

Aggressive Engineering for Passive Houses

The real energy guzzler is not the family car, but the family home. More than 25,000 passive houses built in Europe during the last 20 years demonstrate how engineering can slash residential energy consumption by up to 90 percent.

by Trudy E. Bell

build a house without a conventional furnace in the snow belt of Cleveland, OH—where average annual snowfall is a good five feet and mean winter daytime temperature is 28°F—and heat it with the equivalent of two portable hairdryers?

A house that can maintain a comfortable indoor temperature of 68°F year-round, even in summer without a traditional air conditioner?

Exactly such a house is receiving finishing touches right now on the grounds of the Cleveland Museum of Natural History as a demonstration project, and it will be open for the public to tour from the end of July into September as part of a traveling exhibit.¹ Called PNC SmartHome Cleveland, the 3,000-square-foot house will showcase home-construction techniques and technologies developed since the 1990s by the Passivhaus Institut (Passive House Institute) in Darmstadt, Germany, and gaining wide acceptance in Europe to slash dependence on fossil fuels.² Indeed, in 2008, the European Union ruled that all new construction beginning in 2016 must meet Passivhaus Institut standards. Although an estimated 25,000 homes built to Passivhaus Institut standards have already been built across Europe, fewer than 100 currently exist in North America—but their locations range from balmy California and tropical Florida to wintry Wisconsin, Maine, and Quebec.³

In essence, a passive house is a super-insulated, airtight structure designed with one primary goal: to reclaim and recycle energy with the highest possible efficiency, to maintain a comfortable interior temperature year-round without conventional HVAC (heating, ventilation, and air conditioning) technology or photovoltaic solar panels. Natural heat sources include not only the sun shining onto the house, but also waste heat from lighting and electrical appliances, the body heat of the occupants, and possibly even the ground itself. Interior air is kept fresh by use of an energy recovery ventilation system, which maintains a steady flow of outdoor air into the house, while filtering it and reclaiming energy from the exhaust air.

Houses as energy hogs

After nearly two decades of measurements and statistics by the Passivhaus Institut in monitoring the performance of passive houses across Europe, the numbers are in. Although the initial construction cost of a passive house can run 10 to 20 percent higher than conventional well-built custom construction, the elimination of a furnace and ductwork represents an immediate savings. But the real payback comes over the first decade from an annual heating bill that is only 10 to 15 percent that of a conventional house. Indeed, the goal for a passive house is to be cost effective: for capital and operating costs to be no more than—and

ideally far less than—those of a conventional house over a 30-year mortgage.⁴

The true cost of home-ownership is not just the purchase price, even including the cost of capital improvements (which everyone hopes to make back on resale). It's the total life-cycle cost of operating the house.⁵ Buildings are the single largest consumers of energy (49 percent), about equal to transportation and industry combined.⁶ Of those, according to the McKinsey Global Institute, “The residential sector is the largest single energy consumer worldwide, and



also the one where the largest uncaptured energy productivity improvement opportunities lie.”⁷

Let's bring that statistic home, so to speak, with a case in point. As any owner of a charming older house in the winter-dominated Great Plains, Midwest, or Northeast can attest, charm costs dearly. In northeast Ohio, the heating season usually lasts from October through March, but can back into September or edge into May (as this year on May 16 when daytime highs were in the 40s). My 1914 two-story, wood-



The Passive House in the Woods is a 1,940-square-foot private home on a one-acre lot just outside the town of Hudson, WI. Designed by architect Tim Delhey Eian of TE Studio, it actually exceeds PassivHaus Institut space-conditioning requirements by 30 percent. The 22-inch walls have an overall R-value of R-70 and the flat roof R-95. Despite its northern latitude, it has no furnace; south-facing triple-pane windows collect warmth from winter sun. The solar panels provide electricity.



