Comfort, Indoor Air Quality, and Energy Consumption in Low Energy Homes

P. Engelmann, K. Roth, and V. Tiefenbeck
Fraunhofer Center for Sustainable Energy Systems

January 2013

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, subcontractors, or affiliated partners makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof.The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email:mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Comfort, Indoor Air Quality, and Energy Consumption in Low Energy Homes

Prepared for:
The National Renewable Energy Laboratory
On behalf of the U.S. Department of Energy's Building America Program
Office of Energy Efficiency and Renewable Energy
15013 Denver West Parkway
Golden, CO 80401
NREL Contract No. DE-AC36-08GO28308

Prepared by:

P. Engelmann, K. Roth, and V. Tiefenbeck

Fraunhofer Center for Sustainable Energy Systems

25 First Street

Cambridge, MA 02141

NREL Technical Monitor: Chuck Booten

Prepared under Subcontract No. KNDJ-0-40345-00

January 2013

[This page left blank]

Contents

List of Figures

Unless otherwise indicated, all figures were created by Fraunhofer CSE.

List of Tables

Unless otherwise indicated, all tables were created by Fraunhofer CSE.

Definitions

ACH	Air changes per hour
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
CO_2	Carbon dioxide
COP	Coefficient of performance
DHW	Domestic hot water
ERV	Energy recovery ventilator
HB	hexafluorobenzene
HRV	Heat recovery ventilator
IAQ	Indoor air quality
LBNL	Lawrence Berkeley National Laboratory
NZEH	Net zero-energy home
OA	Outdoor air
PFT	Perfluorocarbon tracer
PDCB	perfluorodimethylcyclobutane
PMCH	perfluoromethylcyclohexane
PMV	Predicted mean vote
PPD	Percentage of dissatisfaction
PV	Photovoltaics
RH	Relative humidity
VOC	Volatile organic compound

Executive Summary

A home with an optimized building envelope, including enhanced insulated walls, high-efficiency windows, and airtight construction, can achieve very low energy consumption, foremost in cold climates. These measures also have a substantial impact on indoor conditions, notably occupant comfort in winter and indoor air quality (IAQ). Specifically, high insulation levels produce indoor surface temperatures close to the indoor air temperature, increasing the mean radiant temperature in winter and (to a lesser extent) decreasing it in summer. Airtight construction prevents uncontrolled ventilation heat losses and protects the building structure, but creates the need for mechanical ventilation to ensure sufficient outdoor air supply.

A marketing claim frequently made about high performance homes is that, in addition to being extremely energy efficient, they offer increased comfort and IAQ, and are thus healthier than conventional homes. This study investigates whether these claims can be supported by measured field data.

This report documents the results of an in-depth evaluation of thermal comfort for two potential net zero-energy homes (NZEHs) in Massachusetts. We also present the results of an IAQ evaluation that was part of a larger study done in conjunction with Lawrence Berkeley National Laboratory (LBNL). Even though the homes were monitored and evaluated in great detail, the results must be seen as case studies, as occupant behavior has a dramatic impact on energy consumption. Nevertheless, research in the United States (Parker 2008) and Europe (Feist et al. 2001; Passipedia 2012) clearly shows that improvements in energy efficiency measures lead to significant reductions in energy consumption.

The report first gives a brief comparative outline of the two homes and describes the data acquisition methods and instrumentation. Section 2 analyzes energy consumption and production of both homes over the course of the year, from monthly energy balance down to 5-minute interval load data. One home did not reach a “zero” balance (over a full year); the other produced nearly 30% more energy than it consumed.

Section 3 evaluates the homes’ thermal comfort performance. In both homes, residents reported no discomfort issues, although indoor temperatures in winter often fell below ASHRAE’s comfort range. The heating systems in both homes did not operate at their full capacities, suggesting that the heating systems did not limit comfort and the homes seemed to meet residents’ comfort preferences. Summer indoor temperatures remained below 82°F (28°C) in both homes, thus within ASHRAE’s comfort range. However, higher relative humidity levels could cause discomfort.

Section 4 addresses IAQ, focusing on carbon dioxide as indicator for air exchange rates and indoor air pollutants. More detailed tests were carried out over three-week periods in collaboration with LBNL. The results underline the necessity of mechanical ventilation in airtight homes, but also the challenges in commissioning and running these systems, mainly because information about “proper” ventilation for occupants and for the builder is lacking.

Overall, the report shows that aggressive NZEH goals are realistic in terms of their energy balance at comfort levels that can meet residents' preferences. Whether (and to what extent) this holds true for residents with more typical comfort preferences, especially with respect to indoor temperatures in winter, remains to be evaluated. The report also shows the importance of IAQ testing in these tight constructions to ensure these homes meet the claims of being "healthier" than typical homes.

From the detailed analysis of the energy flows we can draw the following conclusions:

- Even with a highly optimized thermal envelope, nearly half the energy is still used for space conditioning (dominated by space heating). But both homes have unusually low loads for other electricity consumption (appliances, miscellaneous, and plug loads).
- The indoor thermal comfort met user expectations, although the homes *as operated by the occupants* did not always meet ASHRAE comfort standards.
- Occupants do not fully understand IAQ. As long as there are no odorous pollutants, they have no sensor for air quality. A sufficient air exchange must be ensured; in low energy homes this is typically done by mechanical ventilation.
- The installation, commissioning, maintenance, and operation of mechanical ventilation show room for improvement.

Acknowledgments

The authors thank Drs. Henry Willem and Brett Singer of LBNL for their collaboration on this project and for composing most of the section on "Volatile Organic Compound and Aldehyde Concentrations." We also thank the Fraunhofer Institute for Solar Energy Systems for enabling the continued participation of the lead author after he moved from Fraunhofer Center for Sustainable Energy to Fraunhofer Institute for Solar Energy Systems. We also thank Mr. Carter Scott of Transformations, Inc. for his support in pursuing in-depth monitoring of the two homes his company built. Finally, we thank the owners and occupants of the two homes, who enthusiastically welcomed us to monitor their homes.

This project was supported by the U.S. Department of Energy Building America program beginning in April 2012. Before that time (beginning in spring 2010), the project was funded entirely by Fraunhofer Center for Sustainable Energy.

1 Introduction

A home with an optimized building envelope, including enhanced insulated walls, high-efficiency windows, and airtight construction, can achieve very low energy consumption, foremost in cold climates. These measures also have a substantial impact on indoor conditions, notably occupant comfort in winter and indoor air quality (IAQ). Specifically, high insulation levels produce indoor surface temperatures close to the indoor air temperature, increasing the mean radiant temperature in winter and (to a lesser extent) decreasing it in summer. Airtight construction prevents uncontrolled ventilation heat losses, but creates the need for mechanical ventilation to ensure sufficient outdoor air (OA) supply.

Furthermore, a marketing claim frequently made about high-performance homes is that, in addition to being extremely energy efficient, they offer increased comfort and IAQ, and are thus healthier than conventional homes.

Achieving widespread deployment of very low-energy homes is a core goal of the Building America program. To date, however, very few such homes have been built. In this project, we performed an in-depth evaluation of two potential net zero-energy homes (NZEHs)recently constructed in Massachusetts to provide data to help evaluate three questions that need to be affirmatively addressed to achieve broad market acceptance of such homes:

- Can they consume much less energy than conventional homes?
- Can they provide superior—or at least acceptable—occupant comfort relative to conventional homes?
- Can they provide superior—or at least acceptable—IAQ relative to conventional homes?

Even though the homes were monitored and evaluated in great detail, the results must be seen as case studies, as occupant behavior has a dramatic impact on energy consumption and acceptable comfort conditions.

1.1 Net Zero Energy Balance

The NZEH concept is to greatly reduce energy consumption through energy efficiency and to meet the remaining energy needs with renewable sources (see Figure 1). These buildings are normally connected to the power grid and achieve a net zero energy balance over the course of a year. Different ways of defining a net zero balance, balance boundaries, and type of energy (primary energy, site energy, etc.) is discussed by Torcellini et al. (2006).

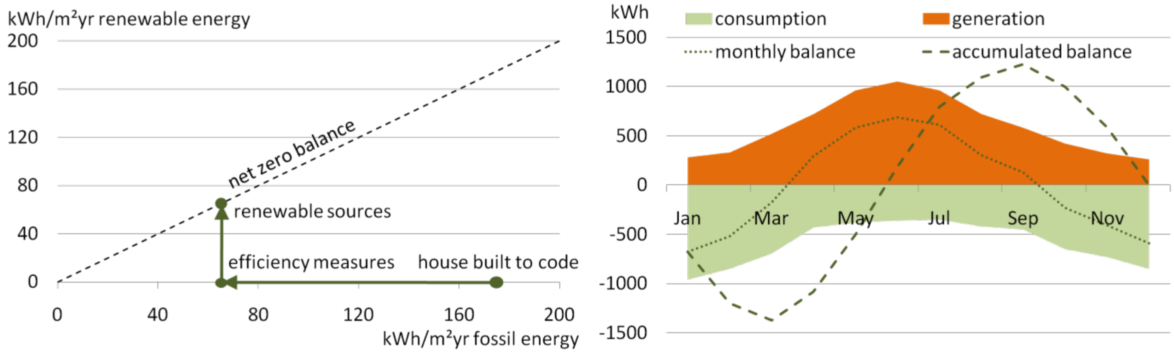

Figure 1. Graphical illustrations of the net zero energy concept

Left: Efficiency measures (enhanced building envelope, energy saving appliances, etc.) reduce energy consumption. Right: The remaining demand is supplied by renewable energy sources supply the remaining demand.

1.2 The Net Zero Energy Home in Stow, Massachusetts

The Stow home (see Figure 2 through Figure 4) was constructed in spring 2010; monitoring started in mid-July, and the new homeowners completely moved in by the end of July. The house is all electric; space heating and cooling are provided by a 10.5-kWth (36,000-Btu/h) ductless mini-split with one outdoor and four indoor units (one on every floor). Potable hot water was initially provided by an electric resistance heater; in October 2010, it was changed to an air-source heat pump (see Table 1).

Figure 2. The NZEH in Stow, Massachusetts

Left: Southeast view. Middle: South and northwest views.
Right: Wall-to-window ratio for the orientations.

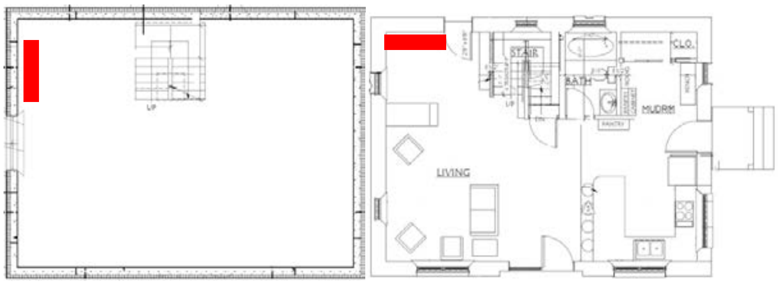

Figure 3. Floor plans and position of the mini-split indoor units (red boxes) in the Stow home Left: Basement. Right: 1st floor. The positions of the mini-split indoor units are marked by the red boxes.

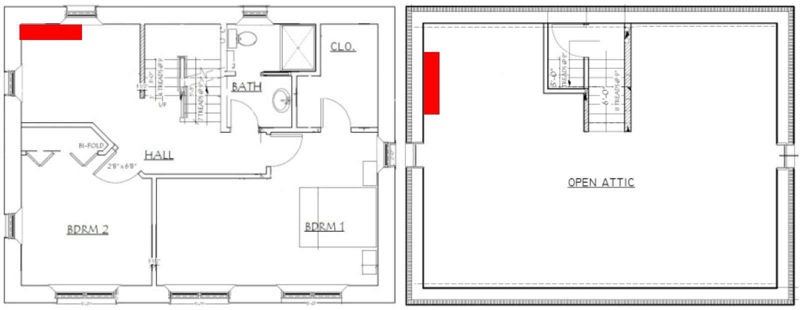

Figure 4. Floor plans from the Stow home. Left: 2nd floor. Right: Finished attic.

Table 1. Characteristic Data for the Stow NZEH

Characteristics	Values	
Floor Area	2964 ft² (275 m²)	
Calculated Demand for Space Heating	12 kBtu/ft^2/yr (37.8 kWh/m²/yr)	
Insulation	(ft^2·°F·h/Btu)	(W/m^{2}K)
Exterior Walls to Ambient	R65	0.09
Exterior Walls to Ground	R25	0.23
Roof	R63	0.09
Windows	R5.1	1.11
Ventilation	Mechanical, with heat recovery, η_{HRV}≅60%	
Photovoltaic (PV) Generator	6.3 kW$_p$	
HERS Index	9	

The retail contract cost on the Stow home was approximately $307,000, including the PV system, or $104/ft^2. The home has four floors and no garage, which brings down specific cost.

1.3 The Near Zero Energy Home in Townsend, Massachusetts

The Townsend home (see Figure 5 and Figure 6) was completed in summer 2010. The new owners moved in during July and August 2010. Two ductless mini-splits, each with a single indoor unit, meet space heating and cooling loads (3.5 kWth/12,000 Btu/h each). Unlike the NZEH in Stow, this house has an instantaneous gas heater for water heating. Despite similar exterior dimensions, the conditioned floor area is smaller relative to the house in Stow because attic and basement are conditioned spaces there. The room above the garage is not conditioned to date, but was prepared as room for expansion (see Table 2).

Figure 5. The NZEH in Townsend
Left: Northeast view. Middle: South view. The building is part of a low-energy homes development, most of them equipped with PV generators. The room above the garage is unconditioned space. Right: Wall-to-window ratios for different orientations (without garage/extension).

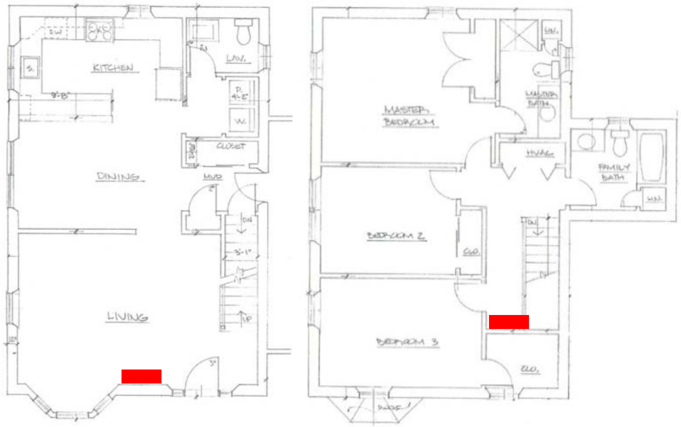

Figure 6. Floor plans for the Townsend home
Left: 1st floor. Right: 2nd floor. Attic and basement are inside the thermal envelope, but are unconditioned spaces. The red boxes mark the position of the mini-split indoor units.

Table 2. Characteristic Data for the Townsend NZEH

Characteristics	Values	
Floor Area	1835 ft^2(170 m^2)	
Calculated Demand for Space Heating	19.2kBtu/ft^2/yr(60.8 kWh/m^2/yr)	
Insulation	($ft^2 \cdot {}^\circ F \cdot h/Btu$)	(W/m^2K)
Exterior Walls to Ambient	R47	0.12
Exterior Walls to Ground	R 24	0.23
Roof	R 63	0.09
Windows	R 4.8	1.2
Ventilation	Mechanical, with heat recovery, $\eta_{HRV} \cong 60\%$	
PV Generator	7.14 kW_p	
HERS Index	2	

The cost of the Townsend home was $245,000, including the PV system, or $134/$ft^2$. This is a two-story home and has a garage.

1.4 Data Acquisition and Instrumentation

We installed fixed components with continuous data recording to collect data in the two homes. We also used temporary sensors and data loggers for short-term and seasonal tests.

