Zero Energy Homes—
The Potential of Large-Scale Implementation

Thomas Kenney, PE
Associate Member ASHRAE

Joseph Wiehagen

ABSTRACT

This paper presents findings from a study that estimates the potential impact of zero energy home (ZEH) technologies on energy consumption through the year 2050 in the United States. The following analytical techniques were used to make estimates: (1) assessment of homeowner perceptions of the concept and willingness to purchase a ZEH through focus group and Internet-based market research, (2) computer optimization techniques to calculate the optimal combination of today's state-of-the-art energy-efficiency and solar technologies to achieve ZEH, (3) market diffusion models, (4) solar technology price projections, and (5) units added and removed from the housing stock.

The study suggests that research and development support for ZEH in conjunction with state and federal tax incentives can accelerate and significantly improve the energy performance of the residential sector in the United States. For the most optimistic scenario considered, by 2030 energy consumption growth reverses and declines indefinitely due to retirement of older homes and zero energy homes added to the housing stock. With this declining energy consumption trend, the study suggests residential energy consumption in 2050 to be equivalent to 2019 energy consumption levels.

INTRODUCTION

This paper is based on a study conducted by the NAHB Research Center in conjunction with the National Renewable Energy Laboratory (NREL) and sponsored by the U.S. Department of Energy (U.S. DOE) (NAHB Research Center 2006a). The study presents a far-reaching outlook into the possibilities for zero energy home (ZEH) technologies in the new home market and their potential impact on energy consumption through 2050 in the United States. Three scenarios are explored to assess impact of the adoption of ZEHs into the single-family home market and the effect of each scenario on residential energy consumption through 2050. A reference case, where household energy use remains relatively constant from today's usage levels, serves as a basis for comparing the potential reduction in energy consumption attributable to technical support programs, federal tax credits, and declining cost for solar equipment.

Economic and energy analytical tools were used to estimate the impact of ZEH—they include (1) removal of old houses and addition of new houses to the housing stock, (2) population and household formation, (3) technology adoption theory (Kobel et al. 2003) to establish market penetration rates of early adopters to steady-state saturation levels, (4) computer optimization techniques (Anderson et al. 2006) to calculate the least cost combination of today's state-of-the-art energy-efficiency and solar technologies to achieve ZEH, and (5) market research data derived from homeowners' opinions on willingness to purchase a ZEH.

The analysis is based on a break-even cash flow where the cost to achieve a ZEH is offset by a reduction in operating expenses. In other words, owning and operating costs (principle, interest, taxes, insurance, and utility bill) for a ZEH were evaluated and compared to an equivalent non-ZEH based on a 30-year fixed mortgage with local utility rates and local solar resources. When the economic test is satisfied,

Thomas Kenney *is vice president of engineering and research and* ***Joseph Wiehagen*** *is senior engineer at the NAHB Research Center, Upper Marlboro, Maryland.*

ZEHs were counted toward the housing stock. The quantity of ZEHs added each year to the housing stock was determined by apportioning a fraction of the housing starts in accordance with the diffusion rate established by the Bass model (Kobel et al. 2003). This evaluation was conducted annually and for each of four regions—the Midwest, Northeast, South, and West.

A few caveats should be mentioned to place this study into context. Favorable economic conditions are a perquisite to achieving the impacts estimated by this study. ZEHs are connected to the electric utility grid to allow shuttling excess solar-generated power onto the utility grid and to provide power during periods of inadequate solar energy. Grid-connected solar power generation also benefits the utility by reducing demand for electric power during system peaks; for the homeowner, the solar resource offsets power purchased from the utility. While there are a variety of sell-back tariffs for distributed energy resources offered by utilities, they are not uniformly structured or available everywhere across the country. Conceptual studies (Wiehagen et al. 2002; Norton and Christensen 2006) and demonstration projects (NAHB Research Center 2006b) have shown that net zero energy use is technically achievable; however, cost and institutional barriers limit the widespread application of ZEH technology. The simplest and most favorable utility tariff from the homeowner's perspective is utility-grid-connected solar electric combined with an annual reconciliation—often referred to as *net metering*. Builders also face challenges (Farhar et al. 2004) with ZEH technology as they position their ZEH product offerings in the local market against lower cost non-ZEH options. Merchandizing the ZEH concept and consumer understanding of the concept are challenges and barriers to market acceptance as well. Technical support for the builder and homeowner for the solar technologies and coordination with utilities are essential to further reduce administrative burdens currently experienced by early adopters of ZEH technology.

