can take a little work since we’re not comparing apples to apples. Different fuels are sold (and priced) in different units: therms or hundred cubic feet (ccf) of natural gas; gallons of propane; gallons of heating oil; tons of pellets; cords of wood; and kilowatt-hours (kWh) of electricity. These different fuels have very different heat values.

Online fuel-cost calculators allow you to plug in the current price of the fuels being compared. The more sophisticated calculators allow you to vary the efficiency with which the fuel is burned (or converted into heat) and even the efficiency with which the heat is distributed, then output a comparison of costs in consistent units—such as dollars per million Btu of delivered heat.

Of course, energy prices fluctuate, so such a comparison is only accurate in the present. But running through these calculations can help you make an informed decision about the costs (and savings) of various heating systems. BuildingGreen’s online calculator (buildinggreen.com/calc/fuel_cost.cfm) was used to create the comparison table below.

Home Heating Costs
<table>
<thead>
<tr>
<th>Heater Type</th>
<th>Fuel Type</th>
<th>Efficiency or COP</th>
<th>Fuel Cost</th>
<th>Operating Cost per Million Btu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydronic heat (boiler)</td>
<td>Heating oil</td>
<td>83%</td>
<td>$3.50 per gal.</td>
<td>$31.03</td>
</tr>
<tr>
<td>Pellet heater</td>
<td>Wood pellets</td>
<td>80%</td>
<td>250.00 per ton</td>
<td>18.94</td>
</tr>
<tr>
<td>ASHP</td>
<td>Electricity</td>
<td>2.25</td>
<td>0.15 per kWh</td>
<td>19.94</td>
</tr>
<tr>
<td>GSHP</td>
<td>Electricity</td>
<td>3.00</td>
<td>0.15 per kWh</td>
<td>14.95</td>
</tr>
<tr>
<td>Central furnace</td>
<td>Natural gas</td>
<td>90%</td>
<td>1.25 per therm</td>
<td>14.17</td>
</tr>
</tbody>
</table>

Source: buildinggreen.com/calc/fuel_cost.cfm

CONSERVATION vs. CONSUMPTION
There’s a disconnect between investing in conservation and investing in consumption. Rather than spending $35,000 on a GSHP or $20,000 on a radiant-floor heat-distribution system, it often makes more sense to put those dollars into energy conservation, passive solar design, and retrofits, like extra insulation, weatherstripping, and high-performance windows. For new construction, in cold climates, get the wall R-values to R-40 or higher. Then install high-performance windows with low-e coatings that provide R-5 or higher, and use air-sealing strategies to provide a tight envelope (1.5 air changes per hour at 50 pascals of pressure is recommended).

In an efficient house, having a high-performance envelope may eliminate the need for a central heating system. A VRF air-source heat pump or a wood heater may be able to meet all of your space-heating needs. It just doesn’t make sense to spend tens of thousands of dollars on a heating system to provide a few hundred dollars’ worth of heat per year.

Most early net-zero-energy homes used GSHPs for heating because they offered the highest COPs. But today’s VRF ASHPs are nearly as efficient, and that efficiency is less likely to drop over time. Plus, because of the significantly lower installation cost of VRF heat pumps, the economics can be far better than with GSHPs, allowing you to invest the savings into a bigger PV system.

PV-powered heat pumps can provide a truly renewable source of heating (and cooling). Avoiding all combustion in the home eliminates the risks inherent with fossil fuel and wood combustion—long-term health problems from air, soil, and water pollution; explosions; etc. This is why more and more, leading energy engineers and builders are now examining VRF air-source heat pumps more closely.

Access