FINAL REPORT

ZERO ENERGY HOME
ARMORY PARK DEL SOL
Tucson, Arizona

Task Ordering Agreement
KAAA-2-31494-00

Task Order 1

Submitted to
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401-3393

Prepared by
NAHB Research Center, Inc.
400 Prince George's Boulevard
Upper Marlboro, MD 20774-8731

June 30, 2004

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ACKNOWLEDGEMENTS

ZEH Builder
John Wesley Miller

The NAHB Research Center would like to thank the participants in this project, especially John Wesley Miller and his employees for construction of the Tucson net-Zero Energy home and the National Renewable Energy Laboratory for their financial support and technical guidance.

All of the project participants would like to recognize the invaluable contribution of Jose and Marciala Reyes who have taken the Tucson ZEH as their own and have made it truly a beautiful renewable home.

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INTRODUCTION

Following is the final report summarizing the design, construction, and monitoring of a Zero Energy Home (ZEH) at Armory Park del Sol in Tucson, Arizona. The project resulted in a 1,718-square-foot home, which combined renewable energy systems with energy efficiency features to achieve a net-zero annual energy consumption design. Although the home was designed for true net-zero energy use, actual energy production was about 70 percent of house use the first year when the home was open as a model for the first six months. Differences from projected to actual are attributed to a variety of factors discussed in the results. A full year of monitoring of the occupied home is expected to be completed in the fall of 2004.

RESULTS OF DESIGN WORK

Design Team and Manufacturer Partners

The group of individuals that contributed to the design process and donated products or services for the Zero Energy Home at Armory Park del Sol is listed in Table 1.

Table 1
Participants in the Design Process in Addition to NAHB Research Center Staff

NAME	COMPANY
JWM Staff and Subcontractors	
John Wesley Miller	JWM Companies
Luis Figueroa	JWM Companies
Mary L'Esperance	JWM Companies
Karen DeCook	DeCook Drafting Services
Renate Stepina	Beyond Design
Katharine Kent	The Solar Store
Kathy Regan and Mary	Sun Lighting
Gary Pruett	Arizona Glass
Bill Sisson	Sisson Plumbing
Principal	Preston Insulation
Randall Bergeron	Elmer Hayes Roofing
Architect	
Bill Devereaux & Sandy Fennell	Devereaux Architects
Manufacturers	
	Seisco
Scott Guerin	Aztec Air Conditioning
	SunEarth, Inc.
	U.S. GreenFiber
Pat O'Neal	Studor, Inc.
Brian Kincaid	Panasonic Ventilating Fans
Beatriz Oliveria	Lightolier
Ron O'Brien	Osram Sylvania
	Nora Lighting
	First Company
	Milgard Windows
Gary Agansky	LP Corporation
Butch Gaudette and Deb Jones	Whirlpool Corporation
Chris Peel	Carrier Corporation
	BP Solar
	Dankoff Solar
	Sioux Chief Manufacturing
	SMA America
	Kohler Plumbing
	SMA America
NREL Staff and Subcontractors	
Russell Hewett	NREL
Craig Christensen	NREL
Tim Merrigan	NREL
Paul Norton	NREL
Les Nelson	California SEIA
Other Partners	
	Tucson Electric Power

DESIGN PROCESS

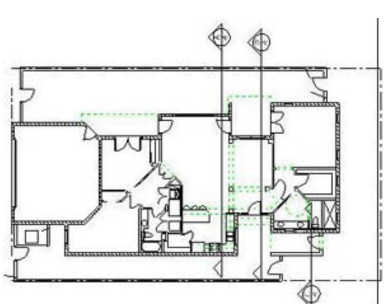
Starting with the goal of achieving a true net-zero energy use home, the design process began by developing a list of design requirements or

Original Rendering

intentions from the NAHB Research Center (Research Center) team and a list of design specifications and practices from the John Wesley Miller Company (JWM) team. The original list of design specifications is found in Attachment A. Existing home layouts were evaluated to find one that was large enough to be desirable to the general consumer but small enough to fit on most lots within the development. The current footprints either had limited roof area, too much glazing, improper location of mechanical equipment, or a combination of limiting factors that may have prevented the home design from reaching the net-zero energy goal. In addition, it was felt that a design that was exclusively the Zero Energy Home would be a potential marketing angle. Finally, if any significant changes were made to an existing house plan, the plan would have to be resubmitted to the city for plan approval. It soon became apparent that, in order to meet the project goals of marketability and net-zero energy use, there would be a benefit to starting from scratch in designing a new floor plan.

ZEH Elevations

Research Center funds were secured for the design development process and a nationally known architect, Devereaux and Associates, was hired to produce a conceptual layout. Working as a team with representatives from JWM, the Research Center, and Devereaux, a preliminary drawing for a Zero Energy Home was developed. The design was reviewed via teleconference with the team and the architect produced subsequent versions. After final approval by the builder and the engineering team, the plans went to a local draftsperson for creation of working drawings. Several changes were made to the layout at that point (e.g., addition of a bump-out to bring the design to over 1,700 square feet) and throughout the working drawing process (e.g., the redesign of the mechanical closet to accommodate the large solar hot water storage tank).



ZEH Floor Plan

In the meantime, the Research Center engineering team held a brainstorming session to identify potential technologies and systems suitable for the energy package for the Zero Energy Home. We researched numerous technologies and worked with the builder to select technologies and systems as appropriate. We worked with various manufacturers to design systems (e.g., the solar water and space heating system) and JWM subcontractors and suppliers to identify other systems (e.g., a fluorescent lighting package). During the process, we were careful to work with subcontractors and suppliers with which JWM has an existing relationship—which proved to be limiting in some of the systems we were able to finally select (e.g., some contractors had specific manufacturers that they worked with, while others had specific systems they were reluctant or unwilling to use).

Armory Park del Sol

A technical design review meeting was held at the building site to review energy and economic performance of the preliminary system design. Based on discussions with the group from this technical review, several changes were made and economic analyses were updated. Over the next few months, in conjunction with all the participants in the design team, a final design was selected based on practical considerations, builder preferences, and engineering and economic performance.

ZEH in Neighborhood

Description of Home

The Zero Energy Home at Armory Park del Sol is a 1,718-square-foot, single-story home. It was designed to fit on most lots within the Armory Park subdivision-an urban infill project located in a historic district in downtown Tucson. Each home in the subdivision meets the Tucson Sustainable Energy Standard (meaning the homes perform 50 percent better than the Model Energy Code) and features a solar water heater and a 1-kW photovoltaic system.

Exterior Insulation

Because of the desert climate, reducing the cooling load was a main focus of the Zero Energy Home design. Special attention was paid to reducing lighting and appliance loads, which are more than double the combined heating and cooling loads in the Zero Energy Home design.

Building Envelope

Blockwall Construction

The homes constructed in Armory Park del Sol (APdS) meet the Tucson Sustainable Energy Standard, meaning that they are designed to perform 50 percent better than the model energy code. Therefore, we had a significant challenge in improving the energy performance of the building shell beyond the builder's standard system. In addition, the builder has worked extensively with his mechanical subcontractors to integrate the mechanical and building shell systems. For these two reasons, we did not attempt to make wholesale changes to the building shell. However, we recognize that there are additional improvements that could have been made to the building shell for this zero energy home design.

Engineered Roof Joists

Roof Sheathing

Reflective Roof Coating

ZEH-HVAC Air Handler

Walls

The home was constructed with solid-filled masonry block—a building method that is perceived as quality construction by homebuyers in the area and provides thermal mass to help offset peak cooling and heating loads. Two inches of polyisocyanurate (R-14) was used on the exterior of the walls before standard 3-coat stucco was applied. The builder traditionally uses 1.5 inches of polyisocyanurate (R-10.5). However, two inches of foam was selected because it is readily available and added only about $0.10 per square foot of wall area (construction methods remain identical, only material cost is higher). The extra ½ inch of insulation was expected to save approximately 110 kWh per year in heating and cooling energy.

The builder's use of a highly massive wall and floor system not only improves energy performance, but also enhances the durability (and the perceived quality) of each home. Other wall systems were considered, but quickly dismissed because the builder's construction technique is well established.

Windows

Windows are low-E, argon-filled, and have a U-value of 0.32 and solar heat gain coefficient of 0.35. Windows were eliminated on the west side of the house and minimized on the south face. There is a large amount of east-facing glass, however, much of it is shaded by large overhangs.

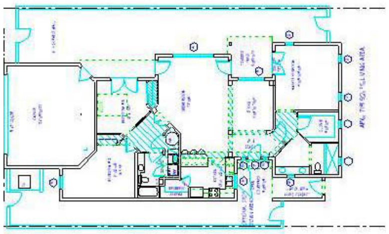
The amount of glass was a compromise between our engineering team's desire to minimize glazing area and the builder's marketing team's desire to maximize natural light.

Passive solar design was considered, but it was determined that, in this climate, the major goal was heat mitigation rather than heat gain in winter. Even during the heating season, there are many days that get rather warm, and it was determined that overheating would likely be a problem.

Ceiling/Attic

Insulation in the ceiling is two layers of fiberglass batt insulation for a total R-value of 41. Radiant barrier roof decking was placed over 14-inch ceiling I-joists, allowing an air space to separate the roof decking from the insulation to ensure proper performance of the radiant barrier.

Roofing



ZEH Duct Drops

A flat roof maximizes area for renewable energy systems while keeping the systems virtually hidden from view from the ground level. A three-ply, built-up roofing product with a reflective coating was used on the flat roof. Flat roofs are common in the region and work well with the architectural style of the neighborhood.

Mechanical Systems

A mechanical closet was designed into the Home to be centrally located and to keep critical equipment in the conditioned space. Ductwork and plumbing runs can be minimized with a central mechanical room, thereby reducing distribution losses. Bulkheads and dropped ceilings were designed in order to keep ductwork and hot water piping within conditioned space.

Duct in Conditioned Space

Duct lengths were minimized and air is delivered from the interior of each room (rather than the traditional method of delivering air near windows to enhance comfort). The combined use of massive walls, high performance windows, and balanced air supply and return eliminate the need for placing supply ducts near windows.

Cooling System

Outdoor Unit

A 2-speed, 3-ton 18-SEER air conditioning unit with variable speed blower was selected as the most energy-efficient compression cooling on the market. Several options were evaluated, such as evaporative cooling (which was described as uncomfortable for about two months of the year) and nighttime ventilation (we looked at a night cooling system, which was not yet commercially available). Even in Tucson, preliminary analysis showed that nighttime ventilation is mostly limited to early and late summer.

Plumbing

The bathrooms and hot water outlets were placed as central as possible to the hot water tank (served by solar and on-demand water heaters). Because of architectural space constraints, the master bath was located farther from the hot water tank than desired by our engineering team.