DISCUSSION

Zero (Net) Energy Home Definition

The U.S. DOE Building Technologies Program defines a *zero-net energy building* as "a residential building with greatly reduced needs for energy through efficiency gains, with the balance of energy needs supplied by renewable sources." A zero-net energy home combines state-of-the-art, highly energy-efficient designs and equipment with on-site renewable energy generation (which typically includes a solar hot water production system and a rooftop photovoltaic [PV] system) to return as much energy to the utility as it takes on an annual basis. The term *net* has been dropped in this paper to be consistent with the terminology used in the study; however, the use of the full name *zero-net energy homes* has become commonly used by researchers since it more accurately describes the concept.

Efficiency Features and Levels

A ZEH is designed to be responsive to the climate and features of (1) high levels of insulation and air sealing windows with energy properties selected for the climate, (2) careful design and installation of HVAC and plumbing systems to minimize energy loss, (3) ducts in conditioned space, (4) high-efficiency HVAC equipment sized according to industry standards, and (5) high-efficiency lights and appliances. A ZEH can use conventional construction methods such as wood framing or innovative systems such as structural insulated panels.

In order to achieve ZEH, a sufficient level of whole-house energy efficiency is required to accommodate available photovoltaic generation capacity. Analysis of cost optimization (Anderson et al. 2006) to achieve ZEH indicates energy reductions in the range of 50% to 60% and PV capacities of 4.8 to 7.6 kW. The reductions and capacities will vary by region in accordance with the cost of power, climate, and solar resource.

On-Site Electrical Energy Production

The components of a PV system that produces electricity from solar energy in a ZEH are depicted in Figure 1. The direct current (DC) electrical output from a PV system is converted to alternating current (AC) power by an inverter. The AC power can be used in the home or fed back into the utility's power grid. In the simplest system with net metering, power sent into the utility grid causes the home's electric meter to operate in reverse. In a ZEH, the power taken from the utility is designed to be equal to the power sent back by the PV system annually.

This study does not evaluate self-sufficient PV systems that include a battery back-up power supply and are independent from the utility grid. However, optional upgrades to ZEH are possible that would allow independence from the utility grid in the event of a power outage.

On-Site Thermal Energy Production

Solar energy can also be harnessed for space and water heating. The most common system is a solar domestic water heater. Components of a typical solar water heating system include a rooftop solar collector, depicted in Figure 2, and a hot-water storage tank. Water that runs through the roof-mounted solar collector is heated by the sun and stored in a hot-water storage tank. Back-up electric or gas water heating is usually provided for periods when hot-water demand exceeds system output, such as during long periods of cloudy weather.

Energy Consumption Trends

Zero energy homes could be an important element for reducing residential energy consumption by reversing the trend of increased energy use (see Figure 3). This trend has