Fixed installations included small weather stations for ambient conditions (onsite measurement of ambient temperature and relative humidity (RH) (see Figure 7) at each site. Data were captured and stored in a battery- and solar-powered data logger. The second permanent installation was an electric power meter that used split-core current transformers to measure the electric power consumption of each circuit at the breaker box, as well as the PV generation, at 1-min intervals. The device, an eMonitor from Powerhouse Dynamics, uploads the data to a Web portal to be processed and visualized for the user (see Figure 7). The electricity consumption values measured were apparent power values at the beginning of the study. In January 2011, the manufacturer conducted a firmware update to measure real power instead. Except for a bathroom circuit in one home (which reported a continuous consumption of 4–5 W before the upgrade and then changed to 0 W), the data did not change significantly, and nothing occurred that would have drastically affected the overall energy balance. In both homes the occupants had access to the Web portal that shows the energy consumption (aggregated and in real time).

Figure 7. Left: Both homes were equipped with sensors for ambient temperature and RH. Middle: Electric power consumption captured on a circuit level at the breaker box. Right: Electric power consumption visualized on a Web portal.

For temporal measurements, small data loggers with integrated or attached sensors were used. These loggers, from the “HOBO” series from onset computers, measured indoor temperature and RH. For IAQ tests they were extended with a carbon dioxide (CO_2) sensor (see Figure 8).

Figure 8. Left: Loggers used for temporary indoor measurements. Right: The loggers have external channels for additional sensors; e.g., for CO_2 concentration.

2 Building Performance

The analysis of the energy consumption and building performance is based on 12 months of data for both homes. The measurement period in Stow was September 1, 2010 to August 31, 2011; for Townsend it was November 1, 2010 to October 31, 2011. Figure 9 gives a graphical overview of the ambient conditions for 2010 and 2011; Table 3 lists characteristic values (heating and cooling degree days) for the observation period (data from September 1, 2010 to August 31, 2011).

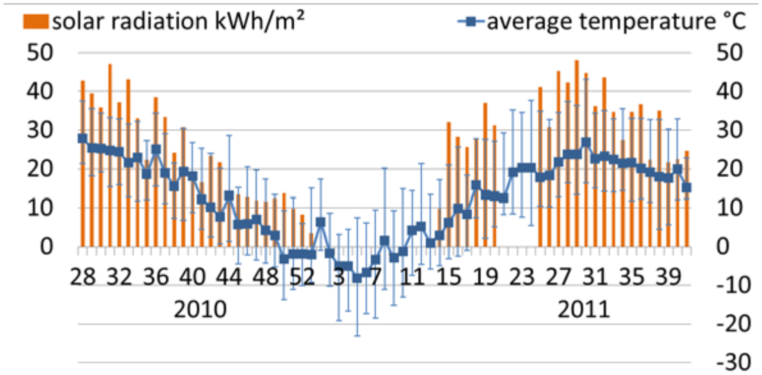

Figure 9. Ambient conditions during the monitoring period as weekly sum (insolation) and weekly averages (temperature). The error bars for temperature indicate minimum and maximum according to week. Due to sensor errors, there are two gaps in the solar irradiation data.

Table 3. Heating and Cooling Degree Days for the Observation Period, Compared to the Long-Term Average for Boston (ASHRAE 2009)

	(°C)	
	2010/2011	Average, Boston
Heating Degree Days 65	3,476	3,123
Cooling Degree Days 65	803	417

The focus of this section is to analyze the overall energy use for various end uses. The question is whether other categories (domestic hot water [DHW] or miscellaneous loads) become more important because building energy efficiency has improved. Another obvious question is whether the net zero-energy balance is achieved.

As mentioned in Section 1.4, we measured only the electric energy consumption. As a heat pump system is used for heating and cooling, a comparison of measured energy consumption (electric) and loads for space heating(thermal) is difficult, because the coefficient of performance (COP, the ratio of electric energy input to thermal energy output) changes with the ambient temperatures. With the given instrumentation we cannot evaluate the performance of the mini-split. Although this is an important question, the space heating loads remain dominant in these buildings.

2.1 Yearly Energy Balance

2.1.1 Stow

As described in Section 1.2, the home is all electric: space heating is provided by a heat pump. DHW was heated with an electric resistance heater in the storage tank at the beginning, later by an air-source heat pump (in the basement), combined with the resistance heater for peak loads.

Figures 10, 11 and 12 show the breakdown of electric energy consumption over 12 months. The consumption is clearly dominated by the mini-split system, which consumes nearly half the energy. DHW is “hidden” in different circuits. Only the direct resistance heater has a dedicated circuit; the heat pump water heater was plugged into different circuit over the course of a year, mainly to basement outlets and later switched to the laundry outlet (see also Figure 15 and Figure 16).One difficulty for assessing and comparing the data was an unusually high occupation density from spring 2011 onward. Because of long-term visitors, the house was occupied by eight people instead of four.

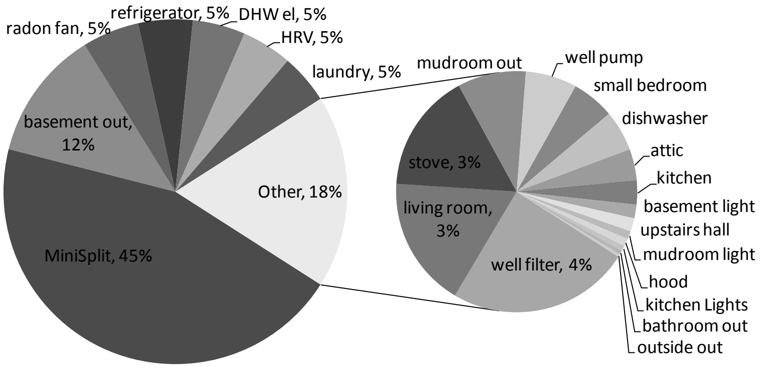

Figure 10. Breakdown of electric energy consumption in Stow[1] by circuits

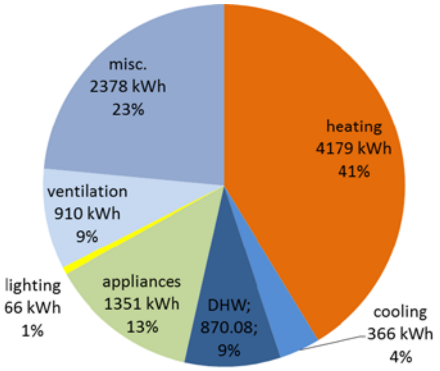

Figure 11. Breakdown of electric energy consumption in Stow by categories

Even though the building is super-insulated, nearly 50% of the electric energy consumption is used for the mini-split. On the other hand, the specific use is very low: 16.5 $\text{kWh}_{el}/\text{m}^2$ for heating and cooling (see Table 4). The mini-split still dominates the overall consumption because the occupants are extremely aware of energy consumption. The electric energy, excluding heating, cooling, DHW, and refrigerator, is approximately 3500 kWh; the national average in the U.S. Northeast is 6,793 kWh (DOE 2010).

---

[1] nomenclature: *out* is used for *outlets.*

Table 4. Total and Specific Energy Consumption for Every Circuit at the Breaker Box in Stow

	kWh	kWh/m²yr	kWh/ft²yr	% of total
Total	**10,120**	**36,8**	**3,4**	
Mini-Split	4,545	16.5	1.5	45%
Basement Outlets	1,237	4.5	0.4	12%
Radon Fan and Smoke Detectors	539	2.0	0.2	5%
Refrigerator	515	1.9	0.2	5%
DHW Direct Electric	500	1.8	0.2	5%
Heat Recovery Ventilator (HRV)	478	1.7	0.2	5%
Laundry	471	1.7	0.2	5%
Well Filter	449	1.6	0.2	4%
Living Room	322	1.2	0.1	3%
Stove	293	1.1	0.1	3%
Mudroom Outlets	169	0.6	0.1	2%
Well Pump	126	0.5	0.04	1%
Small Bedroom	105	0.4	0.04	1%
Dishwasher	100	0.4	0.03	1%
Attic	77	0.3	0.03	1%
Kitchen	60	0.2	0.02	1%
Basement Light	33	0.1	0.01	<1%
Upstairs Hall	33	0.1	0.01	<1%
Mudroom Light	20	0.1	0.01	<1%
Hood	19	0.1	0.01	<1%
Kitchen Lights	13	0.0	0.00	<1%
Bathroom Outlets	10	0.0	0.00	<1%
Outside Outlets	7	0.0	0.00	<1%
	kWh	kWh/kW$_p$		
PV Generation	**7,778**	**1,235**		

The breakdown for the mini-split into heating and cooling is based on the daily average of ambient temperatures; the turnover point is set to 59°F (15°C): on days with an average ambient temperature lower than 59°F (15°C) the power consumption was accounted as heating, above 59°F (15°C) as cooling.

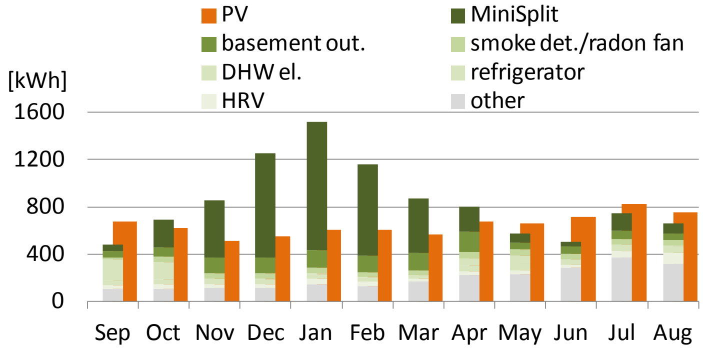

Figure 12. Monthly energy balance for power consumption[2]and PV generation

---

[2] Six circuits with the highest consumption are shown separately, remaining loads are lumped together in "other"

Figure 13 through Figure 16 depict specific and typical patterns in the overall electricity loads, as well as in dedicated circuits. In these carpet plots, the value of electric power (in Watts) is color-coded and the time dimension is plotted against the two axes; the x-axis represents the course of the year, the y-axis the 24 hours of a day.

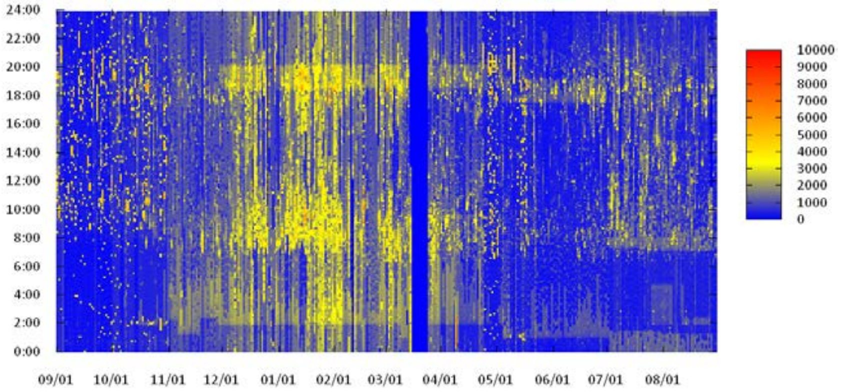

Figure 13. Carpet plot of whole-home average electric power draw throughout the year (5-min intervals)

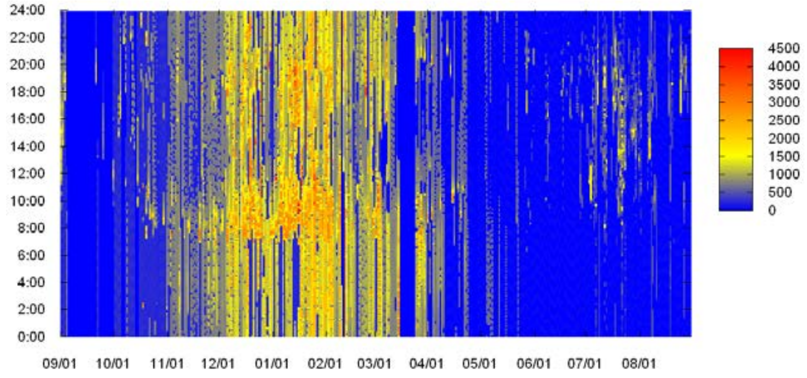

Figure 14. Electricity load pattern for the ductless mini-split system. Power clearly correlates with ambient conditions.

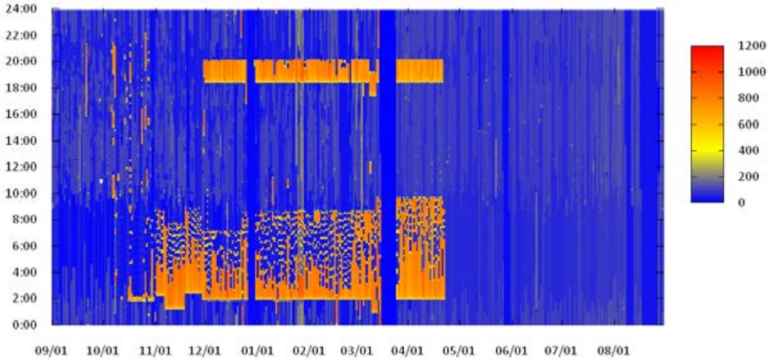

Figure 15. Power draw pattern for the basement outlets circuit[3]

---

[3] The base load of this circuit stems from home office equipment in the basement. In September 2010, the homeowner installed a heat pump for heating DHW (also located in the basement). To avoid acoustic noise problems, the heat pump is controlled by a timer that generates the repetitive patterns seen.

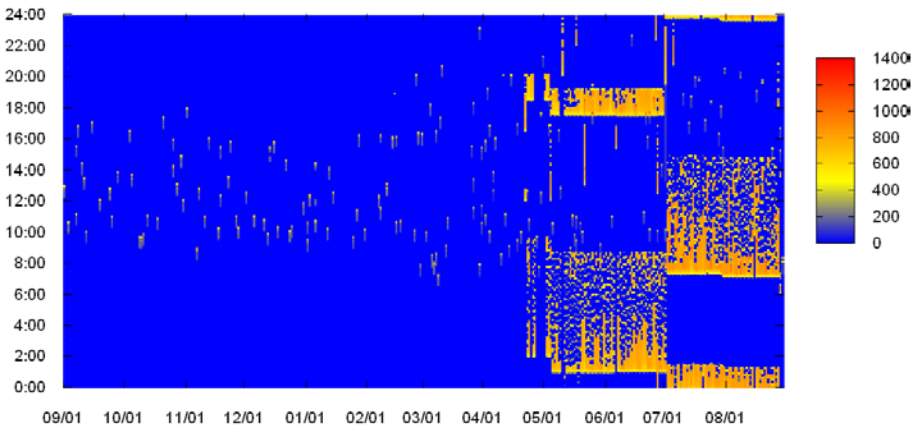

Figure 16. In April 2011 the user switched the water heater pump to the laundry outlets circuit. The reason for the timer schedule change in July 2011 is unknown.

2.1.2 Townsend

As described in Section 1.3, the Townsend home was built and occupied a few months later than the Stow home. The 12-month period for the energy balance is November 1, 2010 to October 31, 2011. Unlike the Stow home, it relies on two energy sources: electricity for space heating (ductless mini-split) and appliances, and natural gas for DHW. The following numbers represent site energy consumption; we did not convert the value to primary or source energy.

The numbers for the total consumption include two smaller and a large data gap: from December 23, 2010 to January 12, 2011 the eMonitor was switched off, so no data were recorded during that period. From February 19 to February 27, 2011, the eMonitor was sent to the manufacturer for an upgrade; from March 6 to March 14 an unknown error interrupted its operation. Table 5 includes an estimate of the consumption during that time, based on average values and outdoor temperature correlations.