A copper manifold (parallel piping) system serves cross-linked polyethylene (PEX) tubing to deliver hot water to outlets around the home through overhead bulkheads in

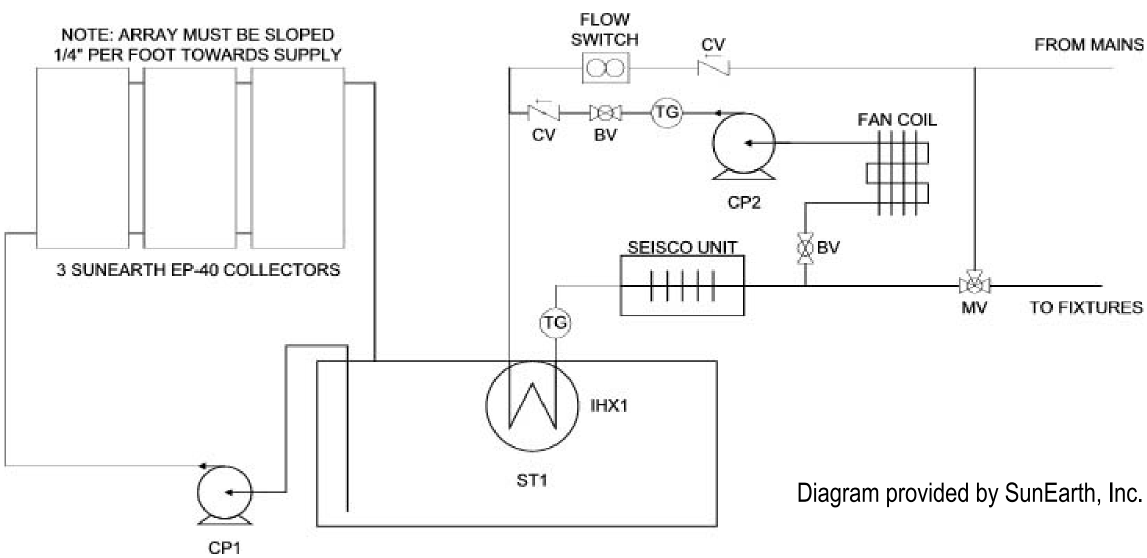
ZEH-Solar Thermal Collectors

ZEH-Hot Water Storage

conditioned space. The PEX tubing has a smaller diameter (⅜ inch) and a lower heat transfer coefficient than copper, which the builder currently uses. Compared with the builder's conventional method of running hot and cold water lines through a 10-inch deep slab, the PEX system in conditioned space should significantly reduce plumbing heat losses and decrease wait time for hot water at taps. Cold-water outlets will be served by conventional copper tubing run through the slab. To reduce roof penetrations, air admittance vents were selected to provide air for the DWV system. Reducing roof penetrations not only improves durability, but also limits complications when installing roof-mounted solar panels.

Solar Domestic Water and Space Heating System

A solar space and water heating system with tankless electric water heating backup provides domestic water and space heating. Four, 4-foot x 8-foot flat plate solar collectors in a drain-back system produce hot water for storage in a 220-gallon hot water tank. The semi-custom



Schematic of Solar Space and Water Heating System.

designed tank fit snugly into the mechanical closet within the home. An internal heat exchanger in the storage tank supplies hot water to a hydronic air handler and hot water for domestic use. A demand water heater boosts delivery temperature to 130°F for the heating system, if required. A limit switch shuts off flow to the solar collectors when the hot water storage tank temperature reaches 160°F. A check valve limits thermo-siphoning that may otherwise occur through the fan coil loop when air conditioning is running. For antiscald purposes, a mixing valve, set to 120°F, will temper water delivered for domestic use. A priority flow switch shuts off water delivery to the heating system when there is a

ZEH Fluorescent Bath Fixture

ZEH Recessed Fluorescent Fixture

ZEH Kitchen with ES Appliances

ZEH HE Washer/Dryer

demand for domestic hot water use above 1 gpm. The system was designed to produce an average of 72,000 Btu per day in winter for space and domestic water heating.

Radiant floor heating was considered. However, the cost of heating (over $5 per square foot) could not be justified with the low heating load of the climate. Logistically, in-floor heating would have been difficult because the builder uses an engineered slab in which heating pipes may not be imbedded. Therefore, more concrete would need to be added on top of the slab foundation. We also felt that the extensive thermal mass of the floor system (10 inches of concrete for the engineered slab plus the additional concrete) could have created control and comfort problems with radiant floor heating.

Lighting

The lighting system was entirely permanent fluorescent lighting fixtures with four-pin type fluorescent bulbs except for one dimmable incandescent chandelier in the dining area. Lamps were selected to provide the most natural lighting possible—having high color rendering index (CRI) greater than 82 and a color temperature close to that of natural light (about 2,800 K). We worked with manufacturers, an interior designer, and a local lighting supplier to find aesthetically pleasing permanent fluorescent fixtures. Tubular skylights were considered, but were not specified because of the desire to minimize heat gain and maximize clear roof space for solar panels.

Appliances

All major appliances were ENERGY STAR-rated washer, dryer, refrigerator, and dishwasher. However, the refrigerator model that was selected was not the lowest-energy consuming model that we had used in our original simulations.

PV Array

A 4.2-kW (dc) photovoltaic array was selected to annually meet 100 percent of the estimated electricity consumption.

ZEH-PV Modules

ZEH-PV Inverters

ENERGY AND ECONOMIC ANALYSES

Building energy simulation software was used to estimate energy consumption of the home under various design scenarios. Initially, several simulation software programs were used. After tuning and comparing the simulation models and using TRNSYS to support our confidence in the simulated results, Energy-10 was selected as the program with which to complete the energy analyses.

Building dimensions and typical Armory Park del Sol construction features, such as a 10-inch concrete slab floor, 10-foot ceiling height and interior ductwork, as well as a flat roof (on which to mount the PV and solar hot water systems) and the window sizes and locations from architectural drawings were entered into the base simulation model. The base model also included a 12 SEER heat pump, incandescent lighting and standard efficiency appliances, all typical of Armory Park del Sol homes. Assumptions used in the simulation models, including properties of construction materials, heating and cooling set points, infiltration levels, occupancy and internal load estimates can be found in Table 2.

Many energy efficiency measures were analyzed in additional simulation runs, including several levels of wall and ceiling insulation, two types of high performance windows, high efficiency lighting systems and appliances, and several levels of split-system heat pump and air conditioner efficiencies. Initially, energy measures were run individually to understand their energy savings and economic value compared to the base case (an Armory Park del Sol home built with typical construction materials and equipped with typical appliances, lighting fixtures, and heating and cooling systems).

Domestic hot water as well as solar thermal space heating analyses were completed by hand and by spreadsheet calculations, and any simulation model inputs for these systems were entered solely for the purposes of determining internal gains from the hot water storage tank and air handler fan usage associated with the solar heating system.

Appliance and other plug loads in the house were estimated using various sources of data, primarily from a Research Center study[1]. Data available through the ENERGY STAR program and for specific manufacturer's products were also used. A summary of energy use assumptions for appliances and plug loads can be found in Table 3. A summary of lighting loads for conventional and energy-efficient lighting packages, based on lighting designs provided by the lighting supply company, can be found in Table 4 and Table 5.

Many different energy measures were analyzed in initial simulations, including several levels of wall and ceiling insulation, two types of high-performance windows, high efficiency lighting systems and appliances, and several levels of split-system heat pump and air conditioner efficiencies. Initially, energy measures were run individually to understand their energy savings and economic value compared to the base case—an Armory Park del Sol home built with typical regional construction materials (e.g., double-pane aluminum windows, R-30 attic insulation, minimum efficiency heat pump) and equipped with typical appliances, lighting fixtures, and heating and cooling systems. The wall system for the base case in this analysis was kept as solid masonry with 1.5-inch rigid foam insulation for practical purposes (although few houses in the area are other than light frame). Table 6 is a summary of the life cycle cost of upgrading to individual energy features from the base case. A life cycle analysis of 30 years was chosen to match the mortgage term.

Based on the effect of individual energy features on energy performance and life cycle cost, combined with builder preferences on materials and systems, several energy features were chosen for further analysis including:

A. Two inches of polyisocyanurate wall insulation (in place of the typical 1½ inches);
B. R-41 ceiling insulation (in place of the typical R-38);
C. High efficiency air conditioner (18 SEER) and solar thermal space heating system (in place of the typical 12 SEER heat pump system);
D. ENERGY STAR-rated appliances (refrigerator, clothes washer, dryer, and dishwasher); and
E. Energy-efficient lighting (fluorescent fixtures in place of typical incandescent).

Using a factorial design, energy features were combined and simulated to determine the best energy package for least upfront and life cycle cost. Table 7 (simulation) and Table 8 (economic analysis) summarize these results.

A total of 32 simulations (including the base case with none of the measures) were completed for this analysis, and the estimated total annual energy use ranged from 12,377 kWh/yr for the base case to 6,831 kWh/yr[2] for the case including all five of the measures. The size and cost of the PV system required to meet the projected annual energy consumption was determined for each of the 32 options, and then the total cost of the energy efficiency measures and the required PV system for each option was calculated. Those options with the lowest total costs (all of which include the high-efficiency air conditioning and solar heating system, high efficiency appliances and high efficiency lighting)

[1] Wiehagen, Joe, *A Net-Zero Fossil Fuel Use Home Case Study*, NAHB Research Center, February 2002.
[2] Based on a heating set point of 68°F and cooling set point of 76°F.

were then considered for the final design. The combination of using the energy features A+C+D+E (from above list) was selected based on lowest life cycle cost and incremental upfront cost and excellent energy performance.

Economic Assumptions

For life cycle cost analysis, a term of 30 years at 7.5 percent interest rate was selected to reflect typical mortgage rates and terms. An inflation rate of 3 percent was chosen based on historical inflation data. Energy prices were taken from Tucson Electric Power rates: an average annual rate for the flat-rate plans was used. The flat rate was chosen (as opposed to a time-of-use rate) because homeowners wishing to use net metering need to be on the flat-rate plans.

The PV system was de-rated at 1 percent per year, based on manufacturers' typical warranties that the system will output 80 percent of the initial output after 20 years.

Incremental Cost

The anticipated incremental cost for the selected energy package (ACDE) was $38,344, (representing about 14 percent increase in sales price over a standard APdS home). The builder's price premium for the home was $46,100, representing a 14.7 percent increase in sales price.

The incremental cost does not include financial incentives for renewable energy systems, which would total between $6,000 and $8,400 depending on the type of rebate program selected from the utility. A state tax incentive of $1,000 is also not included because this is already exhausted with the base system in an APdS standard home.