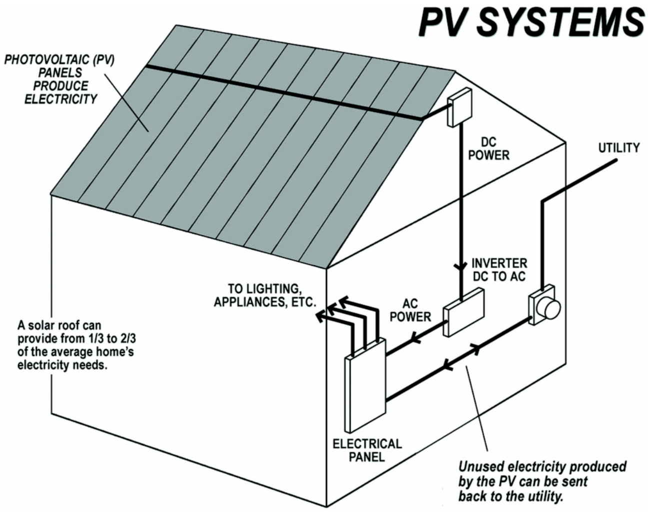

Figure 1 *Diagram of a grid-connected photovoltaic (PV) system.*

Figure 2 *Neighborhood installations of solar thermal and electric collectors.*

continued, despite advances in energy efficiency—as noted by the declining energy intensity (Btu/ft^2)—which is attributable to improvements to components of a house (e.g., windows, insulation, equipment, appliances, and lighting); however, per-household energy use is steadily increasing, as noted by the rising bars.

Homeowner Attitudes Toward ZEH

Homeowners' interest in the ZEH concept and willingness to purchase those features was explored with focus group discovery sessions and quantified through a survey of over 1700 consumers. Focus groups provided insight into consumer attitudes about the ZEH concept as well as refined questions for a national Internet questionnaire. The focus group gathered qualitative information on issues important to potential home buyers and their perspectives on the value of features and benefits inherent in highly energy-efficient homes. The label or term *zero energy home* was not used in the survey since the terminology was not universally understood. Rather, features and benefits were used to describe a "concept house." An Internet-based questionnaire was conducted to gather quantitative data about potential home buyers' willingness to buy a concept house. Included in the concept house description was the idea of annual zero energy, where there would be little or no utility bills for the life of the home and that the concept house is more comfortable, has better indoor air quality, is better for the environment, and may have a higher resale value than a conventional home.

The concept house received an 82% favorable rating (NAHB Research Center 2006a, Appendix B) to the question: "Would you buy a home with these new energy technologies if the savings on your energy bill offset the increase in your mortgage?" Also, more than 78% indicated that they were willing to pay more in response to this question: "Taking into consideration that utility prices fluctuate over time, how much more monthly would you be willing to pay to avoid fluctuations in your energy costs?" While this survey is a hypothetical situation and was not based on an actual purchase, the overall impressions derived from the respondents are: (1) that the concept of ZEH is an attractive one, and (2) a break-even cash flow for mortgage and utility bill is a viable concept.

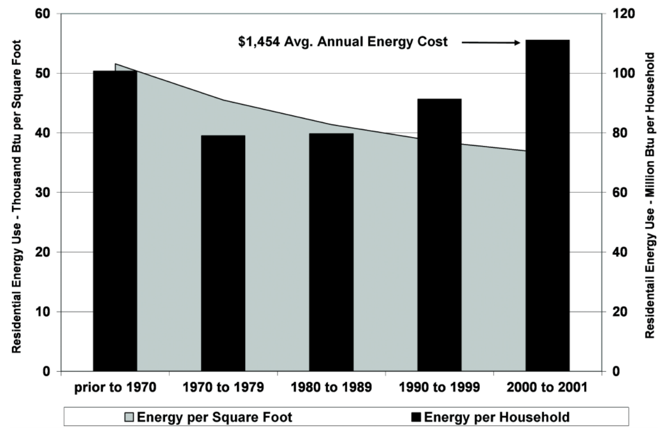

Figure 3 *Energy use density of housing (Source: Energy Information Administration).*

Optimization to Determine Cost-Effectiveness of Zero Energy Homes

Energy use optimizations were run for a typical US house in representative cities from the four census regions to determine the year in which ZEH construction becomes cost-effective for new home buyers in each region. It was assumed that home buyers do not adopt the portfolio of ZEH technologies until the additional cost of the ZEH is completely offset by energy savings. Four cities were chosen to represent each region in the analysis.