Photos pp. 16-17: Chad Holder (www.chadholder.com)

frame house with 2,100 square feet of living area is typical of the local housing stock. Even with the thermostat set to 62°F in the daytime when I am there working, the cost of both natural gas for the forced-air furnace (new in 2008) and small electric oil radiators in my office and bedroom (turned on only when I occupy each room for the day or night) regularly exceed \$300 per month in the heating season and have topped \$400. When insulation was blown into the walls in December 2010, monthly heating bills dropped to about \$225 (even though I bumped the thermostat up to 63°F as a treat). Every energy improvement (insulating the attic, replacing all 30 century-old windows with double-pane windows, caulking gaps)

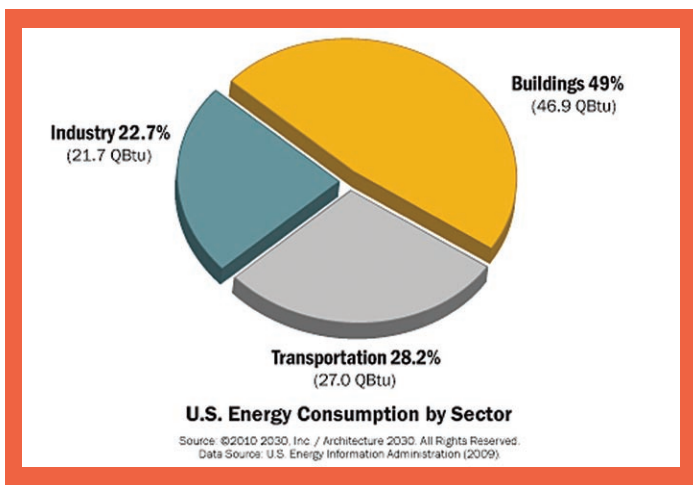
has made a perceptible difference in comfort and heating bills. But there are limits. The construction of this century-old house is inherently drafty—and the inexorable net rise in the cost of fossil fuels over the years has steadily eroded any savings I might have realized.

Upshot: Even at a winter interior temperature many people consider 5° to 10° too cold, heating alone blows \$2,000 to \$3,000 up the chimney each year, followed by perhaps another \$500 for air conditioning in the summer (used only on

days when it's 85+°F and muggy). That's money never, ever to be recouped in home value, tax write-offs, or any other way. Multiply that loss by the roughly 190,000 households in the Cleveland metropolitan area, and a bit shy of a billion dollars are annually going up in smoke just in the 43rd largest city in the land. With a nationwide stock of 105.5 million houses⁸—*not counting* office buildings, schools, and stores—American residences alone may be incinerating on the order of a third of a trillion personal dollars every year just for heating and cooling.⁹

So for me, the prospect of maintaining an interior temperature comfy enough not to require a hot water bottle or fleece pullover indoors, for a heating bill of maybe just \$30 per month in a Midwest winter, immediately triggered the engineering question: *how?*

Historically, energy costs have not much influenced home design. My 1914 house was built with 2-by-4 studs on 16-inch centers that separated the exterior wooden wall from the interior plaster wall with an air space. That's right, there was zero wall insulation, even for a house built in Ohio. That was pretty typical nationwide for U.S. home construction until the 1970s oil embargo of the Organization of Petroleum Exporting Countries (OPEC), which raised awareness of the energy use of automobiles and homes. In the late 1970s, home construction entered a short-lived energy-efficiency revolution. Some pioneering architects, civil engineers, and home builders experimented with home designs, construction techniques, and the positioning of windows and roofs to maximize solar energy for heating water and the home's interior. Some also experimented with super-insulation in walls built with 2-by-6 or even wider studs. But some design experiments did not work as well as anticipated;



some passive solar houses got uncomfortably hot or cold; photovoltaic solar panels were limited in their efficiency; and calculating an effective design for each local climate (a roll-up of latitude, altitude, wind direction, angle of home site, and other factors) was often complex.