Table 2
Building Energy Simulation Assumptions

Building Feature	Value	Notes
Floor Area	1718 sf	
Volume	17180 cf	Based on 10' ceiling height
Weather File	tucson.et1	
House Orientation	South	South-facing home front
Wall Construction	8" CMU, solid fill	1.5" (R_{eff} = 12.0) or 2" (R_{eff} = 15.3) polyiso foam insulation
Windows	U = 0.32, SHGC - 0.35	Milgard double pane, low-e; gross area = 278 sf
Roof	Flat, R-38 fiberglass batt	R-43 used for Option B models
Floor	10" concrete slab on grade	f Factor = 0.09, slab edge insulation to bottom
Thermal Mass	Block walls and concrete slab	
Infiltration	0.35 ach	
Heating/Cooling Setpoints	68° / 76°	No setbacks or setups
Duct Leakage	0% to outdoor	Ducts in conditioned space
Occupancy	3 people	Energy-10 default schedules for residential use
Internal Lighting (watt/sf)	0.29 (standard), 0.13 (high efficiency)	Values determined through separate lighting analysis
External Lighting (watt/sf)	0.12 (standard), 0.04 (high efficiency)	Values determined through separate lighting analysis
Appliances/Other	0.36 (standard), 0.30 (high efficiency)	Values determined through separate appliance/plug load analysis
Domestic Hot Water	0 watt/sf for passive system case, 0.66 watt/sf for active (storage) system case	No internal gains for solar/tankless hot water system, Energy-10 default values/schedules for storage tank system, used only to incorporate internal loads

Simulation Program: Energy-10 Version 1.3

Table 3
Annual Energy Use Estimates, Appliance and Plug Loads

Appliance or Specific Household Load	Standard Efficiency Appliances kWh/year	Energy Efficient Appliances kWh/year
Refrigerator (19 cubic feet, top freezer)	564.0	434.0
Dishwasher (excluding hot water production)	139.0	121.0
Clothes washer (excluding hot water production)	207.0	82.0
Dryer	1,142.0	800.0
Cooking		
Cook top and oven	580.0	580.0
Microwave	123.0	123.0
Television (assumes multiple units and cable box)	157.0	157.0
Vacuum Cleaner	31.0	31.0
Blender	7.3	7.3
Disposal	9.9	9.9
Mixer	1.5	1.5
Coffee Maker	92.4	92.4
Iron	52.9	52.9
Toaster Oven	49.6	49.6
Hair Dryer	35.0	35.0
Video Recorder	46.0	46.0
Rack Audio	66.5	66.5
Doorbell	44.2	44.2
Computer	101.0	101.0
Clock	25.9	25.9
Radio/Clock	17.9	17.9
Telephone (2 phones with an answering machine)	61.3	61.3
Door Opener	44.2	44.2
Security System	43.1	43.1
Printer	44.9	44.9
Total Annual Use For Appliances and Other Loads	3,687	3,072
Average Daily Use (kWh/day)	10.1	8.4

Table 4
Lighting Load and Cost Summary for Energy Efficient Lighting Package

	Hours On	# of Lamps	Watts/Lamps	Total Watts	Dim Factor	Annual Energy, Fluor kWh/yr	Lamp Life Hrs	Lamp Life Multiplier	Lamp Life, Adj.	Lamp Cost Ea.	Total Lamp Cost	Replacement Increments (Per Year)	Replacement Interval (Yrs)	Initial Fixture Cost	# Fixtures	Total Fixture Cost
Kitchen	2.0	2	26	52	1.00	37.96	10,000	0.9	9,000	$7.70	$15.40	0.08	12.33	$116.03	2	$232.06
Dining room	1.0	5	100	500	0.65	118.63	750	1.9	1,425	$0.43	$2.15	0.26	3.90	$196.35	1	$196.35
Food prep	2.0	4	26	104	1.00	75.92	10,000	0.9	9,000	$7.70	$30.80	0.08	12.33	$116.03	4	$464.12
Great room	3.0	7	26	182	0.75	149.47	10,000	1.0	10,000	$10.60	$74.40	0.11	9.13	$209.00	7	$1,463.00
Main bath	2.0	4	13	52	1.00	37.96	10,000	0.9	9,000	$7.70	$30.80	0.08	12.33	$93.00	2	$186.00
Main bed	1.0	4	26	104	0.75	28.47	10,000	0.7	7,000	$10.60	$42.50	0.05	19.18	$215.04	4	$860.15
Bed 2	1.0	6	26	156	1.00	56.94	10,000	0.7	7,000	$7.70	$46.20	0.05	19.18	$116.03	3	$348.09
Bed 3	1.0	6	26	156	1.00	56.94	10,000	0.7	7,000	$7.70	$46.20	0.05	19.18	$116.03	3	$348.09
Entry hall	2.0	2	26	52	1.00	37.96	10,000	0.9	9,000	$10.60	$21.30	0.08	12.33	$70.50	1	$70.50
Back hall	0.5	2	13	26	1.00	4.75	10,000	0.5	5,000	$7.70	$15.40	0.04	27.40	$80.94	2	$161.88
Laundry	1.0	1	13	13	1.00	4.75	10,000	0.7	7,000	$7.70	$7.70	0.05	19.18	$28.46	1	$28.46
Pantry	0.5	2	13	26	1.00	4.75	10,000	0.5	5,000	$10.60	$21.30	0.04	27.40	$42.08	1	$42.08
Bath 2	1.0	2	25	50	1.00	18.25	20,000	0.7	14,000	$4.66	$9.32	0.03	38.36	$214.50	1	$214.50
Main bath	2.0	2	25	50	1.00	36.50	20,000	0.9	18,000	$4.66	$9.32	0.04	24.66	$183.00	2	$366.00
Master closet	1.0	1	13	13	1.00	4.75	10,000	0.7	7,000	$7.70	$7.70	0.05	19.18	$42.08	1	$42.08
Exterior	0.5	6	15	90	1.00	16.43	10,000	0.5	5,000	$10.00	$60.00	0.04	27.40	$37.13	7	$259.91
Garage	0.5	4	32	128	1.00	23.36	20,000	0.5	10,000	$3.61	$14.40	0.02	54.79	$44.78	2	$89.56
Exterior post	12	1	15	15	1.00	65.70	10,000	1.5	15,000	$10.00	$10.00	0.29	3.42	$100.47	1	$100.47
Total						779					$465.00					$5,473.30

Table 5
Lighting Load and Cost Summary for Conventional Lighting Package

	Hours On	# of Lamps	Watts/Lamps	Total Watts	Dim Factor	Annual Energy, Fluor kWh/yr	Lamp Life Hrs	Lamp Life Multiplier	Lamp Life, Adj.	Lamp Cost Ea.	Total Lamp Cost	Replacement Increments (Per Year)	Replacement Interval (Yrs)	Initial Fixture Cost	# Fixtures	Total Fixture Cost
Kitchen	2.0	2	26	52	1.00	37.960	10,000	0.9	9,000	$7.70	$15.40	0.08	12.33	$116.03	2	$232.06
Dining room	1.0	5	100	500	0.65	118.625	750	1.9	1,425	$0.75	$3.75	0.26	3.90	$196.35	1	$196.35
Food prep	2.0	4	75	300	1.00	219.000	750	1.0	750	$0.75	$3.00	0.97	1.03		4	$0.00
Great room	3.0	4	100	400	0.75	328.500	750	1.9	1,425	$0.75	$3.00	0.77	1.30		7	$0.00
Main bath	2.0	4	60	240	1.00	175.200	1,000	1.0	1,000	$0.75	$3.00	0.73	1.37		2	$0.00
Main bed	1.0	4	75	300	0.75	82.125	750	1.9	1,425	$0.75	$3.00	0.26	3.90		4	$0.00
Bed 2	1.0	3	75	225	1.00	82.125	750	1.0	750	$0.75	$2.25	0.49	2.05		3	$0.00
Bed 3	1.0	3	75	225	1.00	82.125	750	1.0	750	$0.75	$2.25	0.49	2.05		3	$0.00
Entry hall	2.0	2	100	200	1.00	146.000	750	1.0	750	$0.75	$1.50	0.97	1.03		1	$0.00
Back hall	0.5	2	60	120	1.00	21.900	1,000	1.0	1,000	$0.75	$1.50	0.18	5.48		2	$0.00
Laundry	1.0	1	60	60	1.00	21.900	1,000	1.0	1,000	$0.75	$0.75	0.37	2.74		1	$0.00
Pantry	0.5	2	60	120	1.00	21.900	1,000	1.0	1,000	$0.75	$1.50	0.18	5.48		1	$0.00
Bath 2	1.0	2	75	150	1.00	54.750	750	1.0	750	$0.75	$1.50	0.49	2.05		1	$0.00
Main bath	2.0	2	75	150	1.00	109.500	750	1.0	750	$0.75	$1.50	0.97	1.03		2	$0.00
Master closet	1.0	1	60	60	1.00	21.900	1,000	1.0	1,000	$0.75	$0.75	0.37	2.74		1	$0.00
Exterior	0.5	6	60	360	1.00	65.700	1,000	1.0	1,000	$0.75	$4.50	0.18	5.48		7	$0.00
Garage	0.5	4	32	128	1.00	23.360	20,000	0.5	10,000	$3.61	$14.40	0.02	54.79	$44.78	2	$89.56
Exterior post	12	1	60	60	1.00	262.800	1,000	1.0	1,000	$0.75	$0.75	4.38	0.23		1	$0.00
Total						1,875					$64.00					$517.97

Table 6
Summary of Life Cycle Cost of Energy Features Added to Standard Design Individually

System	Description	Life Cycle Cost, 30 Years	Life Cycle Cost Savings (Premium) over Standard
Wall System	8" Block with Solid Grout	$35,053	($2,343)
	R-13 Light Frame	$26,670	$6,040
	Armory Park Standard	$32,710	$0
	Armory Park 3" Insl.	$33,378	($668)
	Armory Park ¾" Insl.	$33,876	($1,166)
	Durisol W25	$34,571	($1,861)
	Durisol W30	$34,826	($2,116)
Ceiling Insulation	R-30 Fiberglass	$12,232	$0
	R-38 Fiberglass	$12,218	$15
	R-42 Cellulose	$12,182	$50
Windows	Aluminum, Double, Clear	$14,241	$0
	Andersen Narroline	$14,387	($147)
	Milgard	$12,697	$1,544
HVAC	Heat Pump SEER 10, HSPF 6.8	$12,865	$0
	Heat Pump SEER 12, HSPF 7.8	$12,658	$207
	Heat Pump SEER 17, HSPF 9.1	$12,169	$696
Radiant Barrier	No Barrier	$11,397	$0
	With Radiant Barrier	$10,756	$641
Ductwork	In Attic	$12,656	$0
	In Conditioned Space	$11,040	$1,616
Washer	Standard	$2,120	$0
	Premium Efficiency	$2,291	($171)
Dryer	Standard	$2,482	$0
	Premium Efficiency	$2,286	$196
Refrigerator	Standard	$1,303	$0
	Premium Efficiency	$1,275	$28
Dishwasher	Standard	$1,485	$0
	Premium Efficiency	$1,373	$111
Water Heater	Electric Tank	$5,996	$0
	Electric Tank with Active Solar	$7,508	($1,512)
	Tankless with Active Solar	$7,136	($1,140)