To calculate cost-effectiveness in each region, inputs to the model included (1) regional energy costs, (2) fuel usage, (3) cost of efficiency options including solar hot-water systems, and (4) projected cost of residential PV systems ($/kilowatt-AC) through the year 2050, as shown in Figure 4 (SEIA 2004).

Other key assumptions include: (1) a PV system life of 30 years, (2) 30-year mortgage term at 7% interest, (3) a 5% discount rate, (4) natural gas cost of $1/therm, and (5) a marginal income tax rate of 28%. The cost of electricity was $0.084/kWh for the Western region, $0.077/kWh for the South, $0.075/kWh for the Midwest, and $0.102/kWh for the Northeast.

Since ZEH technology can realistically return only electricity to the utility grid (homes might use both electricity and fossil fuels), it was necessary to create a consistent accounting system for crediting the production of on-site electricity against consumption of other fuels (in this case, natural gas). For this purpose, 1 Btu of on-site electricity is set equal to 3 Btu of natural gas at a central electrical power generation facility. This accounting system is the basis for renewable energy production to affect both gas and electricity use.

Using the optimization software (Christensen et al. 2004), thousands of combinations of energy-efficiency measures were examined along with solar water heating and on-site PV power generation for a typical home in each of four cities representing the four US census regions. The program finds the combination of efficiency features that maximizes energy efficiency at the least cost to a point where the marginal cost of improving efficiency is greater than the marginal cost of adding PV capacity. At that point, the program calculates the amount of PV needed to supply the rest of the home's power.

Knowing the optimal efficiency package and the PV capacity required to achieve ZEH, the required cost of the PV system is then iteratively solved. Using the PV cost targets from Figure 4, the year in which PV systems reach the required cost is the year in which market penetration begins. The effect of PV tax credits on the year of market penetration was also examined, since tax credits lower the effective cost of solar technologies and penetration can begin sooner.

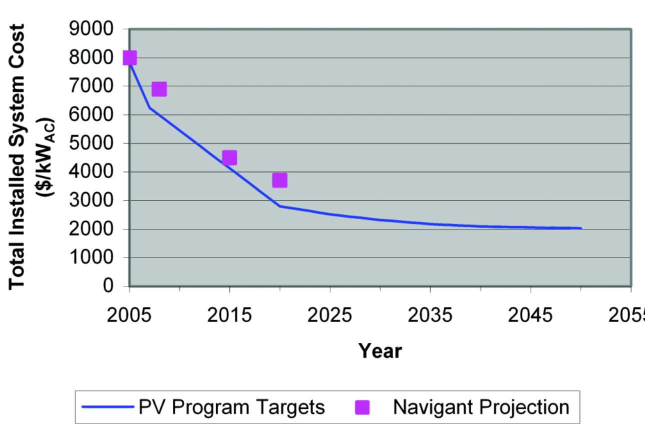

Figure 4 *DOE program and independent estimates for PV system costs.*

Market Adoption of Zero Energy Homes

Starting with the date at which ZEH becomes cost-effective for each of the four locations (determined by the optimization analysis), a diffusion curve was applied to determine the rate of market adoption of ZEH.

Diffusion curves for ZEH technology in each region were based on the Bass Model for diffusion of innovation—a standard market research model for estimating the rate of adoption of new technologies. The model, which is presented conceptually in Figure 5, produces a classic S-shape curve that reflects a slow initial rate of adoption by early adopters—a curve that continues to get steeper as the technology becomes more widely accepted—and a subsequent flattening as the technology matures and approaches market saturation.

It is important to note that this paper only addresses the market adoption of homes that have all their energy needs provided by solar electric and solar thermal systems—i.e., zero energy homes. The estimates in this paper do not include homes that only have a portion of their energy needs met by solar systems—even if that portion approaches 99%. It is reasonable to assume that as the US residential construction market adopts ZEHs, more homes will be built with energy-efficient and solar technologies. However, any energy savings or carbon displacement attributed to these advanced, but non-zero energy, homes are not included in the analysis and results of this paper.