Despite some truly interesting scientific and engineering research and prototypes, the spottiness of success, a bumper crop of architectural designs not pleasing or affordable to many Americans, and a general decline in oil prices in the 1990s together led many families and home builders to return to what felt tried and true: i.e., home-building standards dating back to the 19th century. Moreover, with the heady dot-com technology boom of the '90s, the trend in affluent newer suburbs was to build homes far larger than the U.S. average—those of 3,000 square feet or larger. Today, most builders still design homes purely to meet the layout preferences and aesthetics of the client, and size the HVAC system as needed for the resultant home design. With a few notable exceptions, there is little thought of letting energy efficiency influence, much less drive, the home design.

Meanwhile in Europe, where fossil-fuel prices have always been nearly double those in the U.S., engineering designs of passive houses were first devised in 1988 by Bo Adamson of the University of Lund in Sweden and Wolfgang Feist, a German physicist and architect with an interest in housing, energy, and the environment. In 1991 Feist founded the Passivhaus Institut in Darmstadt, which built the first prototype passive house, instrumented it, and began measuring its energy consumption through the seasons year after year. Its proven performance has since spurred the building of thousands of passive houses, apartment buildings, and schools across Europe. Most innovations for passive houses (and other low-energy houses) have since come from construction companies, national energy programs, and housing companies rather than from the scientific or engineering communities.¹⁰

First, lose no energy

According to the Passivhaus Institut standard now adopted for central Europe, an energy-efficient house can be certified as a passive house if it meets three targets:

1. *The house must be designed to have an annual demand of no more than 15 kilowatt-hours per square meter (4,746 BTU per square foot) per year in heating or cooling energy, or a peak demand of 10 watts per square meter;*
2. *The total primary energy consumption for heating, hot water, and electricity must not be more than 120*

kWh/m² per year (38 kBTU/ft² per year); and

3. *The building must leak air in quantities no greater than 0.6 times the house volume per hour at a pressure of 50 pascals (newtons per square meter, or about a pound per square foot) as tested by a blower door.*

“Three main things lie behind the theory of a passive house,” explained **Mark A. Hoberecht**, *Ohio Epsilon '78*, head of fuel-cell development at NASA Glenn Research Center, founder of HarvestBuild Associates Inc., and a certified passive-house consultant who advised the Cleveland Museum of Natural History on the design of the demonstration PNC SmartHome. “They are super-insulation, air-tight construction, and ultrahigh-performance windows. If you use all three in combination to virtually eliminate heat losses, passive energy—from sunshine, electrical lights and appliances, and even body heat from the occupants—is enough to keep the temperature of a passive house well above about 50°F in Cleveland’s climate, without any additional added energy.”

Super-insulation

Insulation is rated by R-value, meaning thermal resistance or resistance to heat flow. The R-value of insulation varies with the type of material, its density, and its thickness—the higher the R-value, the greater its insulating effectiveness. The U.S. Department of Energy (DOE) recommends, depending on the climatic zone (U.S. climatic zones range from tropical southern Florida and Hawaii to arctic Alaska), that wall insulation in new wood-frame houses should be R-13 to R-21, with additional insulation wrapped around the house to add another R-5 or R-6, for a total wall insulation of R-19 to R-27. The DOE further recommends that floor insulation be R-13 to R-25 and ceiling (attic) insulation be R-39 to R-60.¹¹ The DOE numbers are a step in the right direction; however, even in cool northeast Ohio its recommendations seem to be more honored in the breach than in the observance. Last September (2010), several supposedly *green* builders I consulted tried to discourage me from considering 2-by-6 super-insulated walls for R-21, saying that 2-by-6 construction was “much more expensive” than standard 2-by-4 construction.¹²

The Passivhaus standard is far more rigorous than the DOE recommendations. The PNC SmartHome Cleveland demonstration house, designed for the climate of northeast Ohio, has 12-inch walls insulated to R-50. To attain such wall thickness, some passive houses use wider studs normally reserved for floor joists. Furthermore, the PNC SmartHome’s ceiling (attic) insulation is a phenomenal R-70. Even the foundation is insulated to R-40 to prevent heat from being drawn out of the house into the cooler ground. “We’re using insulated concrete forms for the basement wall that has a total of eight inches of expanded polystyrene foam insulation,” said Hoberecht. “We’re also using eight inches of expanded polystyrene foam insulation underneath the basement floor slab.”