Table 7
Summary of Energy Simulation Results

Option	Description	Annual Electrical Consumption (kWh/yr)						
		Cooling	Heating	Fan	DHW	Lighting	Appl./Other	Total
--	JWM Standard (includes passive SDHW)	3,568	621	772	1,855	1,873	3,687	12,376
A	2" Polyiso	3,443	530	731	1,855	1,873	3,687	12,119
B	R43 Insulation	3,516	611	761	1,855	1,873	3,687	12,303
C	Hi SEER AC&Solar Htg	2,520	200	479	158	1,873	3,687	8,917
D	Hi Eff Appliances	3,438	687	760	1,855	1,873	3,072	11,685
E	Hi Eff Lighting	3,389	714	756	1,855	779	3,687	11,180
A+B	2" Polyiso+R43 Ceiling	3,391	519	719	1,855	1,873	3,687	12,044
A+C	2" Polyiso+Hi SEER AC&Solar Htg	2,441	200	454	158	1,873	3,687	8,813
A+D	2" Polyiso+Hi Eff Appliances	3,309	594	717	1,855	1,873	3,072	11,420
A+E	2" Polyiso+Hi Eff Lighting	3,262	619	713	1,855	779	3,687	10,915
B+C	R43 Insulation+Hi SEER AC&Solar Htg	2,486	200	472	158	1,873	3,687	8,876
B+D	R43 Insulation+Hi Eff Appliances	3,384	676	748	1,855	1,873	3,072	11,608
B+E	R43 Insulation+Hi Eff Lighting	3,338	703	744	1,855	779	3,687	11,106
C+D	Hi SEER AC&Solar Htg+Hi Eff Appliances	2,431	200	470	158	1,873	3,072	8,204
C+E	Hi SEER AC&Solar Htg+Hi Eff Lighting	2,398	200	467	158	779	3,687	7,689
D+E	Hi Eff Appliances+Hi Eff Lighting	3,260	787	746	1,855	779	3,072	10,499
A+B+C	2" Polyiso+R43 Ceiling+Hi SEER AC&Solar Htg	2,407	200	447	158	1,873	3,687	8,772
A+B+D	2" Polyiso+R43 Ceiling+Hi Eff Appliances	3,257	583	706	1,855	1,873	3,072	11,346
A+B+E	2" Polyiso+R43Ceiling+Hi Eff Lighting	3,210	608	701	1,855	779	3,687	10,840
A+C+D	2" Polyiso+Hi SEER AC&Solar Htg+Hi Eff Appliances	2,349	200	445	158	1,873	3,072	8,097
A+C+E	2" Polyiso+Hi SEER AC&Solar Htg+Hi Eff Lighting	2,317	200	442	158	779	3,687	7,583
A+D+E	2" Polyiso+Hi Eff Appliances+Hi Eff Lighting	3,131	688	701	1,855	779	3,072	10,226
B+C+D	R43 Ceiling+Hi SEER AC&Solar Htg+Hi Eff Appliances	2,395	200	463	158	1,873	3,072	8,161
B+C+E	R43 Ceiling+Hi SEER AC&Solar Htg+Hi Eff Lighting	2,364	200	460	158	779	3,687	7,648
B+D+E	R43 Ceiling+Hi SEER AC&Solar Htg+Hi Eff Lighting	3,208	775	734	1,855	779	3,072	10,423
C+D+E	Hi SEER AC&Solar Htg+Hi Eff Appliances+Hi Eff Lighting	2,311	200	459	158	779	3,072	6,979
A+B+C+D	2" Polyiso+R43 Ceiling+Hi SEER AC&Solar Htg+Hi Eff Appliances	2,315	200	438	158	1,873	3,072	8,056
A+B+C+E	2" Polyiso+R43 Ceiling+Hi SEER AC&Solar Htg+Hi Eff Lighting	2,283	200	435	158	779	3,687	7,542
A+B+D+E	2" Polyiso+R43 Ceiling+Hi Eff Appliances+Hi Eff Lighting	3,079	676	689	1,855	779	3,072	10,150
A+C+D+E	2" Polyiso+Hi SEER AC&Solar Htg+Hi Eff Ltg+Hi Eff Appliances	2,228	200	434	158	779	3,072	6,871
B+C+D+E	R43 Ceiling+Hi SEER AC&Solar Htg+Hi Eff Appliances+Hi Eff Ltg	2,277	200	453	158	779	3,072	6,939
A+B+C+D+E	2" Polyiso+R43 Ceiling+Hi SEER AC&Solar Htg+Hi Eff Appls+Hi Eff Ltg	2,194	200	427	158	779	3,072	6,830

Table 8
Summary of Life Cycle Cost and Incremental Cost for Energy Packages

Option	Description	Initial Efficiency Investment Cost	Energy Use of System (kWh/yr)	Efficiency Invest + Energy LCC	Calc PV Size (kW)	Total PV Size (kW)	PV LCC (Investment minus Energy Production)	Total Life Cycle Cost	Incremental Efficiency Investment Cost	Incremental PV cost	Total Incremental Cost over JWM standard
--	JWM Standard (includes passive SDHW)	$13,637	12376	$33,535	7.40	7.5	$49,004	$82,539	$0	$58,500	$58,500
A	2" Polyiso	$13,832	12119	$33,360	7.24	7.5	$49,004	$82,364	$196	$58,500	$58,696
B	R43 Insulation	$14,152	12303	$33,929	7.35	7.5	$49,004	$82,933	$515	$58,500	$59,015
C	Hi SEER AC&Solar Htg	$20,337	8917	$36,737	5.33	5.5	$35,936	$72,673	$6,700	$40,500	$47,200
D	Hi Eff Appliances	$14,717	11685	$34,117	6.98	7.0	$45,737	$79,853	$1,080	$54,000	$55,080
E	Hi Eff Lighting	$17,005	11180	$34,984	6.68	7.0	$45,737	$80,720	$3,368	$54,000	$57,368
A+B	2" Polyiso+R43 Ceiling	$14,347	12044	$33,751	7.20	7.5	$49,004	$82,755	$711	$58,500	$59,211
A+C	2" Polyiso+Hi SEER AC&Solar Htg	$20,532	8813	$36,778	5.27	5.5	$35,936	$72,714	$6,896	$40,500	$47,396
A+D	2" Polyiso+Hi Eff Appliances	$14,912	11420	$33,930	6.83	7.0	$45,737	$79,667	$1,276	$54,000	$55,276
A+E	2" Polyiso+Hi Eff Lighting	$17,200	10915	$34,797	6.52	6.5	$42,470	$77,267	$3,564	$49,500	$53,064
B+C	R43 Insulation+Hi SEER AC&Solar Htg	$20,532	8876	$36,867	5.31	5.5	$35,936	$72,803	$6,896	$40,500	$47,396
B+D	R43 Insulation+Hi Eff Appliances	$15,232	11608	$34,505	6.94	7.0	$45,737	$80,242	$1,595	$54,000	$55,595
B+E	R43 Insulation+Hi Eff Lighting	$17,520	11106	$35,376	6.64	7.0	$45,737	$81,113	$3,883	$54,000	$57,883
C+D	Hi SEER AC&Solar Htg+Hi Eff Appliances	$21,417	8204	$37,287	4.90	5.0	$32,669	$69,956	$7,780	$36,000	$43,780
C+E	Hi SEER AC&Solar Htg+Hi Eff Lighting	$23,705	7689	$38,140	4.60	4.5	$29,402	$67,542	$10,068	$31,500	$41,568
D+E	Hi Eff Appliances+Hi Eff Lighting	$18,085	10499	$35,579	6.28	6.5	$42,470	$78,049	$4,448	$49,500	$53,948
A+B+C	2" Polyiso+R43 Ceiling+Hi SEER AC&Solar Htg	$21,052	8772	$37,221	5.24	5.5	$35,936	$73,157	$7,415	$40,500	$47,915
A+B+D	2" Polyiso+R43 Ceiling+Hi Eff Appliances	$15,427	11346	$34,323	6.78	7.0	$45,737	$80,059	$1,791	$54,000	$55,791
A+B+E	2" Polyiso+R43Ceiling+Hi Eff Lighting	$17,715	10840	$35,188	6.48	6.5	$42,470	$77,658	$4,079	$49,500	$53,579
A+C+D	2" Polyiso+Hi SEER AC&Solar Htg+Hi Eff Appliances	$21,612	8097	$37,324	4.84	5.0	$32,669	$69,993	$7,976	$36,000	$43,976
A+C+E	2" Polyiso+Hi SEER AC&Solar Htg+Hi Eff Lighting	$23,900	7583	$38,178	4.53	4.5	$29,402	$67,580	$10,264	$31,500	$41,764
A+D+E	2" Polyiso+Hi Eff Appliances+Hi Eff Lighting	$18,280	10226	$35,381	6.11	6.0	$42,470	$77,851	$4,644	$45,000	$49,644
B+C+D	R43 Ceiling+Hi SEER AC&Solar Htg+Hi Eff Appliances	$21,932	8161	$37,723	4.88	5.0	$32,669	$70,392	$8,295	$36,000	$44,295
B+C+E	R43 Ceiling+Hi SEER AC&Solar Htg+Hi Eff Lighting	$24,220	7648	$38,579	4.57	4.5	$29,402	$67,981	$10,583	$31,500	$42,083
B+D+E	R43 Ceiling+Hi SEER AC&Solar Htg+Hi Eff Lighting	$18,600	10423	$35,969	6.23	6.0	$39,203	$75,171	$4,963	$45,000	$49,963
C+D+E	Hi SEER AC&Solar Htg+Hi Eff Appliances+Hi Eff Lighting	$24,785	6979	$38,694	4.17	4.5	$29,402	$68,096	$11,148	$31,500	$42,648
A+B+C+D	2" Polyiso+R43 Ceiling+Hi SEER AC&Solar Htg+Hi Eff Appliances	$22,127	8056	$37,763	4.82	5.0	$32,669	$70,432	$8,491	$36,000	$44,491
A+B+C+E	2" Polyiso+R43 Ceiling+Hi SEER AC&Solar Htg+Hi Eff Lighting	$24,415	7542	$38,617	4.51	4.5	$29,402	$68,019	$10,779	$31,500	$42,279
A+B+D+E	2" Polyiso+R43 Ceiling+Hi Eff Appliances+Hi Eff Lighting	$18,795	10150	$35,771	6.07	6.0	$39,203	$74,974	$5,159	$45,000	$50,159
A+C+D+E	2" Polyiso+Hi SEER AC&Solar Htg+Hi Eff Ltg+Hi Eff Appliances	$24,980	6871	$38,730	4.11	4.0	$26,135	$64,865	$11,344	$27,000	$38,344
B+C+D+E	R43 Ceiling+Hi SEER AC&Solar Htg+Hi Eff Appliances+Hi Eff Ltg	$25,300	6939	$39,134	4.15	4.5	$29,402	$68,537	$11,663	$31,500	$43,163
A+B+C+D+E	2" Polyiso+R43 Ceiling+Hi SEER AC&Solar Htg+Hi Eff Appls+Hi Eff Ltg	$25,495	6830	$39,169	4.08	4.0	$26,135	$65,304	$11,859	$27,000	$38,859

RESULTS

Predicted versus Actual Energy Consumption

Although a full year of monitored data for the occupied home is not available, Table 9 is a summary of predicted (simulated) versus actual usage. Actual usage is based on approximately eight months of occupied data, from October 7, 2004 to June 3, 2004. Cooling energy is currently being monitored.

