Case Study: A Wisconsin High-Performance House

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ABSTRACT

In the winter of 1997 to 1998, a new single-family residence was built and occupied in central Wisconsin, a region with an 8,000 heating degree-day climate. The house was designed and built utilizing airtight/superinsulated construction techniques. The building method utilized an "interior-strapped wall" variation on conventional 2 × 6 wall construction, with framing details modified to accommodate critical air-sealing details for a certifiably airtight envelope.

In January 2000, the home received the first-place Gold Energy Value 2000 Award from the National Association of Homebuilders Research Center (NAHBRC). It was selected as the best innovative/advanced residence in a cold-climate region. It also received a 5-Star PLUS rating under the EPA EnergyStar Homes program, with a score of 93.9.

The house is 1,923 ft^2 in area on the main level, with a partially finished lower level and a heated garage workshop. Total heated area is 3,820 ft^2 on two levels.

The home is also an all-electric home, utilizing a closed-loop ground-source geothermal heat pump coupled with hydronic-radiant heating. The home is optimized for solar orientation and has a high level of interior thermal mass. Heat-recovery ventilation and passive cooling are provided, along with a backup central masonry heater.

The home's performance has been carefully tracked, with time-of-day electric usage monitored for both on-peak and off-peak energy usage. Energy bills and usage over three years have been compiled and analyzed. The three-year average total year-round electric bill was $686.38, not including a $7.50 to $8.00/month meter charge. With the meter charge included, average annual electric usage totaled $729.38. Total annual electrical energy consumed was 19,868 kWh, of which 17,682 kWh or 89% was off-peak usage. By subtracting the average summer electric usage from the winter usage, an approximation for total heating usage for the six-month winter heating period was 7,662 kWh for a total cost of $195.57, not including the meter charge. With the meter charge included, total heating usage for the six-month winter heating period was $242.07. Actual energy usage indexes to 1.1 Btu/ft^2 of heated space/heating degree-day or a steady-state heat loss of 15,969 Btu/h at –20ºF.

As can be seen from the actual energy usage, the overall thermal performance has been close to phenomenal for this climate. This is especially true since this is an all-electric home and also has mechanical ventilation provided. The energy usage of the house continues to be monitored, and the consumption figures are being updated to compare consecutive winters.

Several factors contribute to the actual energy performance of the residence. First, the interior strapped-wall construction reduces the average solid content of the walls from about 16% to around 6%, as well as providing a thermal break between the interior and exterior envelope surfaces. Second, several variations from conventional platform construction were employed to ensure continuity of air-infiltration and vapor-retarder barriers. Third, the residence has good passive solar orientation. Fourth, approximately 80 tons of thermal mass in the residence allows for a significant thermal-flywheel effect, optimizing the use of off-peak electricity.

A detailed step-by-step slide tour of the construction process, illustrating the advanced framing techniques utilized for construction, accompanies the presentation. Interior and exterior views of the completed home are also included.

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Sullivan Residence

(built 1997)

Gross Floor Area:		**Steady-State Calculated Heat Loss:**	
Main Floor:	1,596 ft^2	Conduction:	42,652 Btu/h
Entry:	144 ft^2	Infiltration:	25,359 Btu/h
Loft:	196 ft^2	Combined:	68,011 Btu/h
	1,936 ft^2	(Does not take into account internal or passive-solar heat contribution)	
Lower Level:	1, 596 ft^2		
Heated Workshop:	296 ft^2		
Total Heated Area:	3,820 ft^2		

Construction:

Foundation:	10 in. concrete block walls with 2 × 4 interior perimeter wall, set in 3.5 in., with 7 in. fiberglass insulation (R-28).
Lower Floor:	4 in. hydronic-radiant concrete slab floor, with 2 in. rigid R-10 sub-slab insulation and 6 mil poly vapor-barrier (R-10).
Upper Walls:	2 × 6 structural studs with 2 × 2 interior horizontal strapping and thin-coat plaster finish. Insulated with 7 in. fiberglass insulation and continuous vapor-barrier. Vertical “rain-screen” cedar siding over 1 × 3 horizontal furring and an air-barrier over 0.75 in. shiplap pine sheathing (R-31).
Main Floor:	3 in. hydronic-radiant floor slab with ceramic tile over 0.75 in. shiplap pine sheathing and 2 × 12 floor joists. Rim joist recessed 5.5 in. to allow for continuity of vapor barrier with insulated exterior wall dropped down to foundation sill plate (R-22).
Sloped Ceilings:	2 × 8 structural rafters with 2 × 4 drop-rafter supporting 18 in. blown cellulose insulation and continuous vapor barrier (R-50).
Roof:	Site-built standing-seam galvanized metal roof over roofing felt and 0.75 in. shiplap pine sheathing.
Heating system:	Hydronic-radiant floor slab on both lower and main floor levels. Closed-loop ground-source heat pump with five 800 ft exterior closed loops buried at 8 ft depth. Five heating zones with interior distribution circulation tubing in slabs.
	Centrally located Finnish-design masonry fireplace/heater.
Domestic Hot Water:	Electric heat pump with desuperheater.
Mechanical Ventilation:	Air-to-air heat exchanger/heat-recovery ventilator (HRV).

TABLE 1
Sullivan Residence

Main floor = 1596 ft^2 Loft = 196 ft^2 Entry = 144 ft^2 **Main level = 1936 ft^2** Workshop = 296 ft^2 Lower level = 3820 ft^2 **Heated area = 3820 ft^2**
GLAZING South glazing = 372 ft^2 = 10.5% of floor area Other glazing = 371 ft^2 = 10.5% of floor area
THERMAL MASS Radiant Concrete Slab = 3500 ft^2 = 875 ft^3 = 65 tons Thincoat Plaster over 0.625 in. gypsum = 5000 ft^2 = 10 tons Central masonry heating stove
VENTILATION Heat recovery ventilator/air-air heat exchanger
HEATING UNIT Closed-loop ground-source heat pump (five 800 ft ground loops at 8 ft depth)

TABLE 2
Sullivan Residence
1998-2000 Three-Year Average

Period	kWh used	Energy Cost
Annual mid-April to mid-April (total usage)	19,868	$686.38
Summer Average mid-May to mid-September (total usage)	1,010	$41.37
Winter Total mid-October to mid-April (total usage)	13,723	$443.78
Winter Heating mid-October to mid-April (heating only)	7,662	$195.57
Calculated steady-state heat loss = 68,011 Btu/h at –20		
Actual steady-state heat loss = 15,969 Btu/h at –20 (at 3413 Btu/kWh)		
Heating energy consumption = 2.20 Btu/HDD/ft^2 (26.25 MMBtu at 6,141 HDD at 1,936 ft^2) Heating energy consumption = 1.11 Btu/HDD/ft^2 (26.25 MMBtu at 6,141 HDD at 3,820 ft^2)		
Time-of-Day Electricity Cost Savings = $400.40 (36.8%)		
Energy costs do not include customer meter charge of $7.50 < 12/00 > $8.00 per month or nontaxable Public Benefits charge of $1.48 per month > 10/00 or summer-season only sales tax.		

Key Features of Airtight/Superinsulated Construction
(Using an Interior-Strapped Wall)

The purpose of special framing details and air sealing is to ensure quality control in obtaining a tightly built envelope that is certifiable by blower-door pressure testing. Mechanical ventilation, in the form of an air-to-air heat exchanger or heat-recovery ventilator (HRV), is required to ensure good indoor air quality and occupant comfort. The use of sealed-combustion direct-vent appliances is also required. Any wood-burning appliances need gasketed doors and dedicated outside combustion air.

Construction is similar to conventional 2×6 construction with a few differences. These primarily involve inserting vapor-barrier strips in critical floor/wall/roof intersections during rough framing. The interior-strapping is added after rough framing is completed. The resulting additional 1.5 in. wall thickness must be taken into account for window and door casings, as well as any dimension-dependent installations along the exterior walls. These might include stairs, plumbing fixtures, and/or other building elements. Some key features of this type of construction are listed below.