No thermal bridges

But wait, there’s more. Insulation *per se* is only one factor in stopping heat loss. “You absolutely must eliminate

Image source: Krapmeier & Drössler 2001, www.harvestbuild.com/passive.html. See CEPHEUS: Living Comfort without Heating, by Helmut Krapmeier and Eckart Drössler, Springer, 2001

thermal bridges,” Hoberecht declared. “You must make sure that no wood member goes all the way through an external wall—otherwise the wood stud conducts heat around the insulation and outdoors.” Thermal bridging is likely one reason that blowing insulation between the existing studs of my house resulted in only a 25-percent reduction in my heating bill. To avoid thermal bridging, passive houses commonly have double-stud walls—two parallel walls separated by a gap of several inches that is also filled with insulation.

Airtight construction

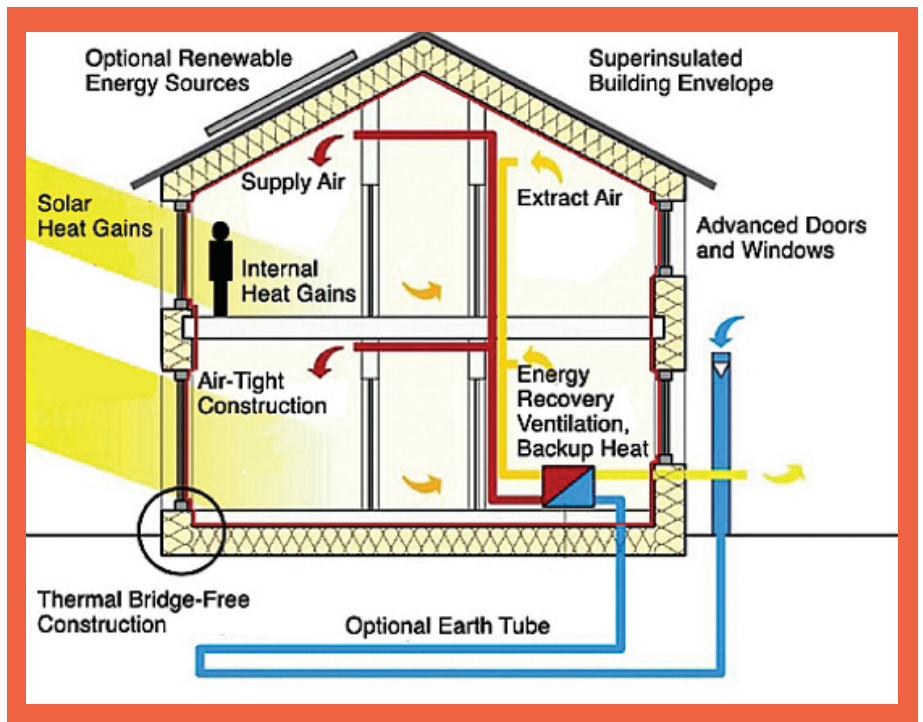
As anyone living in a charming older house knows all too well, drafty construction brings a double-whammy in winter: it lets in cold air (which you must now pay to heat) and lets out warm air (which you’ve already paid to heat). Drafts are worst around places where windows and doors are set into walls, electrical sockets and window-unit air conditioners are mounted to outside walls, and vents in the kitchen, bathrooms, and laundry room exist to the outdoors.