Table 9
Predicted (Simulated) vs. Actual Usage

Load	Predicted Usage	Actual Usage
Residual energy (kWh/day)	8.4	12.8
Heating Energy (Btu/day)	30,700	47,050
Lighting (kWh/day)	2.63	2.13

The brief summary in the Table 9 indicates that the actual energy use for heating is significantly higher than predicted. There are a number of factors that account for this result and are discussed below in the heating summary.

The lighting energy use, which is highly dependent on the homeowners' lifestyle, is about 20 percent less than predicted. However, the residual energy, which is all energy use except for heating, cooling, and water heating, is significantly higher than originally estimated. Figure 8 graphically compares the energy use for the major loads (which are highly dependent of the equipment efficiency and house construction) and the "plug and appliance" loads, which are more in the control of the homeowner but do include the use of high efficiency appliances such as washing machines.

Summary of Actual Energy Consumption

The first year of operation was monitored from April 23, 2003, the day of the grand opening of the Tucson ZEH. The home was open as a model for the next six months until it was purchased an occupied on October 7, 2003. The cooling season data represents an unoccupied home but open for visitors and prospective buyers. During this period all of the lights are on from 10 a.m. through about 9 p.m. In addition, the cooling set point is in the range of 72°F. As an unfortunate consequence when visitors walk through the home, the exterior doors are often left open or ajar for long periods of time.

Table 10
PV System Performance

PV System	Parameter
DC Array Size	4.2 kW
Array Area	37.6 m^2
Solar Input	2,370 kWh/m^2
Total AC Output	7,323 kWh
Average AC Output	20.1 kWh
System Efficiency	8.2%
Efficiency Std. Dev.	0.5%
Maximum AC Out	3,821 watts
Avg. Daily Temp.	72°F
Avg. Daily Max. Temp.	88°F

The following charts provide the first year and occupied period performance data. Figure 1 shows the 1st year energy performance of the Tucson ZEH and demonstrates the PV system supply to the house and utility credit. The credit is available only if the PV supply exceeds the house consumption for the day. During any point during the day, the PV system may be feeding power back to the utility. The sum of the "PV Supply to House" and the "PV Credit to Utility" columns is the total daily output of the PV system. The spring and fall represents the majority of time when there is a net-credit to the utility. Figure 2 shows similar data for only the occupied home for the available nine-month period.

Figures 1 and 2 also show the extent to which the PV system output is available and significant across the entire year. Rarely does the daily supply fall below 5 kWh. In the first year of operation, the PV system produced an average of almost 21 kWh per day and is summarized in Table 10.

For the occupied period (Figure 4, which does not include a summer cooling period), the daily electricity use averages over 25 kWh per day, due in large part to the operation of the demand water heater used to boost the solar thermal storage for use in space and domestic water heating.

Figures 3 and 4 summarize the energy use for the same periods (1st year and partial occupied) by major load and energy supply. Over two thirds of the total household energy use is supplied by the PV and solar thermal systems. The plug and appliance loads account for about 50 percent of the energy use thus far—an area of energy consumption that is the most difficult to reduce.

A significant benefit of the PV system operation is its coincident energy production to the utility peak system demand. Figure 5 shows all of the 15-minute periods for the first year by hour of the day, indicating the relationship between the house consumption and the utility supply. Figure 6 shows the same data but without the demand (instantaneous) heater. In the later case, the peak utility demand to the house is decreased by over half. In addition, the utility has a very reliable daytime source of renewable energy available to the grid.

The PV system operation was effected by the coincident operation of the demand heater. Figure 7 demonstrates this conflict based on 15-minute average data. When the demand heater activates to heat water for domestic or space heating, one of the inverters experiences a fault mode and shuts down for five minutes and then reinitializes. The PV installer returned the inverter for evaluation but no problems with the inverter were found by the manufacturer. The resultant magnitude of energy loss from the PV system is extremely small.