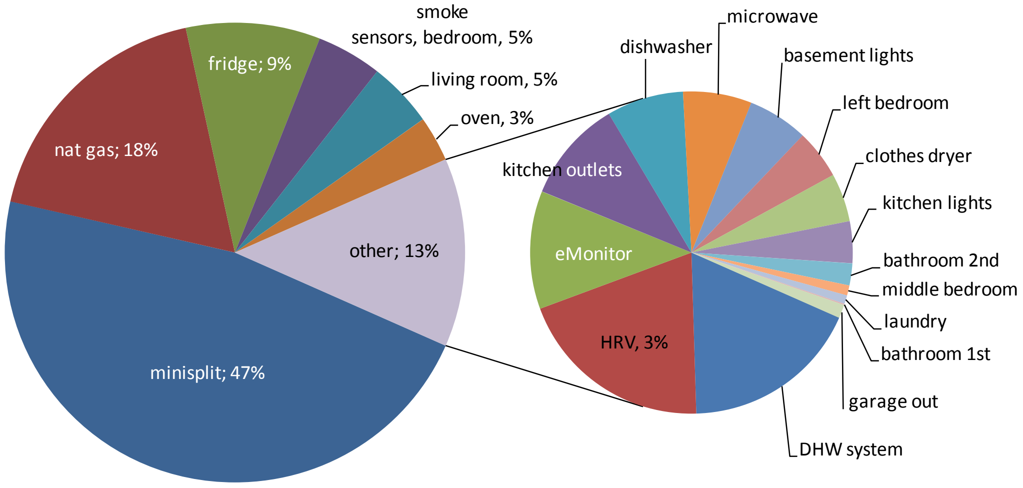

Figure 17. Breakdown of the end-use energy in Townsend, including natural gas for DHW

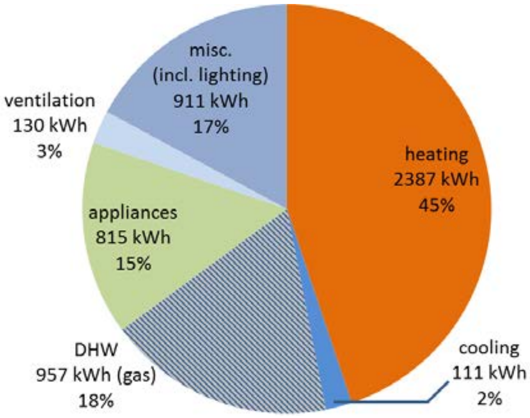

Figure 18. Breakdown of the end-use energy in Townsend by categories

The picture for a breakdown of energy consumption (based on circuits or by category) shows a similar picture as in Stow: by far the biggest load is the mini-split. But again the consumption for household appliances and miscellaneous loads is very low.

The PV generation exceeds the consumption by approximately 1500 kWh (end-use energy balance), even though the specific output of the PV system is rather low: 960 kWh/kW_p is a low yield given the geographic location (compared to Stow: 1,235 kWh/kW_p). This is mainly caused by local shading conditions (see Table 5 and Figure 19 through Figure 22; see also Section 2.2.2 and Figure 26).

Table 5. Total and Specific End-Use Energy Consumption in Townsend

(Due to data gaps in the heating period, an estimate of the real consumption is added in parentheses.)

	kWh[1]	kWh/m²/yr	kWh/ft²/yr	% of Total
Total	Electric: 4364 (4868) Incl. Gas: 5321(5825)	Electric: 25,7 (28,6) Incl. Gas: (34,3)	Electric: 2,4 (2,7) Incl. Gas: (3,2)	
Ductless Mini-split	2498	14.7	1.4	47 %
Refrigerator	503	3.0	0.3	9%
Smoke Sensors, Bedroom	244	1.4	0.1	5%
Living Room	245	1.4	0.1	5%
Oven	170	1.0	0.1	3%
DHW System (Pumps)	126	0.7	0.1	2%
Hrv	140	0.8	0.1	3%
Outlet eMonitor	84	0.5	0.05	2%
Kitchen Outlets	72	0.4	0.04	1%
Dishwasher	54	0.3	0.03	1%
Microwave	48	0.3	0.03	1%

	kWh[1]	$kWh/m^2/yr$	$kWh/ft^2/yr$	% of Total
Basement Lights	43	0.3	0.02	1%
Left Bedroom	35	0.2	0.02	1%
Clothes Dryer	34	0.2	0.02	1%
Kitchen Lights	30	0.2	0.02	1%
Bathroom 2nd	16	0.1	0.01	0%
Middle Bedroom	7	0.0	0.00	0%
Laundry	6	0.0	0.00	0%
Bathroom 1st	1	0.0	0.00	0%
Garage Out	9	0.1	0.01	0%
Natural Gas (DHW)	957	5.6	0.5	18%
	kWh	kWh/kW_p		
PV Generation	**6860**	**961**		

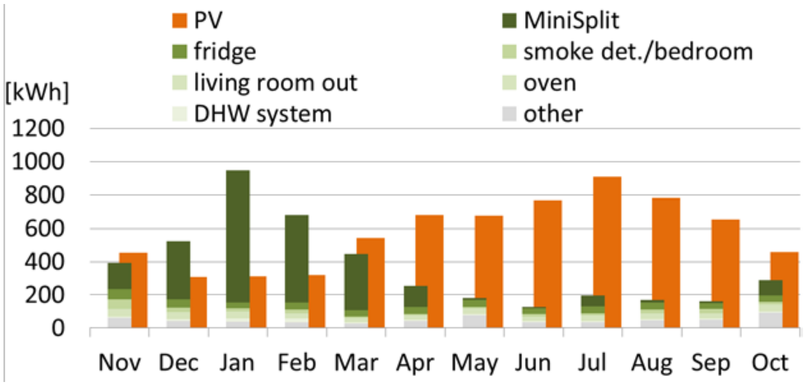

Figure 19. Monthly balance for electric site energy only. DHW is heated by an instantaneous gas heater (no monthly consumption data are available for gas consumption).

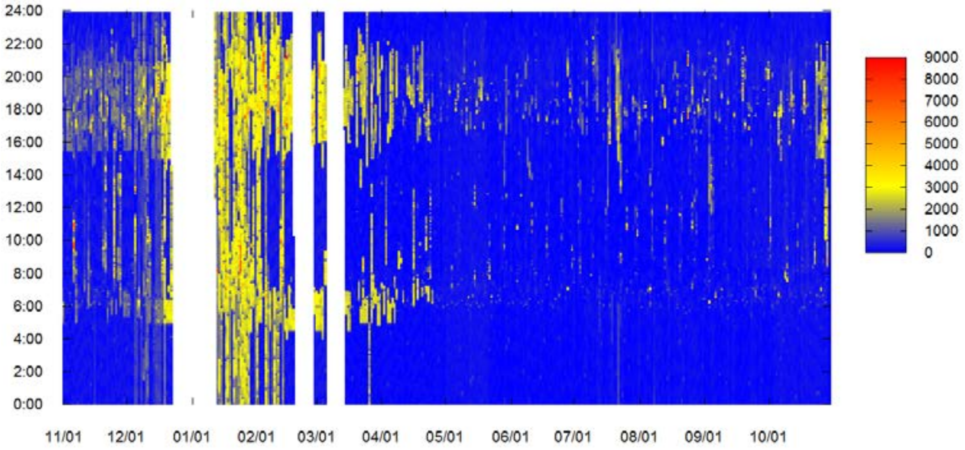

Figure 20. Total electric power draw over the 12-month period

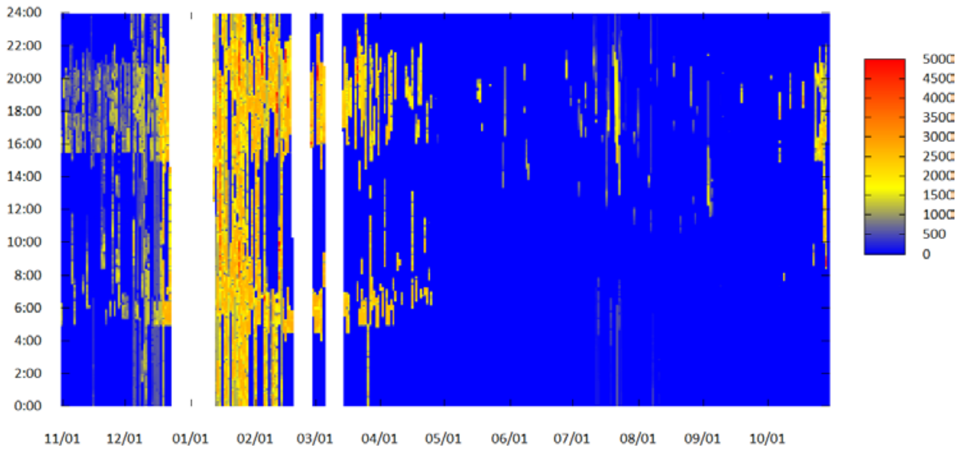

Figure 21. Power draw of the ductless mini-splits (sum of first- and second-floor units)

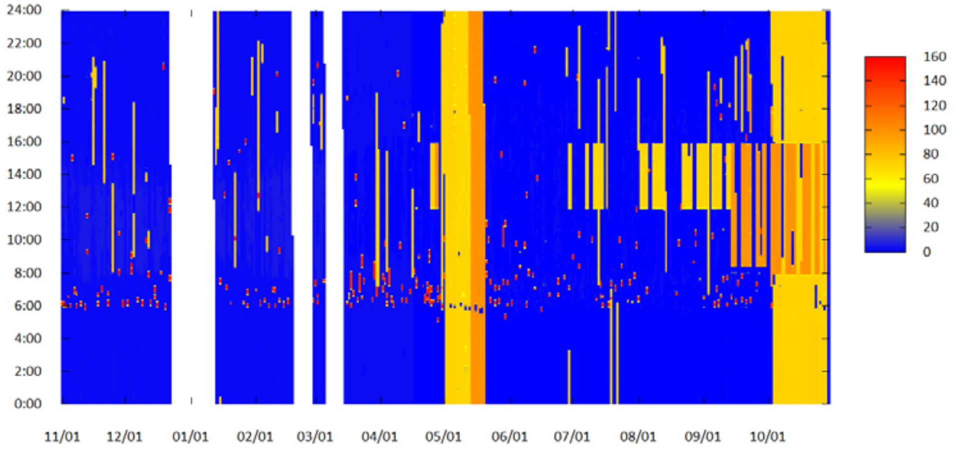

Figure 22. Power draw of the mechanical ventilation system[4]

2.2 Seasonal Energy Balance

In addition to the yearly balance, this section also presents differences in building energy performance for the summer, winter, and shoulder seasons.

2.2.1 Stow

Figure 23 shows loads for PV generation and consumption as average values, based on a three-month time period. Values for the same time of the day were averaged over three months and plotted as a daily load curve. Interesting observations of the loads in Stow include:

- PV peak loads at noon do not largely differ among seasons.
- Energy consumption is very low and consistent in summer and the shoulder seasons.
- In winter, heating loads nearly double the overall load.

---

[4] In May 2011 the system was set to constant operation because of IAQ measurements (see Section 4.2). In autumn 2011 the users switched to automated timer-controlled settings, and from October 2011 onward to 24/7 operation.

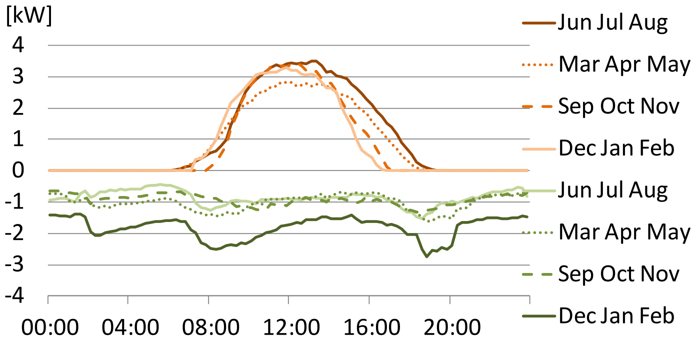

Figure 23. Load patterns for PV generation (orange curves) and power consumption (green curves)

In Figure 24, consumption versus generation is plotted as a three-month-cumulative energy balance over the course of a day. Only in the summer months (July and August) does the PV system provide enough energy for a net-zero balance, or even a small PV surplus. In shoulder seasons the energy balance is slightly negative, and in winter the lower PV yield (in combination with higher loads) leads to a larger overall net import of energy from the grid.

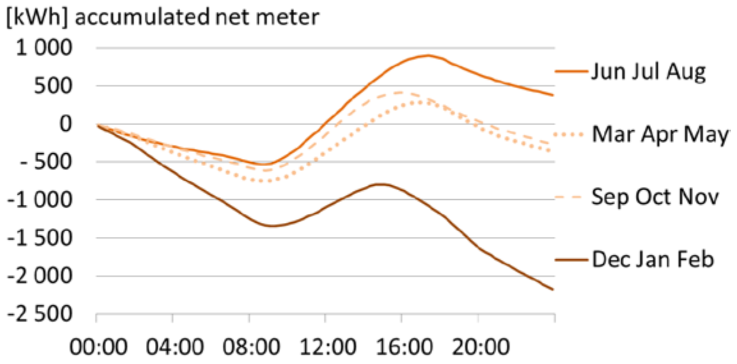

Figure 24. Net energy balance for different seasons as averaged daily balance

We also investigated whether load patterns differ over the course of a week. For Stow there is no evidence for a correlation between electric power consumption and day of the week. Figure 25 shows the accumulated energy consumption for each weekday. The five circuits consuming the most energy are shown separately; the other loads are combined.

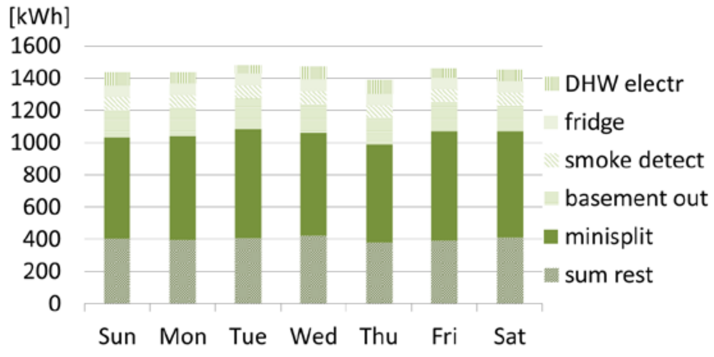

Figure 25. Energy consumption as a function of day of the week

2.2.2 Townsend

The comparison of average loads versus average PV generation between seasons (Figure 26) shows different characteristics from the home in Stow: PV production clearly decreases during winter, mostly because of topography: south of the house a hill and trees block the sun in the early afternoon during the winter.

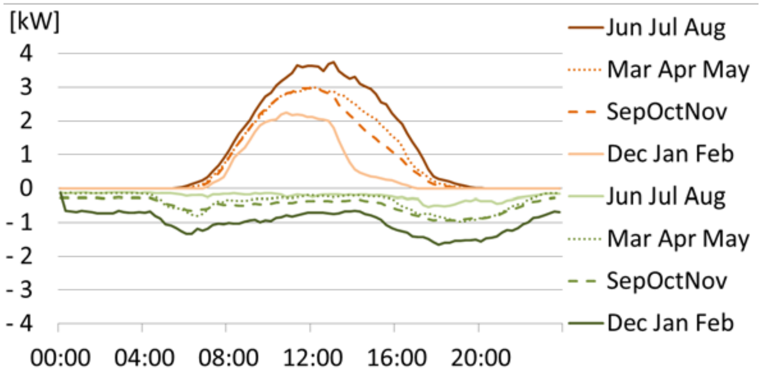

Figure 26. Daily load curves for different seasons in Townsend: PV production (orange), consumption (green curves)

As the accumulated daily net balance shows (see Figure 27), the energy balance is positive most of the year. In the winter months (December, January, and February), consumption exceeds the PV generation by about 1000 kWh, mainly because the PV array is shaded.

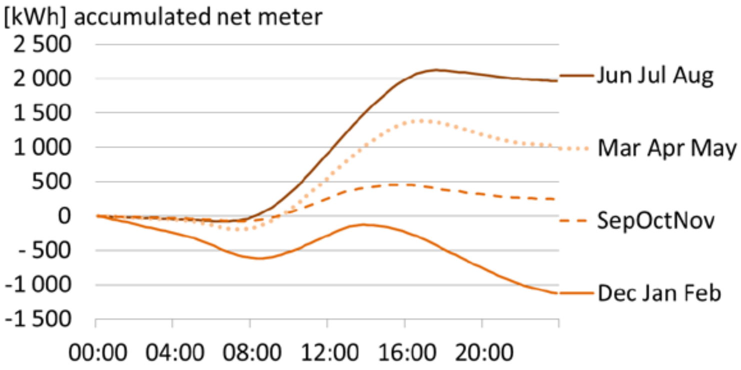

Figure 27. Net energy balance in different seasons as averaged daily balance

In contrast with the Stow house, there is a slight correlation between energy consumption and day of the week; i.e., energy consumption on Sundays is typically somewhat higher. This is caused by higher loads in the living room outlets and kitchen (including oven), but the other loads are quite stable. Figure 28 shows the sum of the five biggest consumers; the other circuits are subsumed in sum rest.