Extrapolation of Market Adoption of Zero Energy Homes to Energy Savings in Single-Family Home Stock

The overall impact of ZEH technology on the energy consumption of single-family homes was extrapolated from estimated energy savings for each ZEH and the number of ZEHs in each region. The energy saved by a ZEH was calculated by comparing its energy use to the Building America benchmark home—a typical home built in the mid-1990s. Energy consumption for each region is presented in Table 1 and they represent source energy for all uses within a house (space heating and cooling, water heating, lights, appliances, and plug loads).

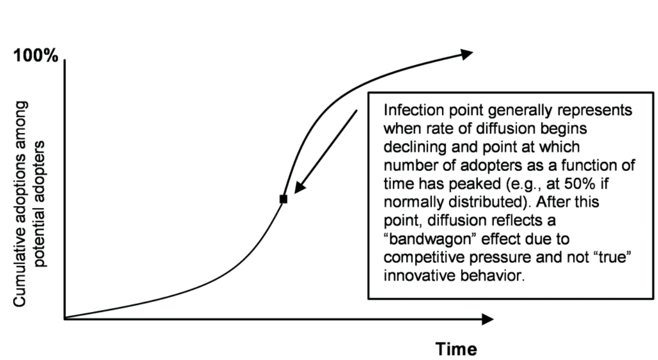

Figure 5 *Theoretical model for technology diffusion.*

Table 1. Per-Household Energy Use Assumptions for Four Census Regions (MBtu/year)

Midwest	Northeast	South	West
180	175	160	195

Next, the number of ZEHs built each year and cumulatively was calculated using projections of single-family housing through 2050 in Figure 6. Market penetration rates were then determined for each of the four regions under various scenarios. The overall energy savings attributed to the construction of ZEH was then calculated for each year by multiplying the number of ZEHs in each region by the energy savings per home. The resulting series of annual savings was combined into an estimate of cumulative annual energy savings accruing over time.

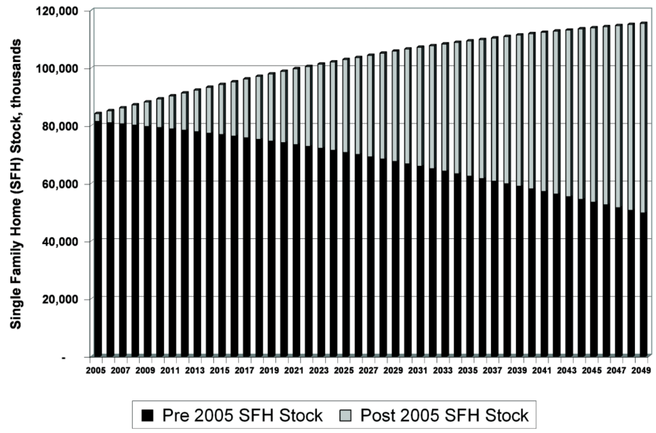

Figure 6 *Housing stock projection.*

Scenarios for Market Penetration

Three scenarios for market penetration and one reference case were evaluated:

- **Reference Case.** Assumes that household energy consumption remains relatively flat as projected by the Energy Information Administration (EIA) through 2025. The EIA reference case forecasts no significant market penetration of PV systems in single-family homes and also projects that any gains in household energy efficiency due to advanced technology are offset by increased energy uses in the average house.
- **Reference Case with PV.** Same assumptions as the reference case, but as future PV costs decrease, this scenario assumes PV systems are included in new homes based on a break-even cash flow analysis that compares the increased monthly mortgage cost to the decreased monthly utility bills. This scenario assumes that costs for PV systems will fall according to the DOE Solar Energy Technologies Program Multi-Year Technical Plan, as depicted in Figure 4. Like the reference case, this scenario also assumes that energy-efficiency technologies and solar water heating are incorporated into new homes. To account for shading, lot orientation, and other factors that are likely to make solar impractical on some sites, this scenario (as well as the subsequent two scenarios) assumes that the PV home market becomes saturated if and when it reaches 70% of new home starts. However, this saturation level probably cannot ever be practically reached under the reference case with PV scenario, since there is generally not enough south-facing roof space available on most conventional (standard efficiency) homes to generate all the energy that the typical new home requires.
- **Zero Energy Home (ZEH) Integration.** This scenario accounts for the beneficial interaction of bundling energy efficiency, solar water heating, and PV technologies together when new homes are constructed. All of these energy technologies are now included in new homes based on a break-even mortgage cost/utility bill cash flow analysis. All cost assumptions are the same as in the reference case with PV scenario, but this scenario differs from the reference case with PV scenario in that energy efficiency and solar water heating are now actively employed (based on monthly cash flow) to reduce the energy load of the new home before PV generation is applied. Therefore, the PV system size is considerably smaller than the PV system in the reference case with PV scenario and is typically able to fit on the available south-facing roof space of the zero energy home. Duration from market introduction to full market saturation is set at 30 years.
- **ZEH Integration + 30 Percent Tax Credit.** Combines the ZEH Integration scenario with a solar tax credit of 30%. This credit could be a combination of state and federal tax credits, with varying maximum amounts for each. For example, the Energy Policy Act of 2005 provides for a 30% tax credit for the purchase of solar water heating or PV equipment with the maximum credit for each of these systems set at $2000. In addition, the Energy Policy Act of 2005 also provides a $2000 tax credit for new homes that reduce energy consumption by 50%. Other assumptions in this scenario are the same as in the ZEH Integration scenario.

Combining the regional data for diffusion of ZEH into a national curve results in national diffusion curves for each scenario depicted in Figure 7.

Extrapolation of Market Adoption of Zero Energy Homes to Total Single-Family Housing Energy Savings

How soon ZEH achieves its market potential has a major influence on the magnitude of its impact on residential sector energy use. The energy savings associated with ZEH diffusion accumulates each year so that, by 2050, the annual energy

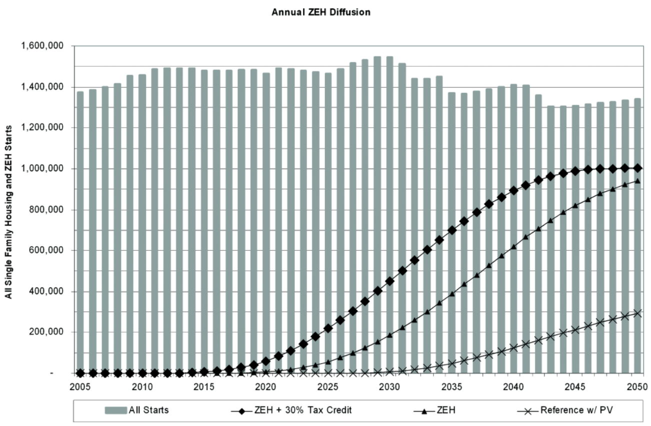

Figure 7 *National Diffusion Curves for ZEH Technology Under Various Scenarios*

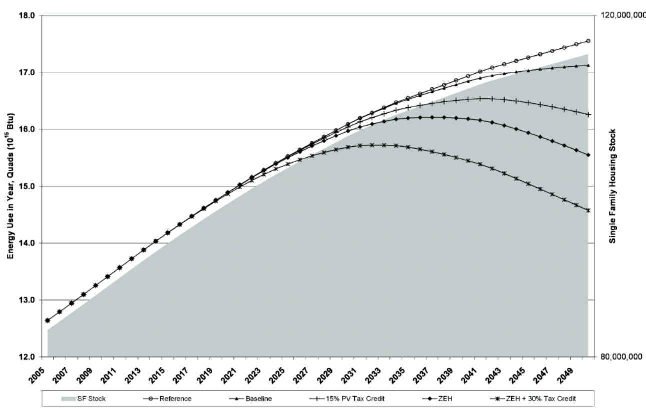

Figure 8 *Annual U.S. Housing Energy Consumption Estimates Under Various ZEH Scenarios*

consumption of single-family homes can be reduced as depicted in Figure 8. Reductions are:

- Two percent over the reference case scenario with the reference case with PV scenario,
- Eleven percent over the reference case scenario by implementing the ZEH integration scenario, and
- Seventeen percent over the reference case scenario with the combined ZEH integration + 30% tax credit scenarios.