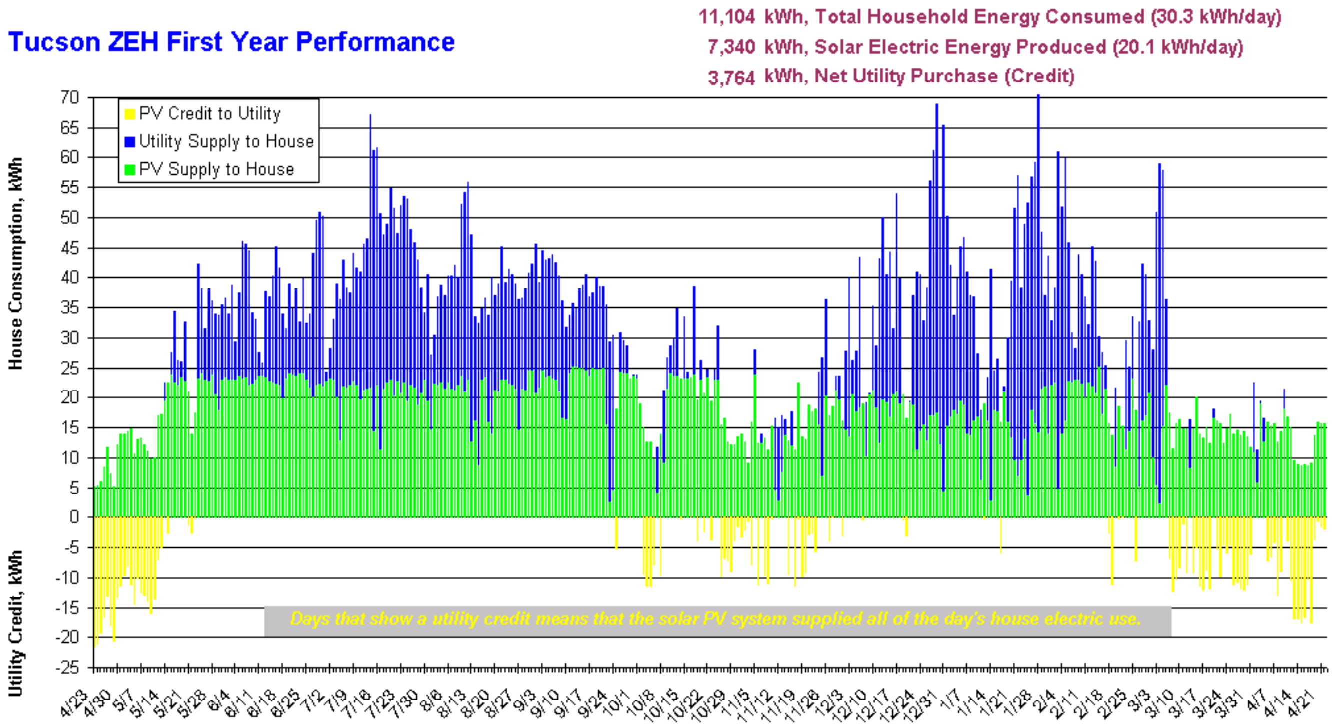


Figure 1: ZEH Energy Consumption/Credit—1st Year

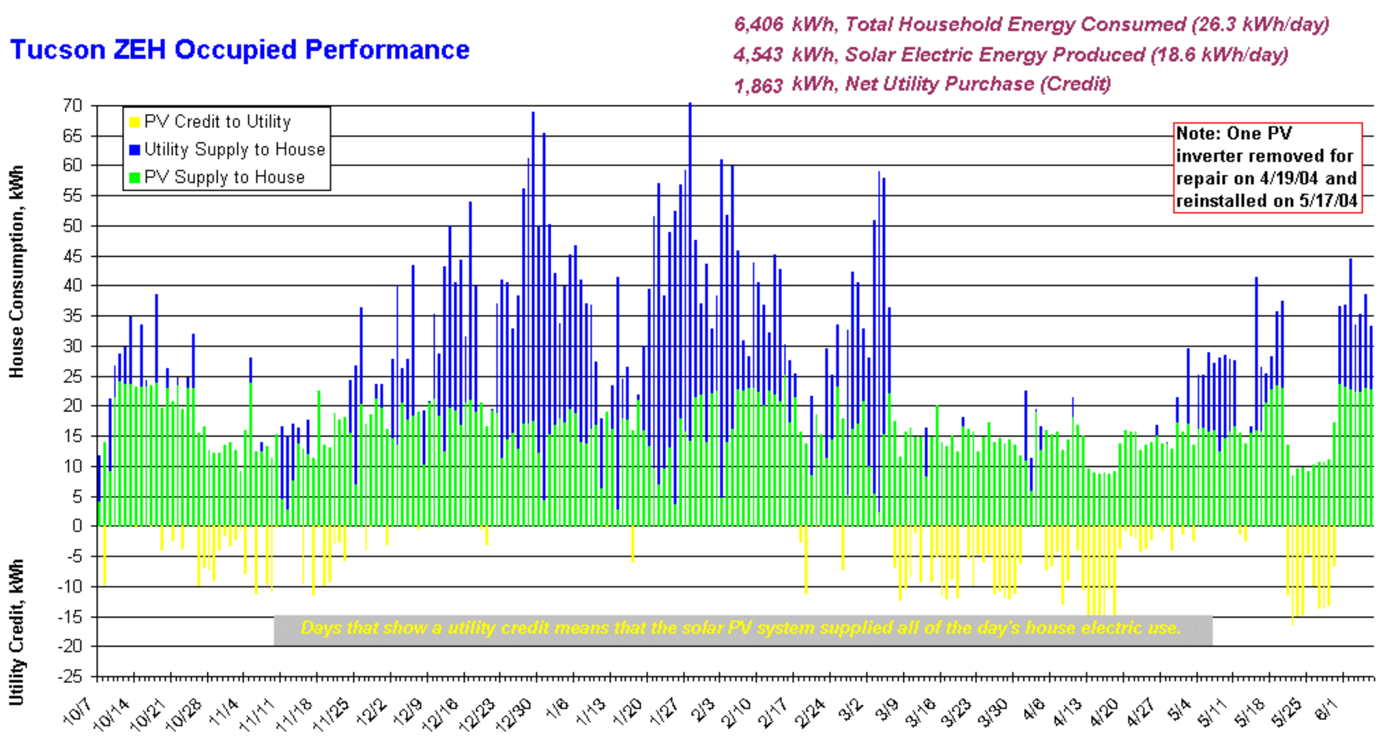


Figure 2: ZEH Energy Consumption/Credit—Occupied Period

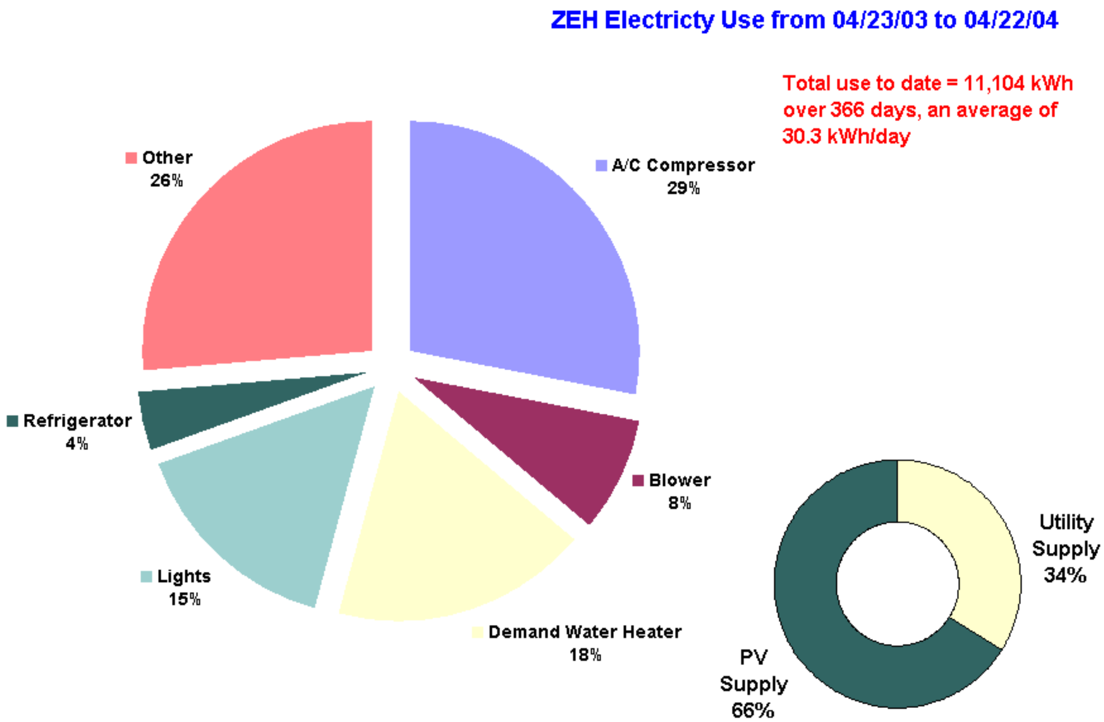


Figure 3: Energy Consumption End Use and Supply—1st Year

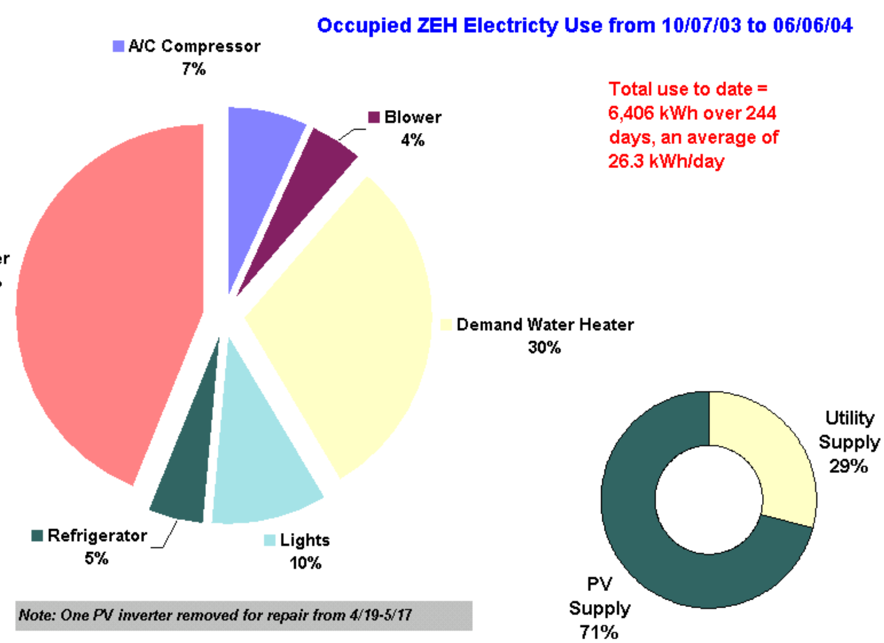


Figure 4: Energy Consumption End Use and Supply—Occupied Period

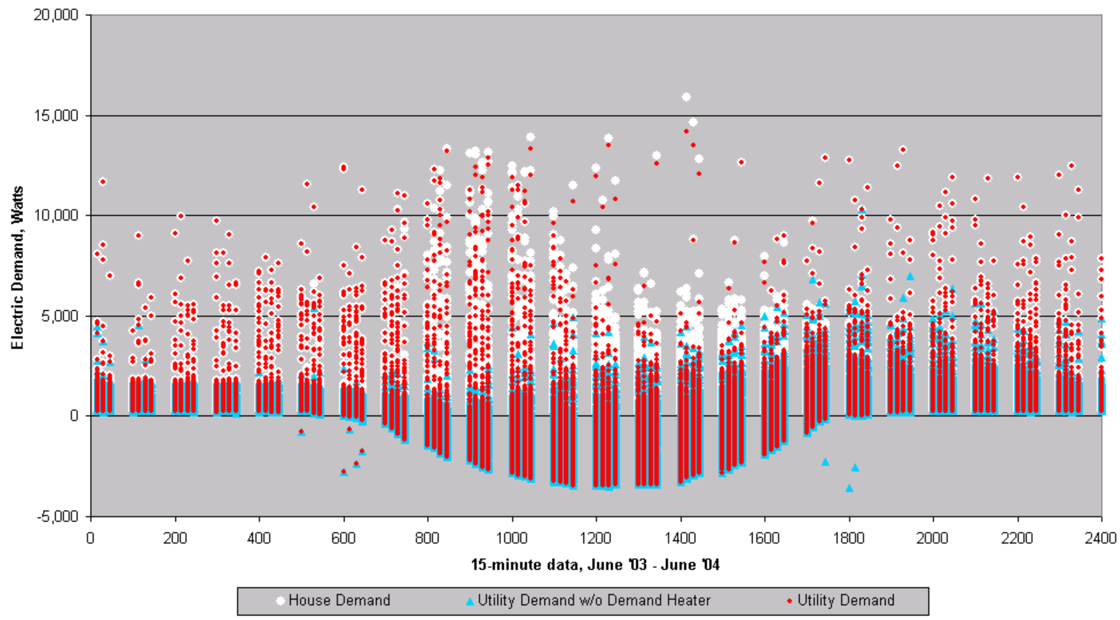


Figure 5: Electricity Demand—15-Minute Periods

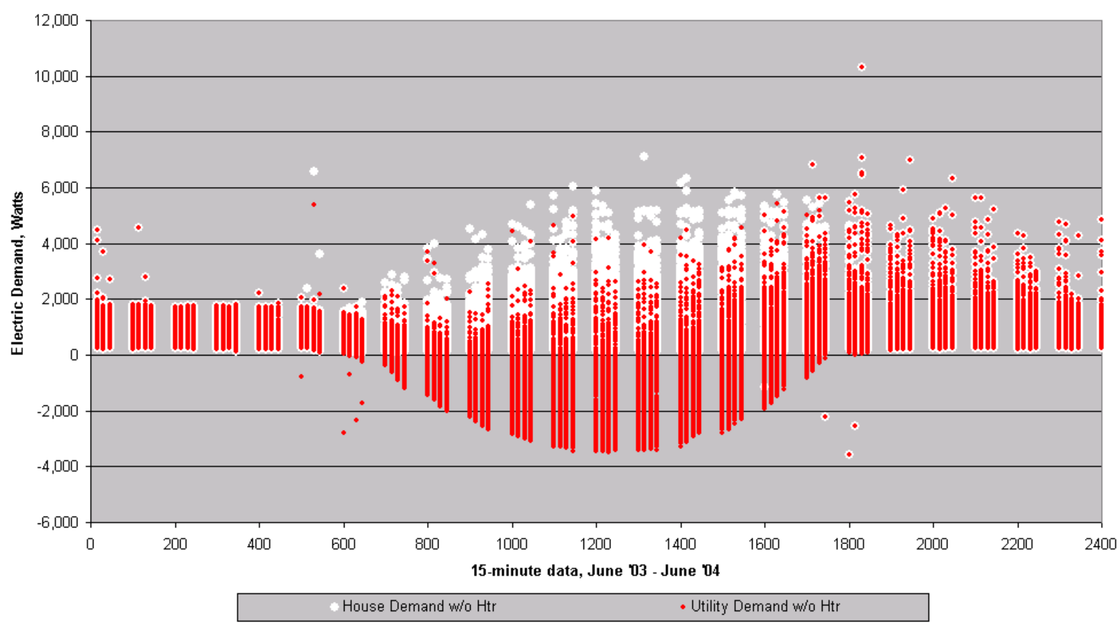


Figure 6: Electricity Demand Profile Without Instantaneous Heater—15-Minute Periods