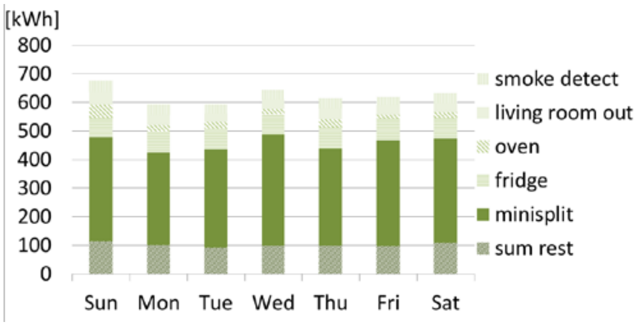

Figure 28. Energy consumption as a function of weekdays

2.3 Correlation of Energy Consumption and Ambient Conditions

A key question is how much energy is used to maintain comfortable conditions (primarily stable indoor temperatures). The graphical analysis of the correlation of ambient temperature and loads for space conditioning can be used to answer this. Reduced heat exchange with the environment, combined with solar and internal gains, drastically reduces sensible heating and cooling loads. In theory, the temperature range where a building stays comfortable with passive measures widens and the temperature slope (load correlation) has a flatter angle (see Figure 29).

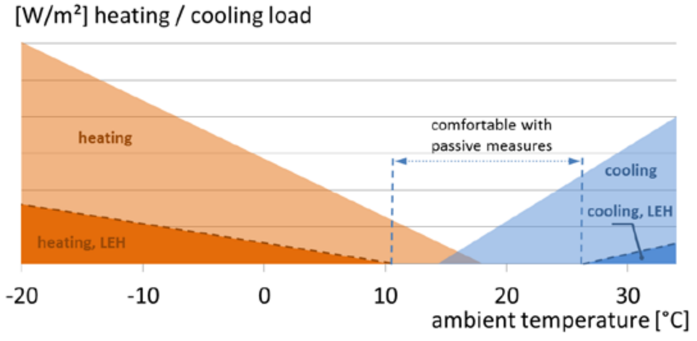

Figure 29. Schematic sketch of ambient conditions and heating/cooling loads in conventional (light color) and optimized/low energy homes (dark color)

Figure 30 shows specific daily average loads of the ductless mini-split, correlated to daily mean values of the ambient temperature. The correlation plots for both homes confirm that the dominating loads are caused by low ambient temperatures in winter. Cooling loads in summer are small or occur for only a limited part of the day, resulting in low daily average values (hardly more than 2 $W/m^2_{electric}$).

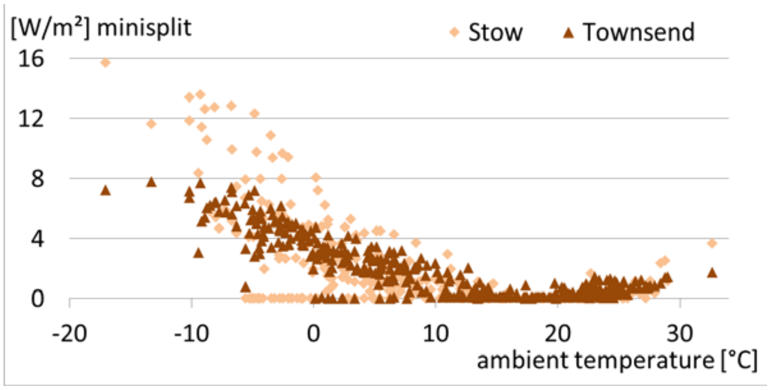

Figure 30. Correlation of ambient temperature and average annual specific electric energy loads[5] for the ductless mini-split in both NZEHs

2.4 Summary Energy Consumption

The main results from the overall analysis of the energy consumption are:

- Even though the loads for space conditioning are drastically reduced (specific electric energy consumption for the mini-splits: 15 and 16 kWh/m²/yr) remain the biggest loads in terms of percentage from the total consumption.
- The remaining loads (appliances and miscellaneous electric loads) are very low. This is mostly because the occupants of both homes decided to buy energy efficient houses and tried to use as little energy as possible. They did nothing extraordinary to achieve a low consumption level. They used compact fluorescent lamps for lighting and switched off devices that were not in use (partly by using switchable power strips). It shows bigger differences in user behavior, even though the energy consumption is quite similar.
- The measured performance of these buildings proofs them as very energy efficient. Without knowing the COP of the mini-split, a comparison of measured consumption and calculated demand is difficult. Assuming an average COP of 2.5 (manufacturer manual: COP for heating = 3.9), both buildings perform as well as, or better than, calculated. A comparison of energy for space heating:
    - Stow: calculated demand: 37.8 kWh/m²/yr; measured consumption: 38.0 kWh/m²/yr
    - Townsend: calculated demand: 60.8 kWh/m²/yr; measured consumption: 35.1 kWh/m²/yr
    - The discrepancy between measurement and calculation in Townsend can be explained by lower indoor temperatures during the heating season (see Section 3).

Without having data on the performance of the mini-split it is hard to tell how much additional energy savings might be possible by optimizing the heat pump system. To further reduce energy consumption for space conditioning, either the heat loss could be further reduced: the weakest components are the ventilation units with a heat recovery efficiency of only about 60%. Or the COP of the mini-split could be enhanced.

---

[5] X-axis: daily average of ambient temperature, Y-axis: daily average of electric load from mini-split, divided by conditioned floor space.

3 Thermal Comfort

Apart from energy consumption, another key question for the performance of super-insulated buildings is indoor thermal comfort in winter and summer. This is particularly of interest for both homes because each uses a point heat/cooling source (only one mini-split indoor unit) on each floor. We measured temperature and RH in different rooms in the summer and winter periods and assessed the thermal comfort rating according to ASHRAE 55(2010). The comfort models (static and adaptive) are explained in Sections 3.1 and 3.2.

For the NZEH, the adaptive model of EN 15251 (2008) is not directly applicable because the homes have air conditioning. The adaptive model in ASHRAE 55 is difficult for short-term measurement because indoor values are compared to a monthly mean for the ambient temperature: for a three-month measurement period the values can be compared to only three reference points. Instead we decided to use the static comfort model of ASHRAE 55that defines comfort zones for indoor temperature and RH and is based on the EN ISO 7730:2005 PMV comfort model.

3.1 Static Comfort Models

The static approach to thermal comfort (ISO 7730) is derived from the physics of heat transfer and is combined with an empirical fit to sensation (predicted mean vote, PMV and predicted percentage of dissatisfaction, PPD) (Fanger 1970). The required four environmental input variables are air and mean radiant temperature, air speed, and RH. The two personal variables are clothing and metabolic heat production. The PMV is probably the index of thermal comfort most widely used for assessing moderate indoor thermal environments. It rests on steady-state heat transfer theory, obtained during a series of studies in climatic chambers, where the climate was held constant. It predicts the comfort vote of occupants on the ASHRAE scale of subjective warmth (–3 cold to +3 hot) as well as the PPD for a certain indoor condition.

Thermal comfort requirements in ISO 7730 rest on the heat balance approach (Fanger 1970) and are distinguished into a summer and a winter season. The ranges of temperature that occupants find comfortable are merely influenced by the characteristic heat insulation of clothing. Therefore, the defined comfort criteria are generally applicable for all rooms independent of the building technology for heating, cooling, and ventilation.

$\theta_{\mathrm{o,c,summer}} = 24.5\ ^{\circ}\mathrm{C}$ for summer season

$\theta_{\mathrm{o,c,winter}} = 22\ ^{\circ}\mathrm{C}$ for winter season

The criterion for thermal comfort is stipulated as an average operative room temperature of 76.1°F (24.5°C) for the summer and 71.6°F (22°C) for the winter, with a tolerance range depending on the predicted PPD: ±33.8°F, ±34.7°F, and ±36.5°F (±1.0°C, ±1.5°C, and ±2.5°C) (classes I, II, and III).

Fanger's thermal comfort model requires the input variables metabolic rate and the insulation level of clothing. For the winter period, a *clo* of 1.0 is assumed, which represents typical winter clothing with long-sleeved shirt and long pants. The summer period is described with a *clo* factor of 0.5, representing a light, short-sleeved shirt and light pants. The prevailing ambient conditions are not considered. Therefore, it is not explicit whether Fanger's model refers to summer or winter conditions.

3.2 Adaptive Comfort Models

Since the publication of the PMV equation in the 1970s, many studies have been published on thermal comfort in buildings under operation. Some have given support to PMV; others have found discrepancies. It has become apparent that no individual field study can adequately validate PMV for everyday use in buildings (Humphreys and Nicol 2002). The fundamental assumption of the adaptive approach is expressed by the adaptive principle: "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" (Nicol and Humphreys 2002; Nicol and McCartney 2002). EN 15251:2007-08 and ASHRAE 55 describe the adaptive approach that includes the variations in the outdoor climate and the person's control over interior conditions to determine thermal preferences. It is based on findings of surveys on thermal comfort conducted in the field. Data about the thermal environment were correlated to the simultaneous response of subjects under real working conditions. The thermal response is usually measured by asking occupants for a comfort vote on a descriptive scale such as the ASHRAE or Bedford scale (Nicol and Humphreys 2002; Nicol and McCartney 2002; Nicol and Roaf 2005). Based on field studies, de Dear and Brager (1998) proposed new thermal comfort standards for naturally ventilated buildings, leaving PMV as the standard for air-conditioned buildings.

The adaptive comfort model takes into account the thermal sensation of the occupants, different actions to adapt to the (changing) thermal environment (e.g., change of clothes, opening windows) as well as variable expectations with respect to outdoor and indoor climate, seeking a customary temperature. The underlying assumption is that people are able to act as meters of their environment and that perceived discomfort is a trigger for behavioral responses to the thermal environment. Although these behavioral phenomena cannot yet be described theoretically in full detail, a model was derived from results of field studies that represents limits for the operative temperature as a function of the outdoor temperature. This simplified approach also avoids difficulties occurring with the assumption of appropriate clo- and meteorological values, as it has to be done with the PMV approach. They are included in the resulting accepted temperature as part of the adaptation.

As mentioned in the beginning of this section, for the adaptive comfort model ASHRAE 55defines thermal comfort for naturally ventilated buildings with reference to the monthly mean ambient air temperature $\theta_{e,month}$ for the adaptive model as this is generally available from meteorological stations.

$$\theta_{o,c} = 17.8°C + 0.31 \cdot \theta_{e,month}$$

The tolerance range is determined by dependence on occupant satisfaction, namely ±4.5°F (±2.5°C) for 90% acceptance and ±6.3°F (±3.5°C) for 80% acceptance.

3.3 Thermal Comfort in Winter

3.3.1 Stow

The indoor conditions were recorded from February to May 2011. Temperature loggers were placed in the living room and in the master bedroom on the second floor.

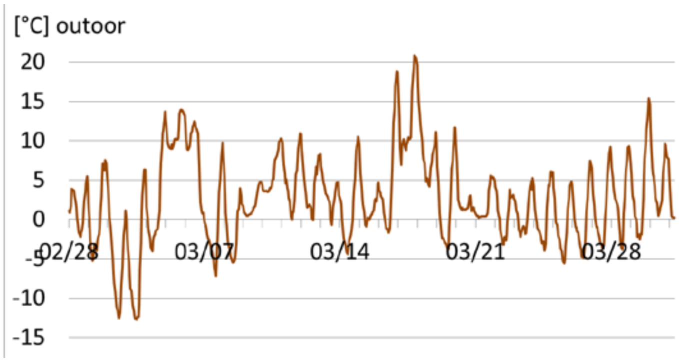

Figure 31. Ambient temperature in the first weeks of the test period

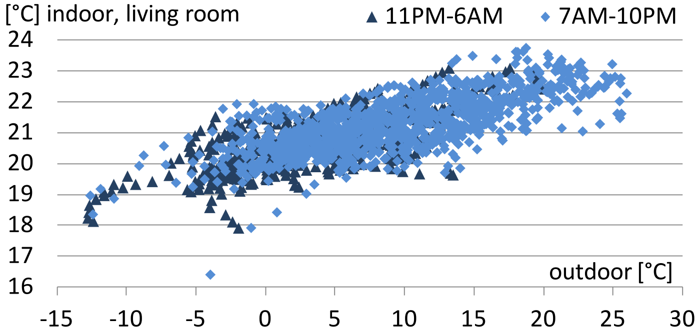

Figure 32. Plot of indoor against ambient temperatures, divided into daytime and night

Even though about 13% of the hourly mean indoor temperatures were below 68°F (20°C), the occupants felt comfortable and had no complaints about low temperatures (to the contrary, the homeowners considered it to be "the warmest house we ever lived in"). This can be confirmed by the space heating capacity, i.e., the occupants were always able to set the system to higher set points to increase the runtime of the heating system, but did not do that.

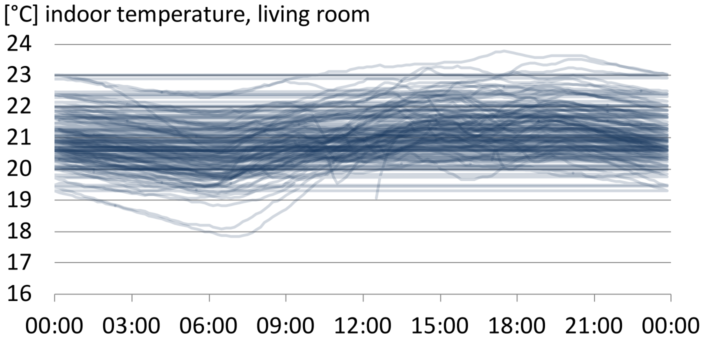

Figure 33. Overlay of indoor temperature curves over the course of the day throughout the year in the Stow house

Figure 33 shows the indoor temperature over the course of the day (for the entire measurement period). The temperature is very stable: the deviation over a day is rarely more than 3.6°F (2°C). In Figure 34 these curves are averaged to a median temperature. The median and the mode are close together, indicating a very stable indoor environment.

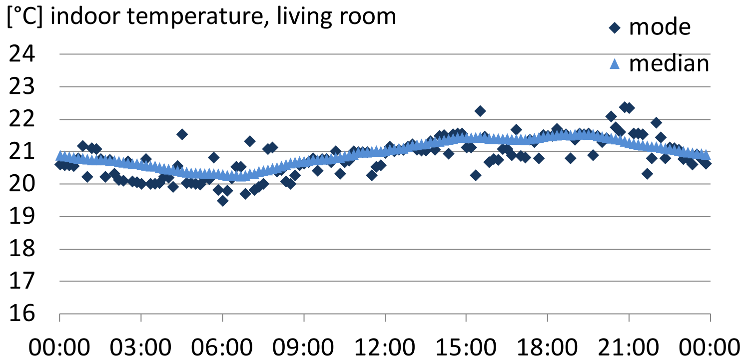

Figure 34. Temperature measurements averaged over the test period (Stow)

To put the data in the context other comfort analyses, we also evaluated the temperature and RH relative to ASHRAE 55-2010. The underlying comfort model is the Fanger comfort model, defined in ISO 7730. The "clothing rate" "clo 1.0" is referring to long trousers and a sweater, "clo 0.5" represents a T-shirt and shorts.

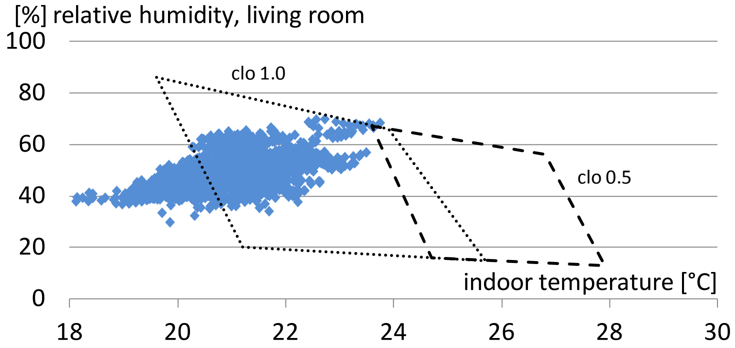

Figure 35. Indoor conditions and comfort zones according to ASHRAE 55 (Stow)

Figure 35 shows that indoor conditions are usually in a comfortable range (assuming an equivalent clothing rate), but for some time temperatures fell below the comfort minimum.