In a passive house, all plywood joints are sealed with building tape. Architect Katrin Klingenberg, executive director of the Passive House Institute US (PHIUS) in Urbana, IL, founded in 2007, originally went so far as to eliminate all electrical sockets on exterior walls, but has since figured out how to include the exterior electrical sockets and still maintain an effective air barrier. “Yes, the initial cost is 10 to 20 percent more than standard high-quality construction for the super-insulation, the double-stud construction, and the extra attention to detail required for air-tight construction,” Hoberecht acknowledged. “But the energy bill of a passive house is so low that the payback period should be under 10 years, depending on the cost of fossil fuels.”

Insulated windows and doors

In Europe, the outer doors themselves are well insulated and may be more than three inches thick. Furthermore, “the seals are tremendous,” Hoberecht said. “It’s like opening a door on a commercial freezer.”

The windows for passive houses are triple-pane, yielding R-values as high as R-11 for the glass—better than the walls of many existing homes. “Another key for these windows is warm-edge spacers,” Hoberecht continued, referring to the edging structures that separate and hold the parallel panes of glass apart and seal in argon gas between them. “The frames are also very well-insulated, some with cork in the middle to eliminate thermal bridges.” As a result, the window frames can be as high as R-8 or R-9. For comparison, a typical double-pane window (perhaps like the ones installed 10 years ago in my house) is probably R-4 or R-5 for the glass and only R-2 or R-3 for the frame.



Moreover, the new triple-pane window glass has thin-film coatings to maximize solar heat gain (admit maximal sunlight) in winter; in summer, awnings above the windows can shade them from the much higher-altitude sun. And yes, the windows can be opened when outdoor temperatures are pleasant; the European tilt-turn design allows the window either to be cranked open like a casement window or tilted inward at the top (to avoid letting rain blow inside).¹³

“Adequate windows are not yet widely manufactured in the United States,” said Hoberecht, “so for the PNC SmartHome Cleveland we chose to order them from Germany to highlight their outstanding performance.” They cost about \$100 per square foot, or about \$1,000 for a window the size of a standard sash window. The windows and doors in the 3,000-square-foot PNC SmartHome alone cost \$50,000, probably double that of high-quality conventional windows and doors. However, “costs should decline as U.S. manufacturers climb on board and we don’t have to pay for exchange rates or shipping from Europe,” Hoberecht predicted. Moreover, as with any technology, costs should decline as demand rises, and payback time will depend on the future cost of fossil fuels.

Excellent ventilation

Despite the airtight construction, passive homes are designed to be thoroughly ventilated by outdoor air—just in a controlled way that allows heat energy to be reclaimed, not by random drafts. The air is exchanged by an energy recovery ventilator, which is designed to operate at low speed 24/7 year-round to exchange 40 percent of the air volume of the house each hour—enough to ensure no buildup of moisture or volatile organic compounds that may be outgassed by carpets, furniture, or plastics. With some units, the air may be filtered to HEPA standards, removing pollens, dusts, bacteria, and mold spores.

Passive houses generally have no separate kitchen or bath fans—to minimize penetrations through the building envelope and to guarantee heat exchange with any exhausted air. Stale air from the kitchen/baths/laundry is



exhausted out, and fresh filtered air is supplied to the bedrooms and living areas. According to the Passive House Institute US, “studies have shown most people do not ventilate their home as they should. ...Regular home owners should open their windows every two hours for two minutes to ventilate properly (including night hours).”¹⁴ Thus, the

continuous ventilation in a passive house can result in indoor air quality higher than that in a conventional home.

The exhaust air exchanges its heat with the incoming air on its way out. In the winter, warm exhaust air is run by the cold intake air in the energy recovery ventilator to reclaim as much as 95 percent of the heat energy. “Exhaust air at 70°F preheats incoming air to 67°F,” explained Hoberecht, “reducing the amount of additional energy needed to boost it to 70°F. Range hoods are typically of the recirculating type using charcoal filters.”

In dryer central Europe, the air may be run through earth-warming tubes to further pre-warm it (or pre-cool it in summer) to ground temperature near 50°F. In a humid climate like Cleveland’s, “a better approach is to use a loop of PEX tubing filled with a glycol solution that is placed around the foundation of the house or under the slab,” said Hoberecht. “Using a very small pump, this solution is pumped through a heat exchanger, effectively pre-heating the incoming air in the winter and pre-cooling it in the summer.”