Foundation/Basement:

- sealed vapor-barrier below slab, above or below rigid insulation
- rigid insulation below slab with optional sand bed for protection
- optional sub-slab radon-mitigation gravel bed below vapor-barrier
- interior 2×4 insulated perimeter stud wall, set in 1.5 in. from foundation wall
- wall vapor-barrier sealed to sub-slab and rim-joist vapor-barrier
- electrical boxes mounted in plastic vapor-barrier surrounds or gasketed

Floor Deck:

- vapor-barrier strip laid over wider sill plate prior to setting joists
- rim-joist recessed 5.5 in. to allow insulated exterior walls to rest on sill plate, or
- rim-joist recessed 2 in. to allow for rigid insulation outside box sill
- vapor-barrier strip folded up and over subfloor to allow for continuity with wall vapor-barrier

Walls:

- window and door unit frames wrapped with vapor-barrier strip prior to installation
- wall vapor-barrier sealed to rim joist and ceiling/upper floor vapor-barrier
- wall vapor-barrier sealed to window and door vapor-barrier wrapping
- 2×2 horizontal strapping across interior face of studs to create thermal break/7 in. cavity
- 2×4 horizontal strapping at base and at mid-height for base and drywall attachment
- vapor-barrier strip inserted behind end stud of partitions intersecting outside wall
- electrical boxes mounted in plastic vapor-barrier surrounds or gasketed
- 1×3 furring over housewrap at exterior for wood-siding rain-screen/drying cavity

Upper Floor Deck:

- vapor-barrier strip laid over wall top plate prior to setting joists
- rim-joist recessed 2 in. to allow for rigid insulation outside box sill
- vapor-barrier strip folded up and over subfloor to allow for continuity with wall vapor-barrier

Ceiling/Roof Truss:

- raised-heel energy trusses or raised-plate platform framing for flat ceilings
- raised-heel scissors-trusses, parallel-chord trusses, or false drop-rafters for sloped ceilings
- vapor-barrier strip inserted at all roof/wall framing intersections
- vapor-barrier sealed to wall vapor-barrier

Sullivan Residence - Energy Usage Summary (3-year Average 1998-2001)