The picture in the master bedroom is similar. Outdoor temperatures lower than 50°F (10°C) cause indoor temperatures to fall below 68°F (20°C). Again, the occupants reported no discomfort.

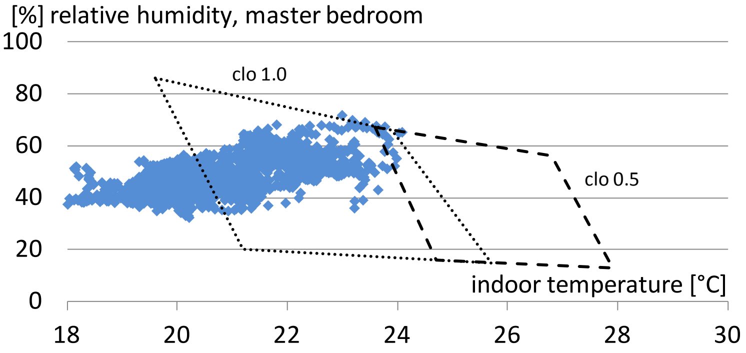

Figure 36. Indoor comfort and comfort zones in the master bedroom (Stow)

3.3.2 Townsend

The measurement for indoor comfort in winter took place at the same time as in Stow (February to May 2011).

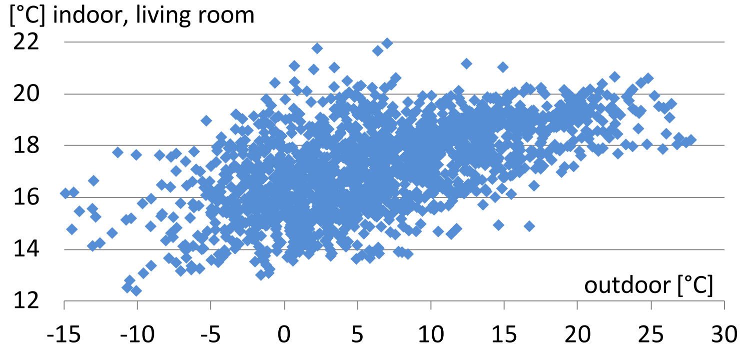

Figure 37. Correlation of indoor and outdoor temperature in Townsend

Figure 37 shows that indoor temperatures were usually below 68°F (20°C). However, occupants neither complained nor set the thermostat to higher set points, indicating that their preferences deviated from the ASHRAE standard.

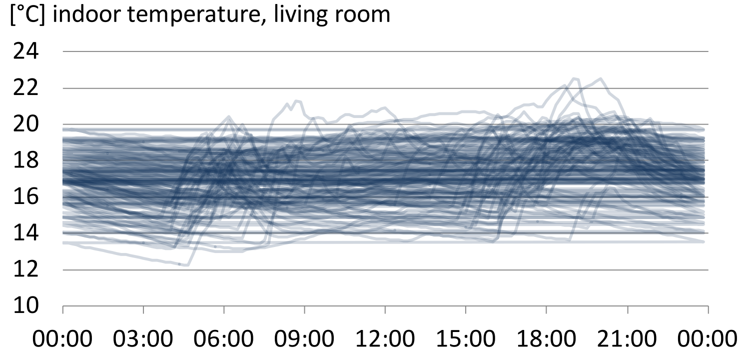

Figure 38. Overlay of indoor temperature curves over the course of the day throughout the year in the Townsend house

Figure 38 shows combined indoor temperature characteristics in the living room. Again, the temperature level is usually below 68°F (20°C). However, instead of a rather flat curve, two spikes occur: in the morning around 6:00 a.m. and in the afternoon after 5:00 p.m. It shows that the occupants systematically set the set points for space heating higher only when they needed more warmth.

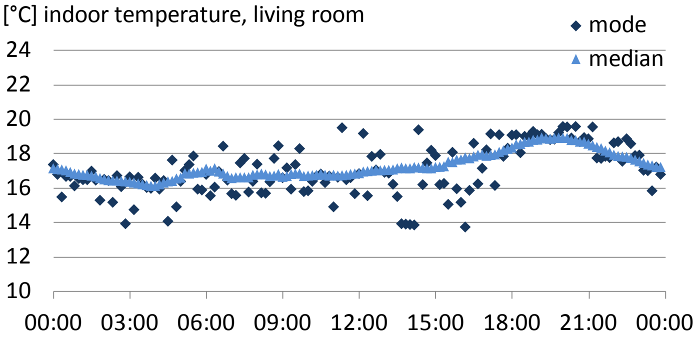

Figure 39. Averaged indoor temperature profile in the living room (Townsend)

According to the comfort limits defined in ASHRAE 55, the house is almost always too cold. The occupants compensate by using slightly higher clothing rates and accepting lower temperatures. The RH values for the living room and the master bedroom are different because the master bedroom is used by only one person and there are other moisture sources (plants and cooking) in and near the living room.

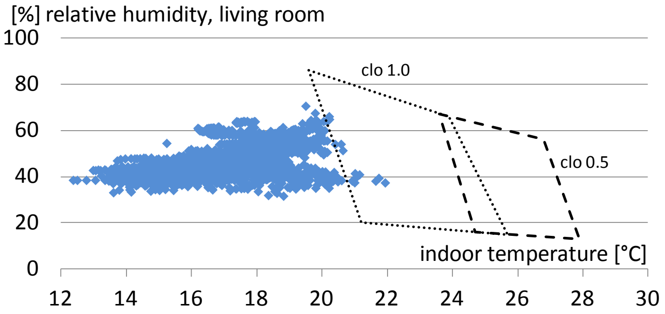

Figure 40. Comfort limits for the living room in Townsend

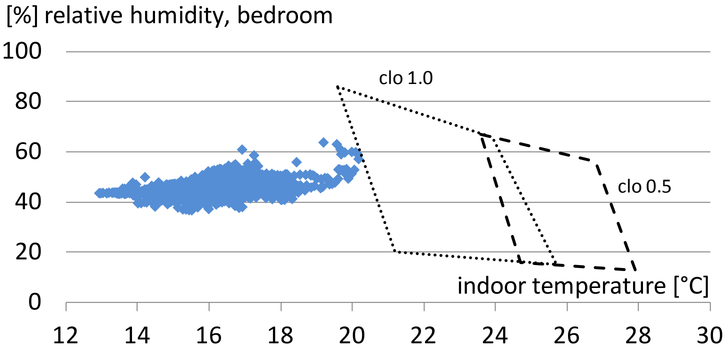

Figure 41. Comfort rating for a bedroom in Townsend

3.3.3 Summary: Thermal Comfort in the Heating Season

The results from two single-family homes depend heavily on occupant behavior and can be hardly used to draw general conclusions. The indoor conditions in Stow are very stable and although temperature drops to levels that are generally rated as uncomfortable, the occupants are satisfied. Whether this is due to individual preferences or to building characteristics (no drafts because of the airtight construction and/or high indoor surface temperatures because of the high insulation levels) cannot be answered without data from a larger number of homes or families. The results from Townsend clearly indicate the influence of occupant acceptance. In that case the occupants were eager to save energy, and did not seem to mind temperatures that many people would consider to be too cold.

The use of a single heat source on each floor seemed to be sufficient. The occupants in both homes stated that they felt no need for an additional heat source in specific rooms. The measured temperatures confirm that: we did not see large differences among rooms.

3.4 Thermal Comfort in Summer

Besides indoor conditions and comfort in winter, we analyzed the performance of the building in the summer. The key question is to what extent the building stays comfortable without additional cooling (which is provided by the ductless mini-split).The test period was from July to September 2011; the ambient conditions for Stow and Townsend are shown in Figure 42 and Figure 43. Indoor conditions were recorded at10-min intervals, the weather data at 5-min intervals.

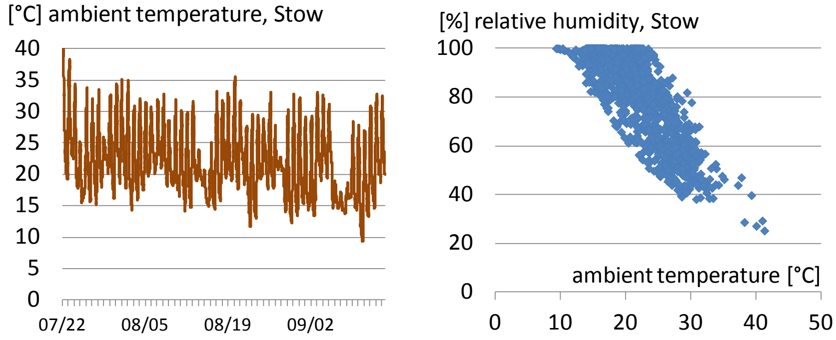

Figure 42. Temperature and RH during the summer months in Stow

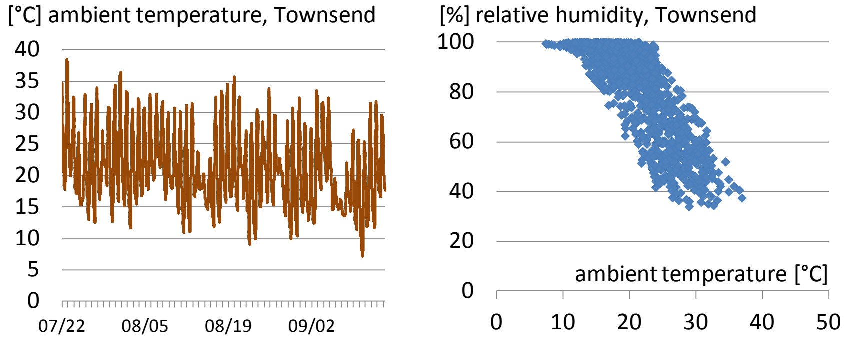

Figure 43. Temperature and RH during the summer months in Townsend

3.4.1 Stow

For comfort analysis in summer, we use the ASHRAE 55 comfort limits to analyze the indoor conditions.

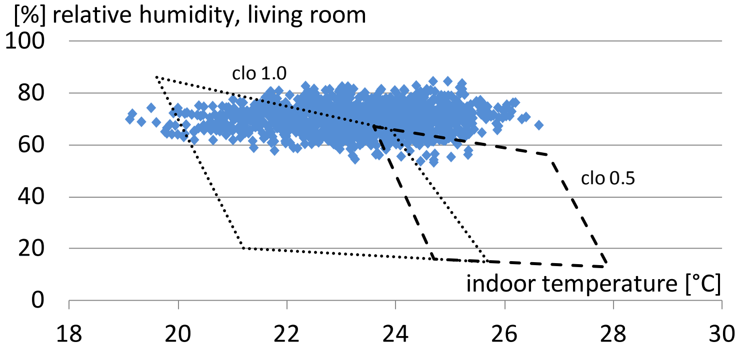

Figure 44. Comfort limits and measured temperature and RH conditions in the living room (Stow)

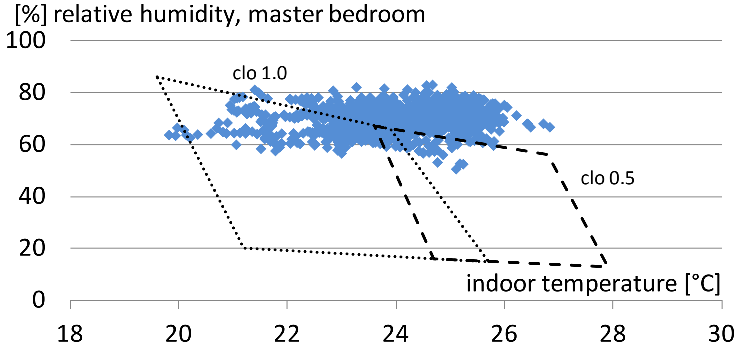

Figure 45. Comfort limits and measured temperature and RH conditions in the master bedroom (Stow)

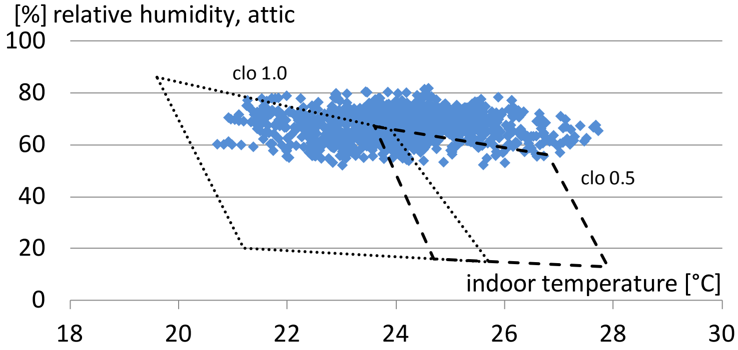

Figure 46. Comfort limits and measured temperature and RH conditions in the finished attic (Stow)

These figures show a similar picture: indoor temperatures never exceed 82.4°F (28°C), and periods with values exceeding 78.8°F (26°C) are limited. Potential discomfort would rather be due to high RH. The mechanical ventilation introduces (rather than reduces) additional latent loads: the heat recovery has the benefit of cooling OA (we measured temperature drops of 41°–46.4°F [5°–8°C]), but the moisture content remained the same.

The overall temperature difference between the floors was minimal (we expected the top floor would be warmer).

3.4.2 Townsend

The indoor conditions in Townsend were measured over the same time period as in Stow. The picture for summer comfort is similar: indoor temperatures typically do not exceed uncomfortable limits, but the RH is high.

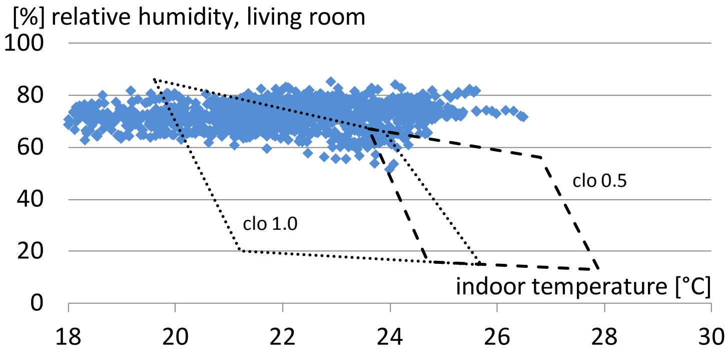

Figure 47. Comfort limits and measured temperature and RH conditions in the living room (Townsend)

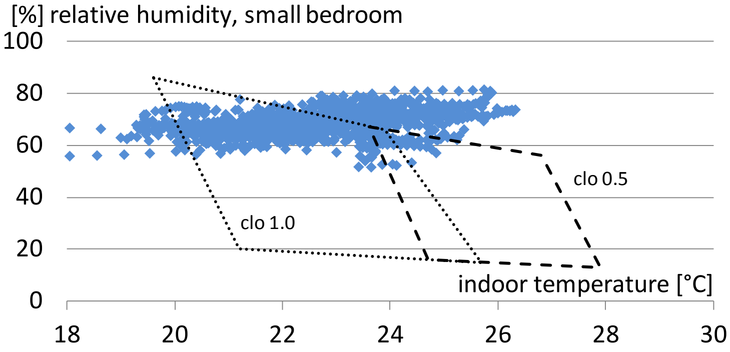

Figure 48. Comfort limits and measured temperature and RH conditions in a bedroom (Townsend)

3.4.3 Summary: Thermal Comfort in the Cooling Season

In contrast to the winter measurements, the results for the summer comfort in Stow and Townsend are rather similar: even though the occupants rarely used the ductless mini-split for space cooling, the temperatures remained in a comfortable range. A potential cause for discomfort is the high RH.

3.5 Summary: Thermal Comfort With Low Energy Consumption

The analysis shows that good indoor comfort can be achieved with passive measures (high insulation levels, air tightness) and the complexity for technical components for space conditioning is drastically reduced. This brings up the opportunity to simplify the systems—a chance to reduce investment costs (smaller units) and running costs (low energy consumption).