Heating with a hair dryer

Although a passive house has no conventional furnace, it may have a small supplemental heat source for colder climates. Most U.S. passive houses use a ductless “mini-split”—a wall-mounted unit with a condenser outdoors and an air handler inside. “These new ductless mini-split units are far more efficient than the old-style heat pumps,” Hoberecht said. “Even with external temperatures below zero [Fahrenheit], they can still produce heat. In the summer, they cool and dehumidify the air and are nearly twice as efficient as traditional air conditioners. And you barely hear them.”

The heating standard of 15kWh/m²/yr is a total requirement for the whole year—more in winter, less in spring and fall, and nothing in summer. The peak heating requirement of 10 W/m² on the coldest winter day “translates into about 1 W/ft², so a 1,500-ft² house would need the equivalent of a single handheld hair dryer,” Hoberecht said. “A larger house would need a second one.”

The bottom line

Some 25,000 European households are one thing. How do American families respond to the idea of passive houses?

Since 2003, Klingenberg and co-director Mike Kernagis have been offering education, consulting, and research across the U.S. and Canada, first as E-Co Lab in Urbana and since 2007 through PHIUS. “We have made great progress to transfer the European experience back to the North American climate zones, identifying and encouraging an impressively growing market,” Klingenberg said. “We have trained over 400 certified consultants and have over 100 passive-house units in all U.S. climate zones in our certification program.” Along with a third author, Mary James, Klingenberg and Kernagis have written the book *Homes for a Changing Climate: Passive Houses in the U.S.*¹⁵

And individual builders are getting the word. For example, Andrew R. Kline and Alex Melamed co-founded Green Generation Building in 2009 in Yellow Springs, OH. With mechanical engineering professor and PHIUS-certified passive house consultant Eric Lang, Kline and Melamed designed and built an 1,800-square-foot passive house in Yellow Springs. They had no client; they raised the financing and built the house on speculation as a learning exercise as well as a demonstration of their craftsmanship. Before the house was even completed last November (2010), Green Generation had a buyer—even though the actual cost of the house was significantly higher than a typical home price in the town.

This past February (2011), the house proved the soundness of super-insulation and air-tight construction in retaining heat. “A severe ice storm knocked out power in southwest Ohio for more than a day and plunged temperatures into single digits,” Kline recounted. “Even though it knocked out lighting, ventilation, and supplemental heating in the passive house, after 24 hours the interior temperature was still above 62°F.” For comparison, when my furnace died during an 18°F cold snap three years ago, in 12 hours the interior temperature of my 1914 then-uninsulated house plummeted to 27°F. It was literally warmer inside my refrigerator (45°F) than it was in my kitchen.

I’m actively ready to go passive.

References

1. Details about the PNC SmartHome Cleveland are at www.cmmh.org/site/atthemuseum/onechibit/smarthome.aspx, including a video with the passive-house consultant and committee. In September 2011, the house will be moved to a permanent site a mile away and offered for sale. Engineering details and photographs of the Passive House in the Woods in Wisconsin are at www.passivehouseinthewoods.com/the-house/.
2. The Passivhaus Institut (Passive House Institute) in Darmstadt, Germany, has an English-language web page www.passiv.de/07_eng/index_e.html as well as a Wikipedia-style reference—the Passipedia (passipedia.passiv.de/passipedia_en/passipedia_a-z). Detailed pages of engineering specifications and data include measurements of the comfort of passive homes (www.passivhaustagung.de/passive_house_el/comfort_passive_house.htm and www.passivhaustagung.de/kran/first_passive_house_kranichstein_en.html). In North America, see the Passive House Institute U.S. www.passivehouse.us/passivehouse/phiushome.html and the Canadian Passive House Institute (www.passivehouse.ca/).
3. Although not all the passive houses in North America have been officially certified by the Passivhaus Institut, several have been featured in newspaper and magazine articles, including in *The New York Times*, *Fine Homebuilder*, *Ottawa Magazine*, *Dwell*



Photos pp. 20-21: Corey Gaffer (gafferphotography.com)

(magazine), (see links at www.passivehouse.us/passivehouse/articles.html). The Canadian Passive House Institute site has many construction photographs.