Utility Billing Dates	ON Peak		OFF Peak		TOTAL		MMBTU	HDD	BTU/HDD	BTU / HDD / SQ FT	Steady-State Heatloss BTUH @-20deg	if Normal Rate	
	$.10300 -.11000/kwh		$.02200 -.02450/kwh		(combined)							@ $.05470/kwh	
	kwh	$	kwh	$	kwh	$	3,413 / kwh					kwh	$
Electric Rates: 12/97-12/98= $.02220 / $.10300 12/98-12/99 = $.02450 / $.11000 12/99-12/00 = $.02701 / $.11251 12/00-date = $.03050 / $.12400 Energy costs do not include customer meter charge of $7.50 < 12/00 > $8.00 per month or non-taxable Public Benefits charge of $1.48 per month > 10/00 or summer-season only sales tax.									Main Floor = 1596 sq ft Loft = 196 sq ft Entry = 144 sq ft **Main Level = 1936 sq ft** Workshop = 296 sq ft Lower Level = 1596 sq ft **Heated Area = 3820 sq ft**				
mid-JAN - mid-FEB	199	21.58	2,201	54.25	2,400	75.83	8.19	1,215				2,400	131.28
mid-FEB - mid-MAR	185	20.06	1,807	44.04	1,992	64.10	6.80	972				1,992	108.96
mid-MAR - mid-APR	141	15.31	1,484	37.08	1,625	52.39	5.54	707				1,625	88.87
mid-APR - mid-MAY	119	12.92	918	22.15	1,037	35.07	3.54	268	(transition month)			1,037	56.74
mid-MAY - mid-JUN	203	21.62	685	17.16	887	38.78	3.03	161				887	48.54
mid-JUN - mid-JUL	192	20.64	833	20.48	1,025	41.12	3.50	12	**4 month summer usage period**			1,025	56.07
mid-JUL - mid-AUG	200	21.59	817	20.13	1,017	41.72	3.47	6	**mid-May - mid-September**			1,017	55.63
mid-AUG - mid-SEP	202	21.65	910	22.20	1,111	43.85	3.79	87				1,111	60.79
summer subtotal	796	85.50	3,245	79.98	4,041	**165.47**	13.79	266	**summer subtotal**			4,041	**221.02**
% annual	**19.7%**	**51.7%**	**80.3%**	**48.3%**									133.6%
mid-SEP - mid-OCT	188	20.20	879	21.86	1,067	42.06	3.64	386	(transition month)			1,067	58.35
mid-OCT - mid-NOV	184	19.87	1,329	32.54	1,513	52.41	5.16	611				1,513	82.76
mid-NOV - mid-DEC	202	21.93	2,184	54.50	2,386	76.43	8.14	1,155				2,386	130.51
mid-DEC - mid-JAN	197	21.97	3,161	72.57	3,358	94.55	11.46	1,623	**6 month winter usage period**			3,358	183.68
mid-JAN - mid-FEB	199	23.02	2,490	68.89	2,689	91.91	9.18	1,357	**mid-October - mid-April**			2,689	147.11
mid-FEB - mid-MAR	166	19.03	1,815	49.75	1,980	68.78	6.76	1,023				1,980	108.32
mid-MAR - mid-APR	134	15.37	1,663	44.33	1,797	59.71	6.13	772				1,797	98.28
winter subtotal;	1,083	121.19	12,641	322.59	13,723	**443.78**	46.84	6,540	**winter subtotal**			13,723	**750.67**
% annual	**7.9%**	**27.3%**	**92.1%**	**72.7%**									169.2%
mid-APR - mid-MAY	117	12.95	790	20.30	906	33.24	3.09	281	(transition month)			906	49.56
mid-MAY - mid-JUN	135	15.03	790	20.53	925	35.55	3.16	151				925	50.60
mid-JUN - mid-JUL	165	18.29	868	22.32	1,033	40.61	3.52	18	4 month summer usage period			1,033	56.48
mid-JUL - mid-AUG	181	20.08	846	21.84	1,026	41.92	3.50	9	mid-May - mid-September			1,026	56.12
mid-AUG - mid-SEP	163	18.10	889	22.84	1,052	40.94	3.59	107				1,052	57.52
summer subtotal	643	71.49	3,392	87.52	4,035	159.01	13.77	284	summer subtotal			4,035	220.71
% annual	15.9%	45.0%	84.1%	55.0%									
mid-SEP - mid-OCT	154	17.12	988	25.52			0.00	407	(transition month)				
mid-OCT - mid-NOV	161	17.85	1,322	34.06	1,483	51.91	5.06	568				1,483	81.09
mid-NOV - mid-DEC	200	22.19	2,485	64.35	2,684	86.54	9.16	1,350				2,684	146.81
mid-DEC - mid-JAN	186	21.50	3,127	72.64	3,313	94.14	11.31	1,478				3,313	181.22
Annual Total									(based on **1936 sq ft** heated area)				
mid-April - mid-April	2,186	239.81	17,682	446.57	19,868	**686.38**	67.81	7,460	9,090	4.70	34,087	19,868	**1086.78**
% annual	**11.0%**	**34.9%**	**89.0%**	**65.1%**					(includes ALL energy usage)				158.3%
Winter Total (6 months)		mid-October - mid-April			13,723	443.78	46.84	6,540	7,162	3.70	26,857	(total energy usage)	
Summer Total (4 months)		mid-May - mid-September			4,041	165.47	13.79	266					
Winter Total (heating only)		mid-October - mid-April			7,662	**195.57**	26.15	**6,141**	4,259	**2.20**	**15,969**	(summer avg deducted)	
Winter Average (monthly)		mid-October - mid-April			2,287	73.96	7.81	1,090	7,162	3.70	26,857	(total energy usage)	
Summer Average (monthly)		mid-May - mid-September			1,010	41.37	3.45	67					
Winter Avg (heating only)		mid-October - mid-April			1,277	**32.60**	4.36	**1,024**	4,259	**2.20**	**15,969**	(summer avg deducted)	

BTU/hr = (BTU/yr / HDD/yr) x (Design Temperature Difference / 24)

BTU/yr = (BTU/hr x 24hrs x HDD/yr) / Design Temperature Difference

(one year)