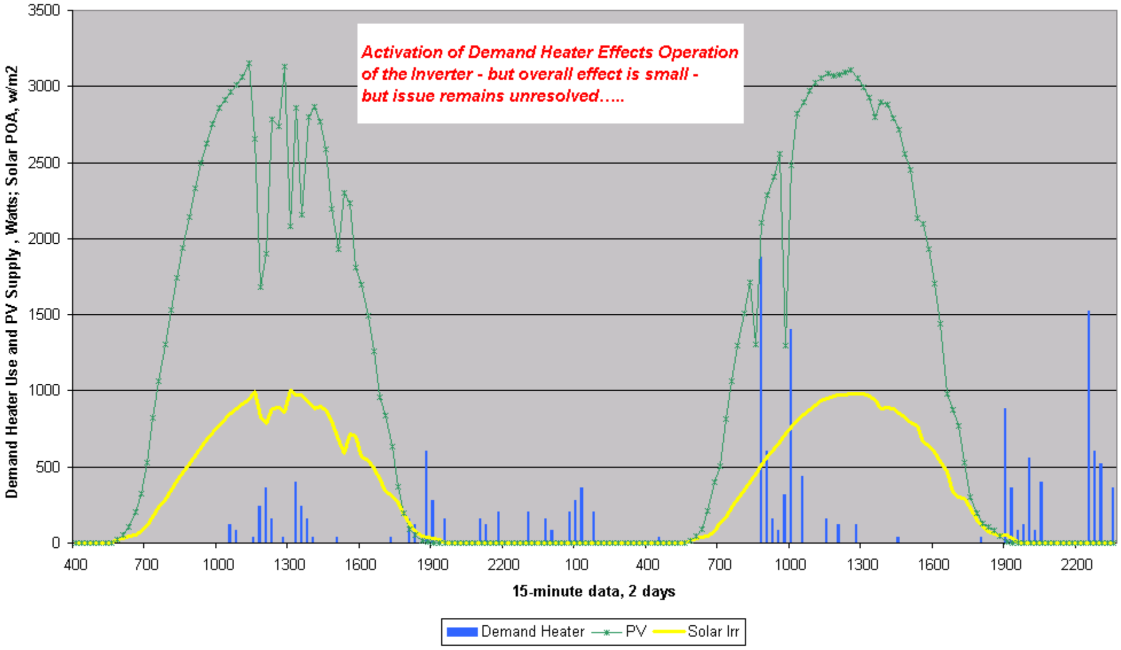


Figure 7: Demand Heater/Inverter Interaction

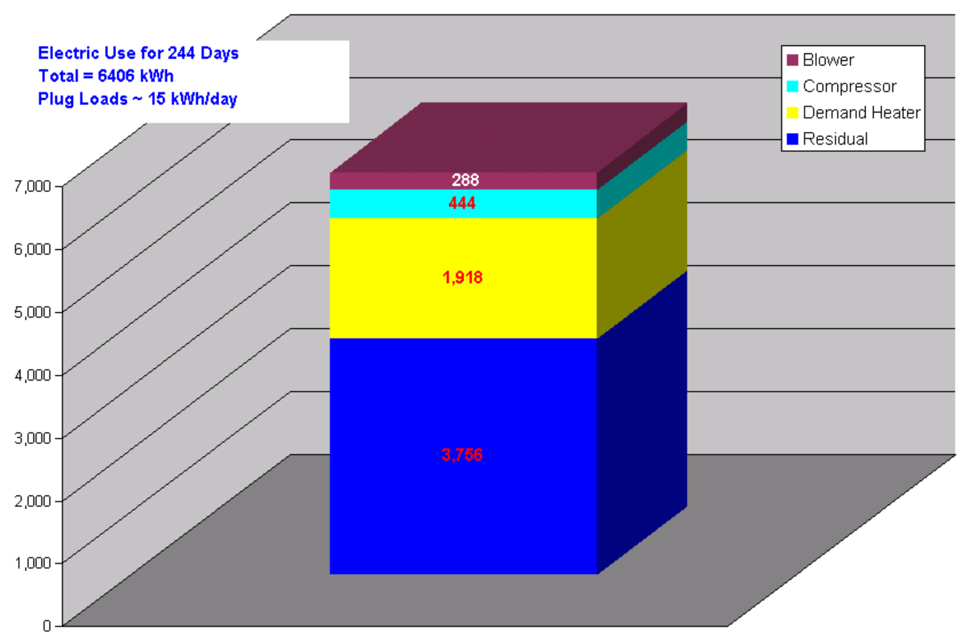


Figure 8: Load Consumption for Occupied Period

Summary Heating System Performance

A significant amount of household energy in the occupied period prior to the main cooling season was used for the heating system. Table 11 summarizes the heating season and energy use for space and domestic water heating. In this system design, the demand water heater is used to boost the temperature of the water used of space and domestic water heating to about 130°F. The water is preheated by running through a heat exchanger in the solar storage tank.

Table 11
Summary of ZEH Heating Season Performance

	Measured Results	Simulated Results
Heating Period (November 1 - March 31)	151 days*	
HDD (November - March)	1,084	1,412
Ambient Temperature (average)	58.1°F	55.3°F
Average Daily Minimum Temperature, °F	44°F	42°F
Average Indoor Air Temperature**	73.6°F	73.3°F
Indoor Thermostat Set Point, °F	72°F	72°F
Heating Energy Used, million Btu	7.105	4.637
Domestic Hot Water Energy Use, million Btu	3.586	
Solar Energy Collected, million Btu	8.512	
Demand Water Heater Supply, million Btu	6.257	
System Losses, million Btu	4.079	
Proportion of Heating Energy Supplied by Solar	60%	
Daily Average Heating Energy Use, Btu/day	47,050	30,700
Daily Average Thermal Load (heat and DHW), Btu/day	70,800	
Average Daily Solar Energy Collected, Btu/day	56,370	(80,000-90,000 per design specs)
*Excluding 1 day of cooling (12/6); **Average at Thermostat		

Although the heating season appears to have been milder than the conditions used in simulation, the data showed a much higher heating energy use than predicted. Of particular concern with the heating season performance is the lower than expected output from the solar thermal collectors and the heating system losses, calculated as the amount of energy input by solar and the demand water heater minus the hot water and heating loads. This loss was over 4 million Btu over the heating season, or about 27,000 Btu/day.

Ventilation Load—Heating Season

The passive ventilation system consists of a six-inch duct from the roof into the return plenum. The flow and temperatures of the passive ventilation system are estimated based on pressure and temperature measurements at the duct prior to the return plenum. The ventilation system, on average, added approximately 1,100 Btu per day of heating load to the house (1,600 Btu/day of heating system operation).

Cooling System Seasonal Performance (Unoccupied Model)

The Tucson ZEH cooling system seasonal period of performance is taken from May 1 through October 31, 2003. During most of this period, the home was unoccupied and available as a model home in the Armory Park development. The cooling system operation is summarized in Table 12.

Table 12
Seasonal Summary of the ZEH Cooling System

	Measured Results	Simulated Results or Base
Cooling Period (May - October)	184 days	
CDD	3,693	2,618 (95% of year)
Ambient Temperature (average)	85°F	79°F
Ambient Temp. (average of daily maximum)	100°F	91°F
Average Indoor Air Temperature **	75°F (range 72 - 77)	75°F (fixed)
Cooling Compressor Energy	3,098 kWh	2,211 kWh
Cooling Blower Energy	760 kWh (20%*)	377 kWh (15%*)
Total Cooling Energy per CDD	1.045 kWh/CDD	0.989 kWh/CDD
Compressor Energy per CDD	0.839 kWh/CDD	0.844 kWh/CDD
Stage 1 (low) vs. Stage 2 (high) Capacity Cooling	~ 90% Stage 1	NA
Average Cooling System Operation per Day	916 min. (15.25 hrs)	NA
Peak Cooling Load (Btu)	~ 26,000	~ 17,500

* Percent of total cooling energy

** During a large portion of the hottest summer period, the thermostat set point was 72°F with the home open and accessible as a model.

The results of the seasonal cooling system operation are based on an unoccupied home that was available as a model for most of the monitoring period. Because of the home's operation as a model, the cooling set point was set lower especially during the hottest months when consumer traffic was heaviest. The lighting load was also higher than it would be for an occupied home since most all the lights were on for about 10 hours per day. The cooling degree-days (CDD) for the monitoring period were over 40 percent higher than the CDD used in the simulations (based on Typical Meteorological Year data). When normalized to CDD from TMY data, the cooling energy is shown to be fairly close to that predicted by the simulation.

The two-speed cooling system appears to be of particular benefit in this climate providing relatively constant cooling at a low capacity for most of the time. However, the observed peak-cooling load was higher than predicted. Possible explanations include the sustained higher than normal peak temperatures, thermostat manipulation by at least four degrees, and direct solar gains through un-shaded windows. However, when reviewing the operation of the cooling system over the period from mid-June through mid-October it was determined that the peak loads were rarely encountered. For this period, the cooling unit operated during some or all of 95 percent of the 15-minute periods. However, in only slightly more than half of this operation, 54 percent, was one ton or more of cooling used. Only two percent of the operation was at least 1½ tons of cooling and a mere 0.2 percent of the operation at greater than two tons. The combination of the efficient operation of the two-speed unit and the large amount of thermal mass contributes to this cycling characteristic. Figure 9 shows the daily operation of the cooling system and clearly indicates the longer run times at lower energy consumption levels.

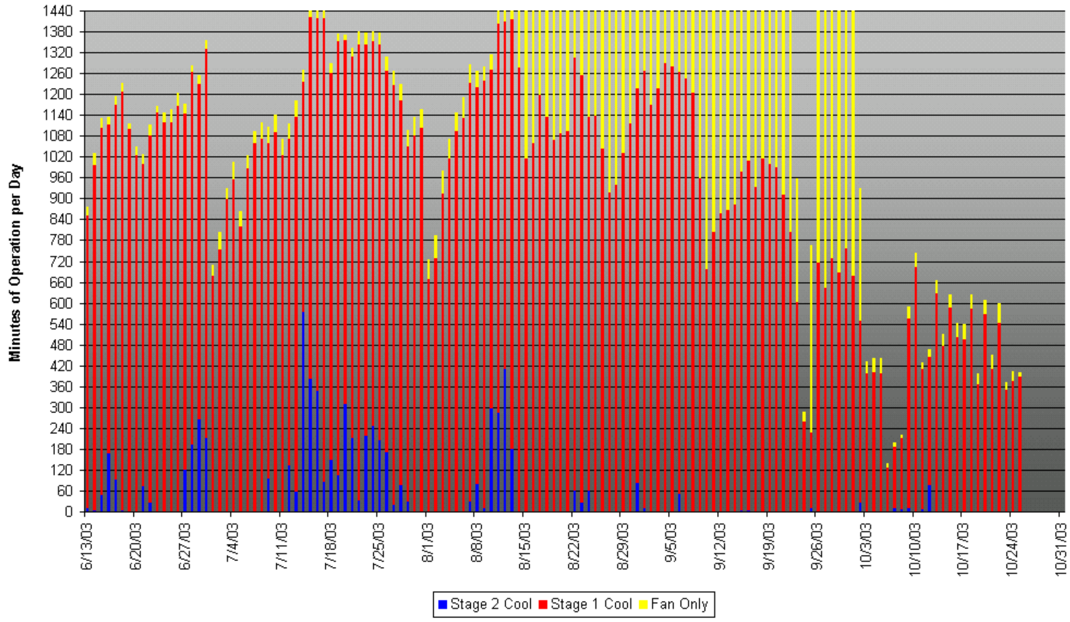


Figure 9: Staged Cooling Operation

Ventilation Load-Cooling Season

The passive ventilation system consists of a six-inch duct from the roof into the return plenum. The flow and temperatures of the passive ventilation system are estimated based on pressure and temperature measurements at the duct prior to the return plenum. The ventilation system averaged approximately 4,900 Btu per day of additional load to the house or about two percent of the coil load of 224,400 Btu/day on average.