4. "What is a Passive House?" www.passiv.de/English/passiveh.htm.

5. Latest statistics from 2009 are summarized in the Residential Energy Consumption Survey, U.S. Energy Information Agency at www.eia.doe.gov/consumption/residential/.

6. EIA statistics are displayed in charts compiled by Architecture 2030 at http://architecture2030.org/the_problem/problem_energy.

7. McKinsey Global Institute, "Curbing Global Energy Demand Growth: The Energy Productivity Opportunity—Residential Sector," McKinsey & Co., May 2007, www.mckinsey.com/mgi/reports/pdfs/curbing_global_energy/mgi_curbing_global_energy_chapter_3.pdf.

8. According to the 2000 U.S. Census, there were 190,638 households in Cleveland (en.wikipedia.org/wiki/Cleveland) and 105.5 million households in the U.S. (Tavia Simmons and Martin O'Connell, "Married-Couple and Unmarried-Partner Households: 2000," Census 2000 Special Report CENSR-5, February 2003, www.census.gov/prod/2003pubs/censr-5.pdf).

9. The EIA estimates \$201 billion per year and includes allowance for warmer climatic zones. Energy Information Agency, "2005 Residential Energy Consumption Survey: Energy Consumption and Expenditures Tables," Table US1. Total Energy Consumption, Expenditures, and Intensities, 2005, Part 1: Housing Unit Characteristics and Energy Usage Indicators, www.eia.doe.gov/emeu/recs/recs2005/c&e/summary/pdf/tables1part1.pdf.

10. In "Low energy buildings—scientific trends and developments," Patrik Rohdin, Wiktor Glad, and Jenny Palm surveyed and categorized the past two decades of literature; the article appears as Chapter 6 of *Energy Efficiency*, edited by Jenny Palm, InTech, August 2010 (www.intechopen.com/articles/show/title/low-energy-buildings-scientific-trends-and-developments).

11. U.S. Department of Energy, "Insulation Fact Sheet," DOE/CE-0180 2008, www.ornl.gov/sci/roofs+walls/insulation/ins_05.html.

12. I didn't just happen to interview the four wrong guys. According to Passivhaus Institut founder Wolfgang Feist, "...[M]ost builders I have talked with in North America still think that increasing insulation is an expensive thing... I'm surprised, because [over the lifetime of home-ownership] insulation is the cheapest thing you

can do." Quoted in the article "An Interview With Wolfgang Feist," *Energy Design Update* 28 (1): 6, January 2008, www.passivehouse.us/passivehouse/articles_files/edu%20jan%202008.pdf.

13. For more about window design, see Frans Freundorfer, Berthold Kaufmann, and Markus John, "Passive House windows completely redesigned," Working Group V: Research and development news, presented at the 13th International Passive House Conference, April 2009.

14. Frequently Asked Questions, Passive House Institute US www.passivehouse.us/passivehouse/faq.html. This page also addresses concerns about radon gas.

15. Katrin Klingenberg, Mike Kernagis, and Mary James, *Homes for a Changing Climate: Passive Houses in the U.S.*, www.passivehouse.us/passivehouse/passivehousebook.html. Mary James has also written *Recreating the American Home: the Passive House Approach*.

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Pump prices on March 28, 2011, in Furnace Creek, CA. Photo: T.E. Bell

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IEEE's millennium book *Engineering Tomorrow: Today's Technology Experts Envision the Twenty-First Century* (IEEE Press 2000); she has also written nine other books and nearly 500 articles for adults and middle-school students.