A single-point heat source is sufficient in the winter, because additional internal gains (people and/or solar gains) are enough to keep indoor temperatures stable. But the installation separate from occupied rooms (in the hallway in the second floor, no direct connection to the bedrooms) causes problems in the summer, because additional heat gains; e.g., from people, are undesirable and can cause rising temperatures and discomfort.

4 Indoor Air Quality

Besides energy consumption and thermal comfort, the monitoring focused on IAQ. Both buildings have airtight envelopes. Blowerdoor tests were conducted in both homes, with an ACH at 50 Pa $n_{50} = 0.5\ h^{-1}$ in Stow and $n_{50} = 0.7\ h^{-1}$ in Townsend. As described in Table 1 and Table 2, both homes have mechanical ventilation. A main construction difference is the routing of the airflow: in Stow the airflow is fully ducted. Exhaust air is taken from the bathrooms and the kitchen and fresh air is blown into the living room and the bedrooms. For cost optimization, the ductwork in Townsend is simplified: exhaust air is taken from the bathrooms as well, but the fresh air is blown into the central hallway and staircase. To increase air exchange between floors and bedrooms, large grilles were installed in the walls, and the kitchen and living room on the first floor are open to the staircase (see Figure 6).

The Stow home has a Lifebreath 155ECM energy recovery ventilator, with an estimated OA volume flow rate of 70–80 cfm ("medium" low speed), consistent with the 70 cfm value used in the Passive House Planning Package. This translates into an air exchange rate of about $0.3\ h^{-1}$. Although we did not measure the airflow rates directly, this is generally consistent with the ACH inferred from perfluorocarbon tracer (PFT) emitter measurements (see Table 7). The Townsend home has a Fantech Model SHR 1504, with an estimated outdoor air volume flow rate of 80–100 cfm. To meet ASHRAE Standard 62.2 (ASHRAE 2010), both homes would require OA volume flow rates of about 50 cfm.

The analysis focuses on two main topics: CO_2 concentration and indoor pollutants. Whereas CO_2 concentration measurements were conducted over several weeks with equipment owned by Fraunhofer Center for Sustainable Energy, the tests for indoor pollutants (VOCs, aldehydes) were performed in collaboration with Lawrence Berkeley National Laboratory (LBNL) over a three-week test period.

4.1 Carbon Dioxide Concentration

CO_2 can be considered as a proxy for air exchange rates relative to occupancy. The gas is odorless and nontoxic. The question about acceptable indoor concentrations remains controversial. We used the limits stated in ASHRAE 62.1 (2007a); i.e., 700 ppm above the outdoor concentration (1050–1200 ppm). The results are shown in a graphical analysis, where the CO_2 concentration is plotted against the indoor RH. In that way, two IAQ parameters are plotted in one graph, along with the limits for a comfortable indoor environment. The limit for RH is set from 30% to 70%, following ASHRAE 55. The range is marked as "comfort area" with dashed lines, similar to the graphs used to present thermal comfort.

4.1.1 Stow

We placed two CO_2 sensors in the Stow home: one in the kitchen/living-room area and one in the master bedroom. We also recorded temperature and RH.

4.1.1.1 Summer Period

The first test, conducted from August 13 to October 4, 2010, show two notable points:

- The RH was rather high (>60%) most of the time.
- The CO_2 concentration was unexpectedly high, especially in the master bedroom.

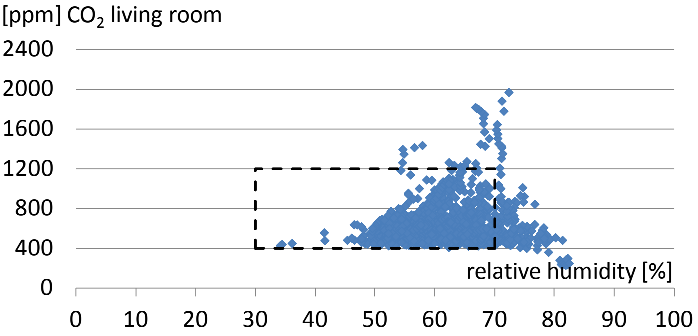

Figure 49. CO_2 **concentration and RH in the Stow living room during the summer test period**

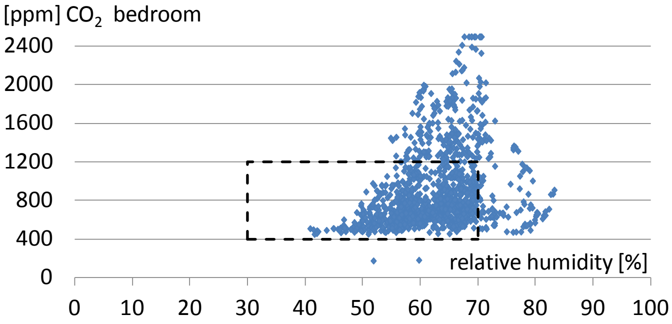

Figure 50. CO_2 **concentration and RH in the Stow master bedroom during the summer test period**

A likely explanation for these values was found in the ventilation unit: the flap for the frost protection was in the wrong position. This flap was built in to prevent icing in the heat exchanger, by closing the fresh air inlet and opening a bypass. Instead of being exchanged with fresh air, exhaust air was recirculated (see Figure 51). The issue was fixed in October 2010.

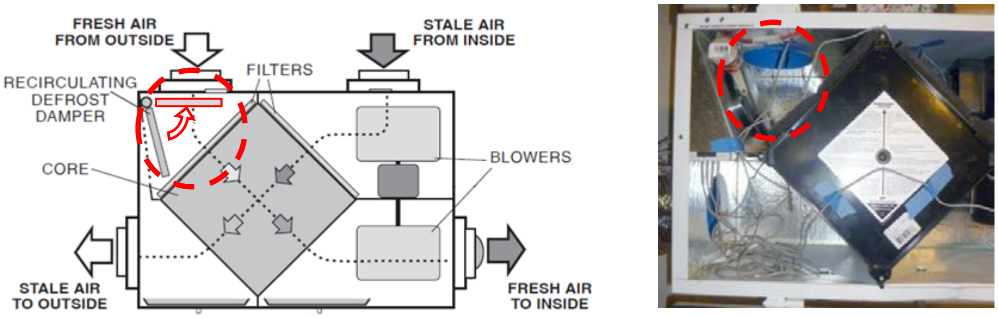

Figure 51. Cross section and picture of the ventilation unit in Stow
When the defrost-damper was in defrost mode, it blocked the fresh air inlet and opened a bypass for the exhaust air.

4.1.1.2 Winter Period

The CO_2 measurement was repeated between February 28 and May 20, 2011. As expected for the winter period, the RH levels were lower, but CO_2 concentrations were still very high, especially for a building with continuously running mechanical ventilation. One obvious reason was a high occupant density. Most of the time during the test period, the home was occupied by eight people—twice the number the ventilation system was designed for. Also, tests performed during the indoor pollutant measurements (see Section 4.2) show air exchange rates (n ≈ 0.3 – 0.4 h^{-1}) that are suitable for “normal” occupation, but too low for that level of occupancy.

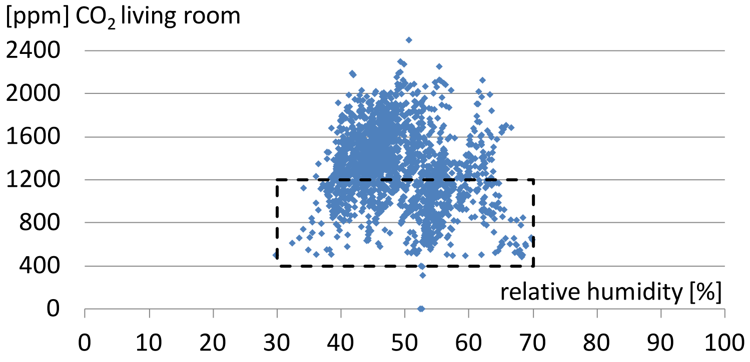

Figure 52.CO_2 concentration and RH in the Stow living room in the winter test period

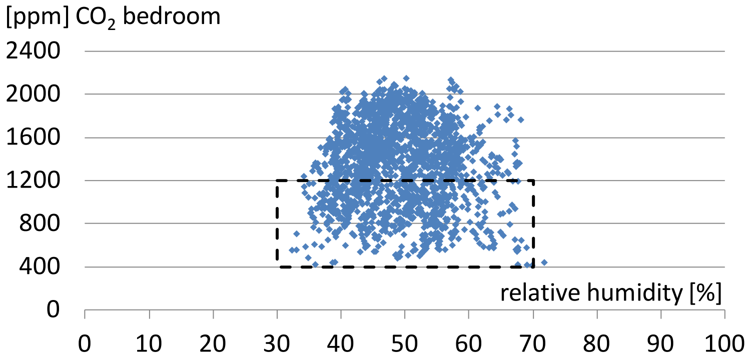

Figure 53.CO_2 concentration and RH in the Stow master bedroom in the winter test period

4.1.2 Townsend

As in Stow, two CO_2 sensors were deployed in Townsend: one in the kitchen/living room area, the other in the master bedroom. Due to a sensor error, data were available only for the winter period.

4.1.2.1 Winter Period

Because of the air quality tests performed in collaboration with LBNL (see next section), the CO_2 test can be split into two operation modes: the time when the HRV was operated manually (switched on and off by the occupants) and constant operation during the LBNL test.

Figure 54 and Figure 55 show the influence of continuous ventilation: while the CO_2 concentration in the living room hardly reached critical limits (even with manual operation of the mechanical ventilation), the bedroom showed insufficient air exchange rates. When the HRV was switched to constant ventilation mode, the CO_2 concentration was always acceptable. The occupants switched off the ventilation because of acoustic noise and to reduce electricity consumption.

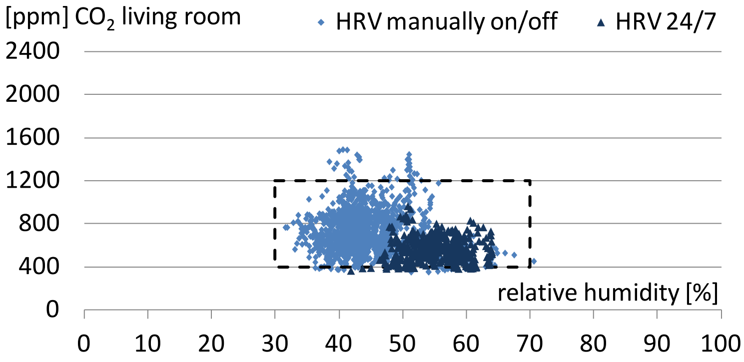

Figure 54. CO_2 **concentration and RH in the Townsend living room in winter with different settings of the mechanical ventilation system**

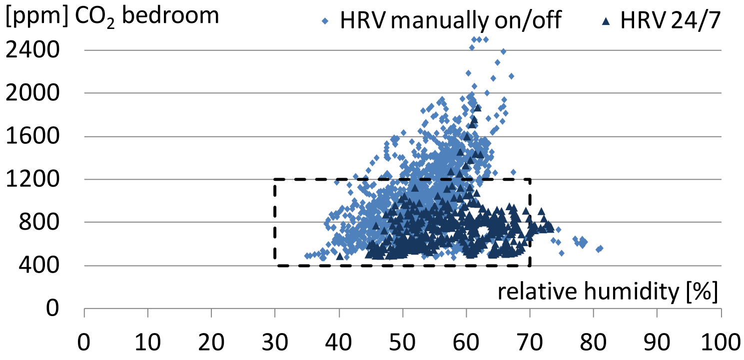

Figure 55. CO_2 **concentration and RH in the Townsend master bedroom in winter with different settings of the mechanical ventilation system**

4.2 Volatile Organic Compound and Aldehyde Concentrations[6]

The main goal of these tests was to evaluate chemical indoor pollutants and understand the impact of ventilation rates on the chemical concentrations and emission rates. The study was conducted simultaneously in both homes from May 6 today 27, 2011). During the study, the average daytime weather condition was cool (48.2°–69.8°F [9°–21°C]) and relatively dry (40%–62% RH) with occasional precipitation events (0–0.3 in.).

4.2.1 Air Sampling Protocol and Analysis

Air was sampled during weekly visits, on Friday afternoons, encompassing three consecutive one-week periods between May 6 and May 27, 2011. These site visits were executed by Fraunhofer CSE staff, henceforth referred to as the field team based on a sampling protocol that was developed with LBNL researchers. The sample and data analyses were carried out at LBNL between May and July 2011. Table 6 summarizes the sampling plan and methods for both study homes. VOCs and aldehydes were actively sampled every Friday at two indoor locations (selected near the center of each floor) and one outdoor location. The programmable PFT sampling systems were also placed at the same indoor locations. Up to 10 passive air samplers were distributed around the house for passive time-integrated VOC, aldehyde, and PFT sampling.

---

[6] Section 4.2 was composed primarily by Dr. Henry Willem of LBNL.

Table 6. Sampling Plan and Measurement Methods

Target chemicals	Sampling Method	Sampling Media	No. of Location	Sampling Plan	Instrument
VOCs (40)	Active	Tenax TA	3 (2 indoor and 1 outdoor)	40 min per sample (every Friday afternoon)	Peristaltic pump
	Passive	Tenax TA	10 (9 indoor and 1 outdoor)	Continuously for one week per sample (samples collected every Friday)	–
Aldehydes (3)	Active	DNPH-coated cartridge	3 (2 indoor and 1 outdoor)	40 min per sample (every Friday afternoon)	Peristaltic pump
	Passive	DNPH-coated cartridge	10 (9 indoor and 1 outdoor)	Continuously for one week per sample (samples collected every Friday)	–
PFTs (3)	Active (PMCH, PDCB)*	Bagsets	2 (both indoor)	2 h and 40 min per bag (daily, afternoon between 2:00 p.m. and 4:40 p.m.)	Programmable air sampler
	Passive (HB)**	Tenax TA	2 (both indoor)	Continuously for one week per sample (samples collected every Friday)	–

*PMCH = perfluoromethylcyclohexane; PDCB = perfluorodimethylcyclobutane
** HB = hexafluorobenzene

Before the study period started, the field team installed small vials to emit PFTs throughout the homes. These tracers were used to determine the whole-house ventilation rates and air exchange rates between zones. At the start of each sampling week the team set a ventilation condition and installed passive samplers for time-integrated measurements of VOCs, aldehydes with low molecular weight formaldehyde and acetaldehyde), and PFT concentrations. The samples were collected before the ventilation setting was changed.

Figure 56. Vials with perfluorocarbon (PMCH and PDCB) and HB emitters

In parallel to the passive sampling method, the team also used active sampling techniques to measure the same parameters. The team installed programmable sampling pumps to collect air samples in bags between 2:00 p.m. and 4:40 p.m. each afternoon. These samples were analyzed for PFT concentrations to determine daily variations of ventilation rates at the specified time. Of note, the PFT types measured in conjunction with bag sampling were different from the PFT collected using passive samplers. After the ventilation setting had been kept continuously for six days, the team returned to the study homes on Friday afternoons to collect air samples. The samples were then analyzed for VOCs and aldehydes. These air sampling visits coincided roughly (but not directly) with ventilation rate data collected from the 2:00 p.m. to 4:40 p.m. PFT bag samples.

One challenge in the study was to achieve and maintain three levels of ventilation rates in each home. To reduce daily variance, the residents were asked to keep windows closed as much as possible throughout the study period, particularly starting from the night before the VOC and aldehyde sampling. Also, the ERV units operated continuously and thermostatic control was set at 72°F±2°F (22.2°C±1.1°C). The environmental control was necessary to maintain a near steady-state condition. Despite these efforts, daily PFT measurements indicated that up to 20% variation was detected, which could be related to external weather conditions, wind direction, windows opening, and occupant behavior.

VOCs and aldehydes were sampled on Tenax TA sorbent tubes (P/N 012347-005-00; Gerstel) and silica gel cartridges coated with 2,4-dinitrophenylhydrazine (DNPH XPoSure Aldehyde Sampler; Waters Corporation) with ozone scrubbers. A peristaltic sampling pump was used to draw the air through the sampling media. Mean VOCs sampling flow rates were 93.2 mL/min (S.D.: 10.7 mL/min) and Aldehyde sampling flow rates were 1030 mL/min (S.D.: 60 mL/min). The simultaneous sampling of both VOCs and aldehydes took 40 min.

