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New England Net Zero Production Houses

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Abstract:

A homebuilder working in the New England area has been building net zero energy single family homes since circa 2008, and is currently continuing with multiple small-scale subdivisions of 20 or more homes. This builder specializes in net zero affordable homes and sustainable net zero communities, while retaining houses with a familiar local vernacular appearance.

Some of the key features of these houses include solar orientation, superinsulated double-stud above grade walls (R-45+ nominal), triple glazed low emissivity krypton-filled windows, and exceptional airtightness.

The mechanical design takes advantage of the reduction in enclosure-based heating loads by using single-point (or one point per floor) heating, in the form of mini-split or ductless split air source heat pumps. This modification substantially reduces installed HVAC system costs relative to a conventional ducted system. The effects of this single-point distribution in superinsulated housing are a matter of further measurement in this study. In addition, the ability of an air source heat pump to meet heating loads in a cold climate is a matter of concern; the ability to maintain setpoint (and dependence on backup heat) is another research topic. The renewable energy component is a roof-mounted photovoltaic system, sized to meet the modeled loads; a PVT system (combined photovoltaic-solar thermal) was also used in some cases.

Controlled mechanical ventilation options have included heat recovery ventilators and simplified supply-only systems. When combining the factors of the installed cost of HRVs, the ventilation rates used, and the increased electrical (fan) energy of HRVs, the cost-benefit relationship of heat recovery appear to be not as advantageous as originally thought.

The builder also has been concentrating on cost control for these houses, given the shift into full-scale production, and has been actively involved in monitoring of the effectiveness of various measures. Energy modeling and analysis have also been used to examine the cost-effectiveness of various options. Avenues examined have included various solar domestic hot water systems, building-integrated photovoltaics, modifications to the wall construction, and modified foundations.

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INTRODUCTION

A homebuilder working in the New England area has been building net zero energy single family homes in Massachusetts since circa 2008, and is currently continuing with multiple small-scale subdivisions of 20 or more homes. This builder specializes in net zero affordable homes and sustainable net zero communities, while retaining houses with a familiar local vernacular appearance. These homes range from 1100 to 2600 square feet (100 to 240 m^2) of finished floor area, with one or two stories, foundation types include both slab-on-grade and unfinished basements.

Some of the key features of these houses include solar orientation, superinsulated double-stud above grade walls (R-45+ / 7.9 m^2K/W nominal), triple glazed low emissivity krypton-filled windows, and exceptional airtightness. The mechanical design takes advantage of the reduction in enclosure-based heating loads by using single-point (or one point per floor) heating, in the form of mini-split or ductless split air source heat pumps. Domestic hot water is supplied by a condensing tankless water heater. All homes have roof-mounted photovoltaic arrays.

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The predicted annual output of the photovoltaic systems equals the predicted annual energy consumption of the houses, on a source energy basis, making these homes net-zero or near net-zero consumers of energy (modeled HERS Indices between -3 and +4). The design is a grid-tied net zero source energy building (as defined by Torcellini et al. 2006), meaning that fossil fuels are burned on site, and excess renewable energy is generated to offset this use. Therefore, when measured in terms of source energy, renewable energy produced at the building site offsets all energy consumption of the building,

Utility bill data were collected for one all-electric home: over one year it had near-net zero energy consumption (net annual energy consumption was 1000 kWh / 3600 MJ). More recently constructed homes have larger solar arrays, and use natural gas for water heating. It is therefore very likely that these houses will produce more energy than they consume, on a source energy basis.

BUILDING CHARACTERISTICS

Building Enclosure

The building enclosure characteristics, including insulating values, are described in Table 1 below.

Table 1. Building Enclosure Characteristics

Component	Description	Performance Characteristics
Roof/Ceiling Assembly	Ventilated attic with insulation on attic floor with 18” (45 cm) cellulose	R-60 nominal value (10.6 m^2K/W)
Floors Above Garage	Cellulose insulation (12”; 30 cm) in joist bays	R-42 nominal (7.4 m^2K/W)
Slab Foundation	Slab on grade with 6” (15 cm) EPS Insulation below entire slab and turned up at perimeter stem wall	R-28 (4.9 m^2K/W)
Basement Foundation	3.5” closed cell (2.0 PCF; 32 kg/m^3) urethane spray foam on walls 2” (5 cm) XPS beneath basement slab	R-22 walls (3.9 m^2K/W) R-10 floor (1.8 m^2K/W)
Fenestration	Vinyl frame windows with triple glazing, krypton blend fill	U=0.20 SHGC=0.26 (1.14 W/m^2K)
Infiltration	1150 CFM 50 / 3.8 ACH 50 targeted value (550 L/s @ 50 Pa) (2.5 sq in leakage area per 100 sf of envelope area)	< 500 CFM 50 / 1.9 ACH 50 (< 240 L/s @ 50 Pa) final tested value

All R values in $ft^2\cdot{}^\circ F\cdot h/Btu$; CFM 50=cubic feet/minute @ 50 Pa; ACH 50=air changes/hour @ 50 Pa

The use of low-density (0.5 lb/cu. ft.; 8 kg/m^3) urethane spray foam (rather than cellulose) in a double-stud wall is not common practice. The foam selected provides a higher R-value (3.7/inch; 0.039 W/m-K) relative to damp-spray cellulose (R-3.5/inch; 0.041 W/m-K). More importantly, spray foam has more effective air sealing characteristics relative to cellulose. In the regions of Massachusetts where this builder is active, this low-density spray foam is available for nearly the same installed cost as cellulose, despite the former’s superior performance. However, recent price instability for spray foam has resulted in the builder evaluating the use of the interior drywall or the exterior structural sheathing as an air barrier. Either or both would be attractive options if the cost of spray foam rises substantially.