CONCLUSIONS

- Near-term action can have a major influence on the ultimate impact of ZEH on the energy consumption of single-family homes—even though the relatively slow replacement of housing stock and historically slow diffusion of new technology in the building industry will mean decades before ZEH can reach its full market potential. Lack of near-term action will result in a lengthening of the time for ZEH to have an impact on the market.
- There is an important government role in ZEH development that will require resources and long-term commitment. By implementing the most aggressive scenario, ZEH integration + 30% tax credit, ZEH begins to penetrate the market between 35 years (Northeast) and 33 years (South) earlier than the reference case scenario, resulting in a final (market saturation) impact by 2050 of 17% less energy use among all single-family homes compared to the reference case scenario.
- ZEH accrues benefits over time. ZEH will not simply penetrate the new home market, but is projected to make up 17% of all single-family housing stock by 2050 under the ZEH Integration + 30% tax credit scenario. Under the reference case with PV scenario, ZEH is projected to make up only 2% of all single-family homes. Under the reference case scenario, ZEH market penetration is insignificant.
- ZEH can have a significant market penetration by 2050 given programs to support its development. The projected share of ZEH among new housing that starts in 2050 is 67% in the ZEH integration + 30% tax credit scenario, 63% in the ZEH integration scenario, 20% in the reference case with PV scenario, and insignificant in the reference case scenario. Under the most aggressive scenario, the total energy consumption of US single-family homes will level off by approximately 2030 and continue to decline in following years. With no action, the total energy consumption will continue to increase as new homes are added.

REFERENCES

Anderson, R., C. Christensen, and S. Horowitz. 2006. Analysis of residential system strategies targeting least-cost solutions leading to net zero energy homes. *ASHRAE Transactions* 112(2):330–41.

Christensen, C., G. Barker, and K. Tupper. 2004. Optimal building designs on the path to zero net energy. *Proceedings of SOLAR 2004, Portland, OR*.

Farhar, B., T. Coburn, and M. Murphy. 2004. Large-production home builder experience with zero energy homes. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, August 22–27.

NAHB Research Center. 2006a. *The Potential Impact of Zero Energy Homes.* http://www.toolbase.org/PDF/CaseStudies/ZEHPotentialImpact.pdf. NAHB Research Center, Upper Marlboro, MD.

NAHB Research Center 2006b. *Energy Use Simulations—Hot/Dry Climate building America Benchmark, 40% Prototype and Zero Energy Home-2 Analysis.* Report. NAHB Research Center, Upper Marlboro, MD.

Norton, P., and C. Christensen. 2006. A cold-climate case study for affordable zero energy homes. Solar 2006 Conference, Denver, CO, July 9–13.

Kobel, T., M. Papadakis, E. Hudson, and M. Cavell. 2003. *The Diffusion of Innovation in the Residential Building Industry.* http://www.toolbase.org/PDF/CaseStudies/Diffusion_Reporta.pdf. U.S. Department of Housing and Urban Development, Washington DC.

SEIA. 2004. *Our Solar Power Future: The U.S. Photovoltaic Industry Roadmap for through 2030 and Beyond*. Solar Energy Industries Association, Washington, DC. www.seia.org/roadmap.pdf.

Wiehagen, J., J. Leggett-Sikora, and C. Fennell. 2002. *A Net-Zero Fossil Fuel Use Home Case Study*. www.toolbase.org/PDF/CaseStudies/Net_ZeroFossilFuelUseHomeCS.pdf. NAHB Research Center, Upper Marlboro, MD.