VOC samples were analyzed using a gas chromatography/mass spectrometry system. The samples were thermally desorbed with cryogenic inlet system. Forty target chemicals were selected for analysis. The list was representative of various sources of indoor VOCs and included 25 target chemicals shortlisted by the California Department of Public Health. Aldehyde samplers were analyzed for formaldehyde and acetaldehyde, using the high-performance liquid chromatography system.

Three types of liquid PFTs were distributed throughout the homes. The team used 2-dram vials for the liquid PMCH and PDCB; and 2-mL vials for liquid HB. All vials were capped with a septum material on the cap and inverted when in use. PFT vials were distributed in both homes one week before air sampling started to allow the concentration to reach pseudo steady-state. To understand the air exchange characteristics in these multilevel homes, the team divided the ventilated spaces into two vertical zones for PFT distribution. In Stow, the finished basement and first floor were designated as zone 1; the second floor and finished attic were zone 2. In the Townsend home, the first floor was zone 1 and the second floor was zone 2. In both homes, the team distributed five vials in zone 1 and five PDCB vials in zone 2. HB vials were distributed at all locations where a PMCH or PDCB vial was placed. We used air bags to sample both PMCH and PDCB, i.e. using the active sampling method. HB was sampled on the passive VOC samplers.

Figure 57. Active samplers for PFT (blue box) and VOC and aldehydes (peristaltic pump)

The mass of each target chemical represented by the area of total-ion current chromatogram was quantified based on calibration curves prepared from its pure chemical. Analytical blanks were included in the analysis. Travel blanks were transported, stored, and analyzed along with all other samples from the same sampling event. A total of 10% duplicate samples were collected with at least one sample for each sampling method every week. Start and stop sampling flow rates and the total sampling duration were recorded for each sample and were used in the calculation of chemical concentrations. Relative precision of the results in terms of sampling and analysis was ±10% for most of the target chemicals. The uncertainty associated with the analytical method of PFTs was ±5%.

4.2.2 Ventilation Rate Settings

The team maintained three levels of OA ventilation rates in both homes by adjusting the flow rate setting of the ERV units. Changes were made every Friday after the active sampling was completed and the passive samples were collected. Ventilation rates were calculated from air concentrations of PMCH and PDCB in both zones using a two-zone mass balance model. There were more air exchanges between zones in the Stow home than in the Townsend home, which is likely related to the ducted air distribution system in Stow. Table 7 summarizes the whole-house ventilation rates for both homes, which were determined from the net amount of air infiltration. The range of ventilation provided in Townsend was substantially higher than that of the Stow home. Altering the flow rate settings of the ERV units—particularly in Stow—did not appear to increase ventilation rate significantly. The passive sampling over a one-week period estimated consistently higher ventilation rates in both homes, indicating that occupants' activities and behaviors could increase ventilation rates. Ventilation rates in the bedrooms of both homes were higher than other locations by up to 40% (data not shown here).

4.3.3 Results

Figure 58 shows a typical air exchange profile in m³/h between zones and across the envelope. There was indication of vertical stack effect from zone 1 to zone 2 and higher infiltration rate on the first (lower) zone of the house. The rate of air exchange was determined from the net infiltration or exfiltration across the envelope estimated for both zones.

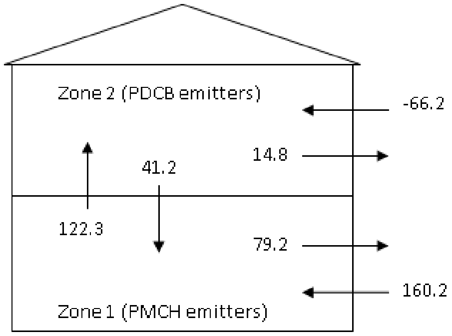

Figure 58. Air exchange profile in m³/h between zones and across the envelope for Townsend

Table 7. Calculated Overall Home Outdoor Air Exchange Rates (Based on PFT Concentrations Measured in Bag Samples Collected 2:00 p.m. to 4:40 p.m. Each Friday Afternoon)

ERV Setting	Stow (h^{-1})	Townsend (h^{-1})
Low	0.25	0.41
Medium	0.36	0.56
High	0.45	0.69

Table 8 and Table 9 list the VOC and aldehyde concentrations in both homes at three ventilation rates. The results were obtained from an active sampling method. Results from the passive sampling are shown in Table 10 to Table 13. Only data collected from main rooms or areas of the house were included as the variations between measurements on the same floor were relatively small. Blank cells indicate that concentration data were below the lower limit of quantitation. Aldehyde concentrations data obtained from passive sampling were generally lower than the active sampling results. This was consistent with the PFT results, which suggested higher integrated air exchange rates over a one-week period and thus better dilution of indoor-generated chemical. The same effects were, however, not clearly seen when comparing active and passive VOC results.

VOC and aldehyde concentrations were relatively constant between locations in both homes. Most variations observed were insignificant. These indicated reasonably good mixing in both homes. There was, however, a trend of lower concentrations in the bedrooms, which could be related to the higher ventilation rates measured in these enclosed areas. The predominant chemicals in both homes were similar: hexanal, α-pinene, d-limonene, nonanal, octanal, 3-carene, and 2-butoxyethanol. Increasing ventilation rates appeared to lower the concentrations of most VOCs and aldehydes, except decanal, nonanal, benzene, and decamethylcyclopentasiloxane. Combining data from active and passive sampling methods, measured indoor formaldehyde concentrations in Stow were in the ranges of 28–44 µg/m^{-3} at low, 24–34 µg/m^{-3} at medium, and 20–32 µg/m^{-3}at high ventilation settings. In Townsend, the ranges were 27–49 µg/m^{-3} at low, 25–47 µg/m^{-3} at medium, and 10–24 µg/m^{-3} at high ventilation rates.

Table 8. VOC Concentrations in Stow and Townsend at Three Ventilation Rate Settings

Class	Target Chemicals ($\mu g/m^3$)	Stow Level 1			Stow Level 2			Townsend Level 1			Townsend Level 2		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Alcohol	2-Ethyl-1-hexanol	9.2	6.1	6.6	10.0	5.8	7.6	9.0	4.6	1.2	7.8	3.4	2.5
Aldehyde	Benzaldehyde	8.6	6.9	5.6	9.1	6.6	5.6	7.1	5.0	6.2	5.7	4.1	8.8
	Butanal	7.4	7.3	–	9.0	7.7	–	5.4	5.1	–	5.5	4.4	–
	Decanal	9.2	11.9	12.4	12.9	11.9	13.4	5.1	4.6	2.2	5.6	3.2	5.8
	Heptanal	16.9	13.6	9.3	19.9	13.4	9.5	7.7	5.5	1.2	7.1	4.3	3.0
	Hexanal	171	147	79.9	203	145	86.7	102	75.0	6.9	102	59.4	29.1
	Nonanal	39.8	33.6	36.5	47.1	32.5	36.4	20.8	14.6	6.3	20.8	11.6	16.4
	Octanal	31.2	26.3	19.9	37.0	25.5	21.4	18.6	12.5	3.4	17.3	9.5	7.6
Alkane	Decane	2.8	2.2	1.6	3.1	2.1	1.7	6.4	5.1	3.0	6.0	4.1	4.9
	Dodecane	8.6	5.8	3.8	9.4	5.7	4.1	1.9	1.3	–	1.7	0.9	1.0
	Heptane	5.7	4.5	2.2	6.5	4.4	2.3	9.7	8.6	1.0	8.6	6.5	2.0
	Hexadecane	4.2	2.4	2.6	4.6	2.2	2.5	2.6	1.2	0.7	2.8	1.0	1.6
	Octane	3.5	2.4	1.8	3.7	2.4	1.9	1.5	1.6	0.6	1.5	1.3	1.2
	Tetradecane	4.6	2.6	1.9	4.8	2.5	2.2	4.8	2.7	0.9	4.5	2.1	2.1
	Undecane	7.6	5.8	3.2	8.9	6.0	3.8	7.0	4.3	2.2	6.1	3.1	4.7
Aromatic	1,2,3-Trimethylbenzene	0.5	0.3	–	0.5	0.3	–	0.5	0.4	–	0.4	0.3	–
	1,2,4-Trimethylbenzene	1.2	0.8	0.3	1.3	0.8	0.4	1.8	1.6	–	1.6	1.2	0.6
	Benzene	2.8	0.6	0.7	3.0	0.6	0.8	1.9	1.7	1.9	0.8	1.4	2.0
	Ethylbenzene	1.5	1.0	0.5	1.6	1.0	0.6	2.0	2.1	–	1.8	1.6	0.7
	o-Xylene	4.0	4.8	2.0	4.7	4.7	2.2	2.8	3.5	0.6	2.6	2.6	1.1
	m/p-Xylene	3.6	2.6	1.3	4.0	2.5	1.6	5.3	6.4	1.0	4.9	4.6	1.9
	Toluene	18.0	9.9	4.5	18.1	9.7	9.0	17.3	17.0	2.8	15.5	12.2	4.9
Ester	TXIB (di-isomer)	12.1	6.3	5.3	9.7	6.2	6.8	0.9	0.4	–	0.8	0.4	0.5

Class	Target Chemicals (µg/m³)	Stow Level 1			Stow Level 2			Townsend Level 1			Townsend Level 2		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
	TXIB (mono-isomer)	2.9	2.1	2.3	2.8	1.8	2.4	3.4	2.2	-	3.0	1.5	2.0
	2-Butoxyethanol	22.3	17.6	14.0	26.1	17.3	15.8	6.7	4.9	-	6.4	3.5	2.5
Siloxane	**Decamethylcyclo-pentasiloxane**	6.0	4.7	24.0	5.6	4.8	11.3	33.1	30.6	1.2	37.3	26.9	3.3
	Octamethylcyclotetrasiloxane	1.2	0.6	0.5	1.0	0.6	0.5	1.3	0.8	–	1.6	0.8	–
	Hexamethyl-cyclotrisiloxane	5.8	3.2	3.5	4.5	4.2	3.5	4.4	3.6	0.7	5.9	4.3	4.0
Terpene	**3-Carene**	25.7	18.7	7.4	28.1	18.4	7.8	24.3	21.6	1.8	22.5	16.4	4.6
	a-Pinene	101	70.1	29.8	116	72.6	32.1	37.7	22.9	3.5	32.6	17.7	6.5
	a-Terpineol	1.0	0.6	0.3	1.1	0.6	0.4	0.5	0.2	–	0.4	0.2	–
	d-Limonene	84.6	16.8	6.7	95.7	16.7	7.6	98.7	20.8	–	58.1	14.7	1.9
	g-Terpinene	0.7	0.5	–	0.8	0.5	–	13.4	0.4	–	6.2	–	–

Table 9. Aldehyde Concentrations in Stow and Townsend at Three Ventilation Rate Settings

Target Chemicals (µg/m³)	Stow Level 1			Stow Level 2			Townsend Level 1			Townsend Level 2		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Formaldehyde	44.0	32.8	25.5	41.9	31.5	20.2	38.8	28.7	10.0	35.3	25.7	18.6
Acetaldehyde	85.9	52.7	27.7	83.0	51.4	21.6	40.5	29.2	5.7	37.6	27.4	10.2

Table 10.VOCs Concentrations in Stow at Three Ventilation Rates Based on Passive Sampling Data (Data Shown for Four Locations)

Class	Target Chemicals ($\mu g/m^3$)	Stow Living Room			Stow Kitchen			Stow Main Bedroom			Stow Common Bedroom		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Alcohol	2-Ethyl-1-hexanol	9.3	7.9	7.5	10.4	9.3	5.9	7.0	7.0	5.0	9.1	15.3	9.1
Aldehyde	Benzaldehyde	7.4	6.6	8.3	7.7	8.0	7.5	6.3	6.9	7.0	9.1	8.5	10.4
	Butanal	10.9	10.3	10.7	10.4	10.2	9.1	7.1	8.7	8.3	10.7	10.9	13.5
	Decanal	9.2	16.5	10.7	11.7	18.0	10.0	19.6	14.2	16.1	11.4	9.7	17.8
	Heptanal	15.0	17.3	17.4	16.4	16.5	14.6	15.9	19.6	17.9	23.0	23.8	28.8
	Hexanal	223	211	221	228	207	172	166	177	167	241	235	289
	Nonanal	32.6	43.6	38.2	40.1	43.5	34.4	37.3	40.7	38.3	42.8	45.6	52.2
	Octanal	24.4	28.0	29.7	27.3	29.3	25.0	29.2	34.2	33.4	39.2	40.1	48.4
Alkane	Decane	4.2	3.0	2.9	4.1	3.0	2.7	3.3	2.6	2.5	3.6	3.2	3.5
	Heptane	5.1	7.2	6.4	6.6	7.7	6.7	2.9	4.0	3.3	3.8	5.2	5.1
	Hexadecane	3.8	5.1	2.8	3.9	4.1	2.4	3.3	3.4	2.2	3.5	3.5	2.6
	Octane	3.5	3.8	3.1	3.9	3.6	3.2	2.5	2.6	2.2	3.3	3.9	4.1
	Tetradecane	4.1	4.4	2.7	4.2	4.0	2.4	3.2	3.2	2.4	4.0	3.6	2.8
	Undecane	8.1	7.8	6.3	8.6	6.8	5.8	7.0	6.9	5.5	10.8	7.2	9.7
Aromatic	1,2,3-Trimethylbenzene	0.7	0.5	0.4	0.8	0.5	0.4	0.4	0.3	-	0.5	0.4	-
	1,2,4-Trimethylbenzene	1.7	1.3	0.9	1.9	1.3	1.0	1.1	0.9	0.7	1.2	1.0	0.8
	Benzene	27.1	10.1	1.0	-	3.8	0.9	0.0	21.9	1.1	13.2	22.7	1.6
	m/p-Xylene	5.4	3.6	3.2	5.6	3.8	3.0	3.8	2.8	2.2	5.8	4.0	4.5
	o-Xylene	3.8	3.6	4.2	3.6	3.2	3.9	2.4	2.4	2.7	3.7	3.3	4.5
	Toluene	16.6	17.8	14.3	16.5	18.1	14.0	10.5	10.9	8.6	15.4	18.0	19.6
Ester	TXIB (di-isomer)	7.7	11.0	5.6	7.2	8.8	4.0	3.9	3.8	2.8	6.4	6.1	5.5
	TXIB (mono-isomer)	8.8	7.5	6.6	7.7	6.8	5.2	4.6	5.2	4.3	12.5	11.9	12.4
	2-Butoxyethanol	19.8	15.5	20.5	23.1	17.7	17.0	16.7	15.9	16.1	23.4	19.7	23.4
Terpene	**3-Carene**	23.6	25.2	21.6	25.1	25.1	20.4	14.6	16.2	12.6	25.0	27.4	26.0
	a-Pinene	100	91.2	90.4	88.7	88.2	81.8	54.0	64.4	52.4	90.3	94.3	89.2
	a-Terpineol	0.8	0.8	0.7	0.9	0.8	0.6	0.6	0.9	0.5	0.9	0.8	0.8
	d-Limonene	35.8	101	35.1	38.3	112	33.6	22.5	26.1	19.8	31.8	35.0	30.5
	g-Terpinene	0.4	0.8	0.8	0.9	0.9	0.7	0.4	-	-	-	-	0.5

Table 11. VOCs Concentrations in Townsend at Three Ventilation Rates Based on Passive Sampling Data (Data Shown for Four Locations)