ZEH Performance Summary

The Tucson ZEH was designed to produce as much electrical energy from renewable resources as was consumed in the home over the course of a year. The first year of operation, which had the home open as a model for nine months, reached 75 percent of that goal. Thus far, since the home was occupied in October 2003, the net energy purchase is about 30 percent with the cooling season remaining.

A higher than expected heating load and a lower than expected solar thermal system performance has resulted in more electricity use for heating than designed. This result is under investigation and will be attempted to be remedied by the next heating season.

The lighting, plug, and appliance loads have resulted in lower daily energy use than a typical home but remain higher than the estimates for the ZEH. Measurements for the next six months will help in identifying potential savings in these loads.

The PV system has performed consistently throughout the year including through a very hot summer. These results are indicative of good power point tracking in the inverter and reliable module performance. The overall dc-to-ac system efficiency is around 8 percent which given the climate and consistent daily output, is very reasonable.

LESSONS LEARNED

Throughout the construction process, there were many lessons that were learned, and practices that could be changed to enhance the energy performance in the next Zero Energy Home. Several issues require attention in order for the practices to become accepted by mainstream homebuilders.

Photovoltaic System Installation

The installation of the PV system was relatively simple given a knowledgeable designer/installer. The parallel connection to the electric grid was straightforward and economical. The aesthetics of the PV system however remain at best neutral. Strong indications at the site was that installation of the PV on a sloped roof would meet much more resistance than on the flat parapet roofs now used to hide much of the array. The utility company, when functioning as a strong proponent for PV systems, adds immense value to the PV system installation.

PV System: Inverter Problems

Incompatibility issues between the inverter and demand water-heating equipment was unexpected and remains unresolved. With an increase in the use of electric demand water heating equipment as well as solar PV systems, further compatibility testing is warranted. Also, more information should be made available concerning the compatibility of inverters with other electronic equipment.

Solar Thermal System Aesthetics

The appearance of the solar thermal system is still an issue. Even after the height of the system was reduced by using eight-foot collectors, instead of ten-foot collectors on a flat roof with a parapet, the collectors still extended high enough to be easily viewed from the ground. These collectors also extended much higher than the PV modules.

Solar Thermal System Performance

Even after a concerted design effort by experienced solar engineers, there continues to be performance issues with the solar thermal system. The source(s) of the disappointing performance of the solar thermal system are yet to be fully identified however, it appears that more design work needs to be done. Turnkey systems for space and water heating would simplify the integration of space and water heating systems and reduce the uncertainty over system design. In addition, losses from the solar tank were significantly higher than design specifications. More information about tank design is needed, and a summer/winter operation mode switch would be helpful especially in limiting summertime losses to the home.

Integration of the HVAC and Solar Thermal Systems

The integration of the HVAC system with the solar thermal system was difficult. Although the HVAC contractor had experience with the hydronic air handler coil, the system still was not installed properly. Turnkey systems with installation manuals would have simplified the process.

Space for Mechanical Equipment and Solar Thermal Storage

With a modestly sized home and the considerable mechanical equipment needed for the innovative mechanical systems, it was difficult to incorporate all of the necessary components into a small interior mechanical room. More architectural and system design work is needed to resolve integrating solar thermal storage into a house plan. The capability of producing thermal energy inexpensively is possible, but thermal storage remains a significant problem.

Thermal Mass

Thermal mass is an energy benefit when passive solar design is applied to a home. However, in production housing where passive solar design is often not feasible, a home having high thermal mass may lead to additional heating energy use. The thermal mass may lead to occupant discomfort, and it also may consume a lot of energy to keep at a stable temperature for comfort. Depending on how the occupants use the thermostat (e.g., set back is often used), this massive structure may need to be charged frequently. More investigation is needed to determine the effect of thermal mass on a home in a climate that has both heating and cooling loads and that is not designed for passive solar gain.

Attic Insulation

Although cellulose insulation was suggested for the attic, the builder was reluctant to use it based on potential moisture problems. Changes to typical construction practices such as insulation are difficult to make if performance issues, either perceived or real, exist to any extent. Moisture concerns are of particular importance since they can be very difficult to remedy. Application of a new technology to a builder's standard practice

Air Admittance Valves

The use of air admittance valves was met with resistance from the trade contractor who was unfamiliar with the product. Therefore, it was very useful to have the design of the AAV system clearly specified in the blueprints by the manufacturer. If the manufacturer had not designed the system, the plumber would not have provided this service and would rather have used a venting system with which they are familiar.

PEX plumbing

There still seems to be a bias against PEX plumbing. The bias mainly seems to stem from past problems with polybutylene plumbing. Having the factory rep or distributor intimately involved in installation and design was very helpful. In addition, in homes where pipes are traditionally buried in the slab, there can be significant advantage to the homeowner in placing pipes in conditioned space (i.e., not having to wait for hot water at distant faucets). However, builders may still be resistant to changing practices due to liability and warranty fears.

Lighting

The technology for incorporating permanent fluorescent lighting into a whole-house lighting package is not yet ready for mainstream housing. First, fixtures and lamps are difficult to find, and they would need to be readily available at big box stores in order for their use by mainstream homebuilders. Contractors often cannot or will not wait days or weeks for a fixture. The cost for fixtures was prohibitive: recessed fixtures were almost 10 times the cost of incandescent recessed fixtures. Improvements in technology are needed including: dimming ballasts, reducing the delay time for a lamp to turn on, and improving color quality are top priorities.

Plug Loads

In our energy simulations, we made very conservative estimates for plug loads, including the assumption that all appliances would be Energy Star rated (including phone, etc.). However, the plug loads are about 50 percent higher than assumed. In order for actual plug load to be closer to the conservative estimates, more education of homeowners about the effect of plug loads on the household energy consumption is necessary.

Need for Homeowner Information

There was a lack of information provided to the homeowner about the design and operation of a Zero Energy Home. Development of a ZEH homeowner's manual would be beneficial, as the operation of a ZEH requires attention and interest by the homeowner.

Value of a ZEH

Certain homeowners are willing to pay a premium buy a ZEH (price premium of over $46,000, but not including utility rebates), even though the reduction in energy cost would not likely be recouped in a relatively short time period. Therefore, the consumer saw enough value in the Zero Energy concept to pay a 14.5 percent premium on the sales price for the home. While this particular consumer probably represents a very small segment of home buyers, they are among those who have a certain amount of flexible income for housing expenditures and simply choose to place it into energy efficiency.

Economic Value of ZEH

Under Tucson Electric Power's rules, a net-metered home must use TEP's flat rate billing. If net-metered homes were permitted to use time-of-use billing, and the solar energy was valued at real time rates, the value of the energy supplied to the grid by PV systems would be much higher (since the bulk of the PV supply is produced during peak electric rates).

Repeatability

In order for the Tucson ZEH to be a repeatable design, more work needs to be done to coordinate the trade contractors for the solar thermal heating and water heating system. The performance issues of the solar thermal system would also need to be resolved before the builder would consider using the same design. In addition, the value of the ZEH performance needs a much higher level of clarity since at this time; utility bill offsets are the primary metric for value.

RECOMMENDATIONS

Continued monitoring

We recommend that monitoring of the Tucson ZEH continue to obtain at least have one full year of data during occupied use. There is a strong interest in documenting the progress toward Zero Energy—among researchers, builders, manufacturers, and consumers—and the Tucson ZEH remains the only home built under the program that was designed to meet 100 percent of its loads through renewable energy. Continued monitoring will allow the chance to determine if the goal has been met and, if not, to assess improvements in future homes to achieve the goal.

Solar Thermal System Design

The solar thermal system should be tested and analyzed in detail to determine why performance was not as expected. Items that need further investigation include the high thermal tank losses, control of the demand heater, the condition of the space heating coil, and the collector performance.

Thermal Mass Analysis

Investigate the thermal mass issues with homes in Armory Park del Sol. The large amount of thermal mass and lack of passive solar design leaves questions regarding the effect of the thermal mass on energy use in the homes. While the thermal mass is likely beneficial under time of use electric rates, it is not apparent that is has a benefit for the ZEH at APdS.

Resolve Inverter/Demand Heater Compatibility

The issue of why the inverter shuts off at certain times of demand heater operation needs to be resolved. Higher output would result from the photovoltaic array if the inverter problem were resolved.

Design for Additional ZEH at Armory Park

Work with the builder and others at Armory Park to design a next-generation ZEH at Armory Park del Sol using lessons learned from the first ZEH. The site is ideal for another ZEH given its emphasis on solar energy, the participation of the utility company, and the vast solar resource in Tucson.

Integration of Mechanical Systems in Conditioned Space

Work on designs that ease the incorporation of mechanical rooms, ductwork, and plumbing pipe into conditioned space. At the Tucson ZEH, this was accomplished with considerable effort and additional cost for dropped soffit construction.

Attachment A:
Design Criteria at Beginning of Design Process

Design Specs per JWM Company

- Three-foot doors
- Four-foot halls or wider
- No steps
- At least one bathroom that's wheelchair accessible
- Historic district in Tucson—vernacular architecture
- Three "good sized bedrooms" (good size is 12x12, "dinky" is 9x10)
- Front porch on every house, can be inset or full width
- Garage is 24-foot wide
- Two full baths

Design Wants per JWM Company

- Atrium off kitchen
- Fourth optional bedroom
- Rear patio area

Design Specs per NAHBRC Team

- Size limit 32x55 feet plus attached 22-foot garage off back.
- Centrally located utility closet
- Keep as many plumbing fixtures that use hot water on same wall as utility closet as possible to avoid running hot water lines through slab. Run a continuous "utility wall" so that hot water plumbing lines can be run to fixtures not immediately adjacent to utility room.
- Insulated box for large (80-120 gal) hot water storage tank.
- Central air handler with star-shaped distribution
- Parapet roof
- Reversible plans
- East or west wall on zero lot line
- Minimize glazing on non-zero lot face
- Use porch roofs to protect glazing, otherwise overhangs are not regionally-appropriate
- Ductwork in conditioned space
- Garage: attached