Class	**Target chemicals ($\mu g/m^3$)**	**Townsend Living Room**			**Townsend Kitchen**			**Townsend Main Bedroom**			**Townsend Common Bedroom**		
		Low	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Alcohol	2-Ethyl-1-hexanol	8.5	6.6	6.2	9.5	7.5	8.5	8.2	6.2	6.8	7.1	6.2	5.9
Aldehyde	Benzaldehyde	7.6	7.7	6.6	8.9	8.3	8.0	6.7	6.1	6.7	6.1	5.7	6.1
	Butanal	10.8	11.3	7.1	11.5	12.9	7.8	8.4	8.3	5.7	7.9	8.4	5.4
	Decanal	5.3	4.1	3.4	5.4	4.0	4.9	5.0	4.4	4.8	5.1	4.8	3.4
	Heptanal	10.6	9.9	6.8	11.9	10.9	8.4	8.0	7.4	6.4	7.6	7.9	5.7
	Hexanal	174	171	120	201	188	142	150	136	117	138	136	94.3
	Nonanal	23.1	19.6	15.4	26.9	21.0	22.0	19.5	16.9	16.5	20.7	18.9	14.9
	Octanal	21.1	18.4	13.2	23.9	20.9	17.4	16.8	15.1	13.4	15.6	14.8	11.2
Alkane	Decane	11.5	10.2	5.0	13.1	11.4	6.9	7.8	7.7	4.2	7.8	8.2	3.7
	Heptane	19.2	19.8	10.7	23.0	26.4	15.4	9.6	10.3	6.2	10.3	11.5	6.1
	Hexadecane	2.2	1.4	1.9	2.1	1.4	2.1	3.7	2.3	2.9	2.6	1.9	2.6
	Octane	3.0	3.1	1.6	3.5	3.7	2.0	2.1	1.9	1.1	2.3	2.1	1.1
	Tetradecane	4.7	3.7	4.0	6.1	4.5	5.9	5.1	3.6	3.9	4.1	3.1	3.6
	Undecane	10.1	8.0	4.9	11.7	8.9	6.5	6.9	6.0	3.9	6.7	6.3	3.3
Aromatic	1,2,3-Trimethylbenzene	0.8	0.6	0.4	0.8	0.7	0.4	0.5	0.4	0.3	0.5	0.4	–
	1,2,4-Trimethylbenzene	3.2	2.4	1.4	3.4	2.9	1.8	1.9	1.7	1.2	1.8	1.7	1.0
	Benzene	2.8	4.5	25.4	1.8	5.0	4.6	21.6	2.8	14.9	21.1	3.0	13.6
	m/p-Xylene	12.7	11.1	4.6	13.9	13.3	6.0	7.0	6.4	3.5	7.1	7.2	3.2
	o-Xylene	5.0	5.4	2.2	5.4	6.3	2.7	3.2	3.5	1.9	3.1	3.7	1.5
	Toluene	35.3	34.7	16.7	39.4	41.6	21.9	20.6	19.4	12.4	20.7	21.3	11.0
Ester	TXIB (di-isomer)	0.7	0.7	0.5	0.8	1.0	1.0	0.6	1.1	-	-	0.4	0.6
	TXIB (mono-isomer)	8.4	8.6	5.7	9.2	9.5	9.1	6.7	7.0	6.1	5.6	7.4	5.4
	2-Butoxyethanol	6.1	7.4	6.4	8.1	8.2	9.8	6.1	6.8	6.9	4.6	6.9	7.0
Terpene	**3-Carene**	41.9	35.5	18.3	45.5	42.3	23.2	26.0	22.4	14.9	25.6	24.7	12.9
	a-Pinene	46.1	40.7	26.3	48.6	46.6	27.7	41.1	31.2	26.2	32.5	29.7	17.8
	a-Terpineol	0.4	–	–	0.6	0.5	0.5	0.4	–	0.4	–	–	–
	d-Limonene	46.8	28.6	19.3	58.6	35.1	27.2	25.4	20.7	15.8	26.6	22.6	13.7
	g-Terpinene	0.8	–	0.5	1.1	0.5	1.5	–	–	0.5	–	–	–

Table 12. Aldehydes Concentrations in Stow at Three Ventilation Rates Based on Passive Sampling Data (Data Shown for Four Locations)

Target Chemicals ($\mu g/m^3$)	Stow Living Room			Stow Kitchen			Stow Main Bedroom			Stow Common Bedroom		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Formaldehyde	39.2	34.2	32.2	35.2	31.4	30.8	29.1	27.1	25.7	28.2	23.7	20.3
Acetaldehyde	61.4	54.6	51.8	65.4	54.8	51.9	41.8	40.9	40.6	68.6	64.1	61.7

Table 13. Aldehydes Concentrations in Townsend at Three Ventilation Rates Based on Passive Sampling Data (Data Shown for Four Locations)

Target Chemicals ($\mu g/m^3$)	Townsend Living Room			Townsend Kitchen			Townsend Main Bedroom			Townsend Common Bedroom		
	Low	Med	High	Low	Low	Med	High	Low	Low	Med	High	Low
Formaldehyde	39.3	33.2	32.9	40.5	37.0	34.0	49.6	46.7	38.3	27.1	26.4	24.9
Acetaldehyde	50.9	39.7	27.3	55.8	46.3	27.5	43.1	31.9	23.1	37.1	34.4	18.3

4.3.4 Summary for Volatile Organic Compounds and Aldehydes

The indoor formaldehyde concentrations in both homes exceeded the chronic and 8 h reference exposure levels, which were set at a stringent limit of 9 µg/m^{-3} by the Office of Environmental Health Hazard Assessments (2008). The measured levels were lower than acute (1 h) REL of 55 µg/m^{-3}. That said, most new homes have indoor formaldehyde concentrations that exceeded this recommended guideline and the levels measured are still within the typical range measured in relatively new homes. For residential, formaldehyde concentrations up to 60 µg/m^{3} are still regarded as acceptable. Offermann (2009) reported a median indoor formaldehyde concentration of 36 µg/m^{3} based on data from 108 new homes in California. Mean concentration of formaldehyde from a large-scale study of 300 homes in three cities in the eastern United States was 21.6 µg/m^{3} (Weisel et al. 2005). Based on all the reviewed studies, the typical formaldehyde levels in residences seem to fall within the range of 20–50 µg/m^{3}. The data are skewed toward higher concentrations for newer homes, as expected. Pressed-wood products, including furniture, some flooring systems, and resins, are some major sources of formaldehyde emissions (Raw et al. 2004; Salthammer and Mentese 2010). Wood flooring, wallboards, laminated furniture, and cabinetry were some of the main sources of formaldehyde uniformly present in both homes.

Figure 59 demonstrates a very clear association between indoor formaldehyde concentrations and ventilation rates for the Stow and Townsend homes. Increasing ventilation by a nominal 0.1 ACH would lead to a reduction of formaldehyde concentration by 25% and 18% in Stow and Townsend, respectively. The positive impact of ventilation rate on formaldehyde concentration is consistent with an earlier report by Hodgson et al. (2000), who conducted an experiment in a single home by switching off the HRV system to alter the ventilation rate. Gilbert et al. (2008) used cross-sectional data of measurements in 96 homes in Canada to develop a linear regression model of formaldehyde concentration as a function of ventilation rates. Lower concentrations were associated with higher ventilation rates following a linear function. Aubin et al. (2010) reported the preliminary findings from a field study of 84 homes of asthmatic children in Canada. Indoor formaldehyde concentrations were lower in homes with higher ventilation rates for data collected in the winter period.

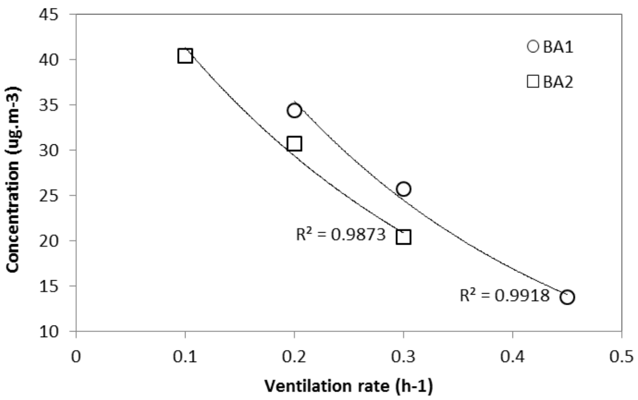

Figure 59. Indoor formaldehyde concentrations at three air exchange rates (BA1 corresponds to Stow, BA2 to Townsend)

The concentration ranges of VOCs, formaldehyde, and acetaldehyde compounds were of similar magnitudes between both homes. This similarity indicated that the IAQ was affected by similar and uniform sources from structural and interior materials installed by the builder. Logue et al.

(2011) identified nine contaminants as the priority hazards for residential chronic exposure. Compared to this list, the chemicals with notable concentrations in both homes were formaldehyde and acetaldehyde. Compared to the summary in Brown et al. (1994) of weighted average (geometric mean) concentrations for VOCs commonly encountered in residences, α-pinene, d-limonene and hexanal had notably elevated concentrations. These odorous VOCs may be off-gassed from various indoor sources such as wood products for α-pinene; and surface treatment and cleaning products for d-limonene and hexanal. With the exception of limonene and hexanal, concentrations of most VOCs with indoor sources were generally low considering that these homes were about one year old. The observed levels were comparable to relatively new (three- to five-year–old) homes in California (Offermann 2009). This suggests that using low-emitting paints, flooring, and other materials may have lowered the initial emissions from indoor surfaces, thus reducing the concentrations. The elevated levels of limonene and hexanal may have come from cleaning products or air fresheners, i.e., products not related to the building/ construction materials.

The chemical exposures could be further reduced with additional ventilation, as 82% of the detected compounds varied with ventilation.

5 Conclusions

This report documents the results of an in-depth evaluation of the energy production and consumption, thermal comfort, and IAQ for two potential NZEHs in Massachusetts over one year. It investigates whether claims about energy efficiency, comfort, and health benefits can be supported by measured field data.

One home did not reach a zero balance (in terms of a whole-year period); the other produced nearly 30% more energy than it consumed. It is noteworthy that (1) both homes have unusually low loads for electricity consumption other than heating, and (2) that even with a highly optimized thermal envelope, nearly half the energy is still used for space conditioning (dominated by space heating).

The indoor thermal comfort in summer and winter met occupants' expectations, although indoor temperatures did not always meet comfort standards (per the ASHRAE55 comfort range) in winter. Yet occupants reported no discomfort issues and the heating systems in both homes did not operate at their full capacity, indicating that the homes seemed to meet residents' comfort preferences. Summer indoor temperatures remained within ASHRAE's comfort range for temperature; a potential cause of discomfort could be relatively high RH levels.

The tests of the air exchange and indoor air pollutants carried out in collaboration with LBNL underline the necessity of mechanical ventilation in airtight homes, but also the challenges in commissioning and effectively running these systems. As long as there are no odorous pollutants, occupants have no sensor for air quality. The installation, commissioning, maintenance, and operation of mechanical ventilation show room for improvement. In particular, the tests carried out in collaboration with LBNL revealed a mechanical problem that caused recirculation of the exhaust air in one home. A second test half a year later revealed that although the home was sufficiently ventilated for its projected occupancy, the air exchange was not sufficient by then, as twice as many occupants were staying in the home as the ventilation system was designed for.

References

ASHRAE 55 (2010).ANSI/ASHRAE Standard 55. (2010). Thermal Environmental Conditions for Human Occupancy. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE (2007). ANSI/ASHRAE Standard 62.1. (2007). Ventilation for Acceptable Indoor Air Quality. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE (2009). *ASHRAE Handbook: 2009 Fundamentals*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE (2010). ANSI/ASHRAE Standard 62.2-2010 – Ventilation and Acceptable Indoor Air. Quality in Low-Rise Residential Buildings. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ISO 7730.(2005). Ergonomics of the Thermal Environment - Analytical Determination and Interpretation Of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. International Organization for Standardization, Geneva.

Aubin, D.; Won, D.Y.; Schleibinger, H. (2010). Preliminary Results from a Field Study Investigating the Impact of Ventilation Rates on Indoor Air Quality and the Respiratory Health of Asthmatic Children in Québec City.NRCC-53547.

Brown, S.K.; Sim, M.R.; Abramson, M.J.; Gray, C.N. (1994). “Concentrations of Volatile Organic Compounds in Indoor Air - A Review.”*Indoor Air* 4:123–134.

deDear, R.J. and G.S. Brager. (1998). “Toward an Adaptive Model of Thermal Comfort and Preference.” *ASHRAE Transactions*, vol. 4, part 1.

DOE. (2010).Buildings Energy Data Book 2010. U.S. Department of Energy, Building Technologies Program.

EN 15251.(2008). Criteria for the Indoor Environment. Beuth Verlag GmbH, Berlin.

Fanger, P.O. (1970). “Thermal Comfort Analysis and Applications.”*Environmental Engineering.* McGraw-Hill, New York.

Feist, W.; Peper, S.; Görg, M. (2001). *Cost Effective Passive Houses as European Standards: CEPHEUS*. Final technical report, Passive House Institute, Darmstadt

Gilbert, N.L.; Guay, M.; Gauvin, D.; Dietz, R.N.; Chan, C.C.; Lévesque, B. (2008). “Air Change Rate and Concentration of Formaldehyde in Residential Indoor Air.” *Atmospheric Environment* 42(10):2424–2428.

Hodgson, A.T.; Rudd, A.F.; Beal, D.; Chandra, S, (2000). "Volatile Organic Compound Concentrations and Emission Rates in New Manufactured and Site-Built Houses." *Indoor Air* 10:178–192.

Humphreys, M.A.; Nicol, J.F. (2002). "The Validity of ISO-PMV for Predicting Comfort Votes in Every-Day Thermal Environments." *Energy and Buildings* 34(6):667–684.

Logue, J.M.; McKone, T.E.; Sherman, M.H.; Singer, B.C. (2011). "Hazard Assessment of Chemical Air Contaminants Measured in Residences." *Indoor Air* 21(2):92–109.

Nicol, J.F.; Humphreys, M.A. (2002). "Adaptive Thermal Comfort and Sustainable Thermal Standards for Buildings." *Energy and Buildings* 34(6):563–572.

Nicol, F.; McCartney, K. (2002). "Developing an Adaptive Control Algorithm for Europe." *Energy and Buildings* 34(6):623–635.

Nicol, J.F.; Roaf, S. (2005). "Post-Occupancy Evaluation and Field Studies of Thermal Comfort." *Building Research & Information* 33(4):338–346.

Office of Environmental Health Hazard Assessment.(2008). OEHHA Acute, 8-hour and Chronic Reference Exposure Levels (chRELs). www.oehha.ca.gov/air/allrels.html. Accessed June 2011.

Offermann, F.J. (2009). Ventilation and Indoor Air Quality in New Homes. CEC-500-2009-085.

Passipedia (2012). Energy use – measurement results, from: http://passipedia.passiv.de/passipedia_en/operation/operation_and_experience/measurement_resresu/energy_use_measurement_results . Accessed June 2012.

Parker, D.S. (2009). "Very Low Energy Homes in the United States: Perspectives on Performance from Measured Data." *Energy and Buildings* 41:512–520.

Raw, G.J.; Coward, S.K.D.; Brown, V.M.; Crump, D.R. (2004). "Exposure to Air Pollutants in English Homes." *Journal of Exposure Analysis and Environmental Epidemiology* 14:S85–S94.

Torcellini, P.; Pless, S.; Deru, M.; Crawley, D. (2006)."Zero Energy Buildings: A Critical Look at the Definition." Presented at ACEEE Summer Study Pacific Grove, California, August 14–18.

Weisel, C.P.; Zhang, J.; Turpin, B.J.; Morandi, M.T.; Colome, S.; Stock, T.H.; Spektor, D.M.; Korn, L.; Winer, A.M.; Kwon, J.; Meng, Q.Y.; Zhang, L.; Harrington, R.; Liu, W.; Reff, A.; Lee, J.H.; Alimokhtari, S.; Mohan, K.; Shendell, D.; Jones, J.; Farrar, L.; Maberti, S.; Fan, T. (2005). "Relationships of Indoor, Outdoor, and Personal Air (RIOPA).Part I. Collection Methods and Descriptive Analyses." *Research Report (Health Effects Institute)* 130:1–107.

Salthammer, T.; Mentese, S. (2010). "Formaldehyde in the Indoor Environment." C*hemical Reviews* 110(4):2536–2572.

buildingamerica.gov

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

DOE/GO-102013-3746 ▪ January 2013

Printed with a renewable-source ink on paper containing at least 50% wastepaper, including 10% post-consumer waste.