In general terms, double stud walls have a higher risk of moisture-related damage than conventional construction. The high insulation value results in colder temperatures at the exterior sheathing, leading to higher average moisture content. This risk can be mitigated by reducing wetting potential from the interior, and by increasing drying potential at the exterior (see Lstiburek 2010). In these houses, the risk of interstitial condensation (interior wetting potential) is reduced by the use of exceptional airtightness, as well as some interior vapor control (Class III vapor retarder - latex paint on gypsum board). A Class III vapor retarder also allows drying to the interior under favorable conditions. The exterior is clad with vinyl siding, which is an intrinsically self-ventilated cladding, allowing ventilation drying of the assembly.

Figure 1 *Completed house example (left), and house under construction, showing exterior air barrier approach (adhesive tape sealed seams on exterior sheathing) (right)*

Air leakage measurements of these houses consistently show less than 500 CFM 50 (cubic feet per minute at 50 Pa test pressure), or 1.3 square inches EqLA (Equivalent Leakage Area, Canadian General Standards Board/CGSB (1986), calculated at a 10 Pa pressure differential) per 100 sf of enclosure area. (240 L/s at 50 Pa; 8.4 x 10^{-4} This is about 1.9 ACH 50 (air changes per hour at 50 Pa test pressure) for houses of median size. Several houses were tested at below 200 CFM 50 (1.2 ACH 50; 94 L/s at 50 Pa) through more careful attention to penetrations and detailing interior drywall or exterior sheathing as an additional air barrier.

Mechanical Systems

Most of the builder's houses are heated using mini split air-source heat pump units. One of the earlier houses used concealed heads mounted in a dropped part of the ceiling, with a small ductwork system to distribute heated air. However, most of the houses use two wall-mounted ductless split heads (one per floor), eliminating the minimal ductwork system. The heat pumps used in recent work are systems documented to 90-100% of their nominal heating capacity at exterior temperatures of 5° F (-15° C) , which addresses one of the primary concerns of using air-source heat pumps in cold climates. For reference, the 99.6% design temperature for these regions of Massachusetts is in the range of 2° F to 7° F (-14° C to -17°C).

A full-ducted central system of similar capacity would require ductwork sufficient to handle roughly 800 CFM (380 L/s) of airflow. Several builders in New England report that such systems have an installed cost premium of roughly $3000 relative to mini split installations. This is the primary motivation reported for installing these systems; some builders and buyers also favor heat pumps in order to reduce fossil fuel combustion within the house (and associated IAQ risks) and/or to increase utilization of site-generated electricity.

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Figure 2 *Minimally-ducted mini split mounted in dropped ceiling space (left) and single-point wall-mounted ductless split indoor unit (right)*

Hot water is provided either by a tankless condensing gas water heater or by an electric heat pump. The gas system is expected to offer higher efficiency, but some homes are located far from gas mains. The analysis of these tradeoffs, and the ongoing study of heat pump water heater performance, are discussed below.

Earlier homes were built with a heat recovery ventilator (HRV) drawing air from one bathroom and supplying to the second floor hallway. However, due to concerns on ventilation distribution and the high installed cost of these systems, alternatives are currently being researched, as discussed below.

RESEARCH TOPICS

Under the auspices of the Department of Energy's Building America Program, the authors are conducting further ongoing research into some of the topics which would improve performance, economics, and/or market acceptance of the houses being built by this builder. The topics discussed here include single point space conditioning systems, alternate ventilation systems, fuel choices in net-zero (or near net-zero) houses, and overall net zero performance of construction to date.

Single Point Space Conditioning Systems

As described above, the mechanical design takes advantage of the reduction in enclosure-based heating loads by using single-point (or one point per floor) heating. The common concern would be whether a single point per floor could maintain even distribution of comfort conditions in a cold climate—even with a highly insulated, airtight enclosure. To date, the occupants of these houses report a high degree of comfort, and all are unaware of (or are not bothered by) the temperature variations within the house. In recommending operational strategies for two-point heating systems, the authors were guided by data from earlier research on single-point heating (Fang 2009).

That research examined performance of single-point heating using sealed-combustion gas heaters on the first floor of a two-story residence, located in Western Massachusetts. A 90 CFM (40 L/s) fan moves air from the first floor to the second floor bedrooms continuously. Year-long temperature data indicate that comfortable temperatures are generally maintained. However, rooms distant from the heating source are slow to recover from thermostat setbacks (Aldrich 2010). Since daily setbacks save little energy in superinsulated houses, it was recommended to the builder and homeowners to set the thermostat for a constant temperature. They were also advised to leave doors to unoccupied rooms open to permit air movement and thermal distribution.

Calculation of heat transfer within the building confirm that only moderate temperature differences would occur even at

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the extremes of local weather. Heat transfer through uninsulated interior walls and floor is quite significant. At 5˚F outside (MA 0.4% design condition; -15° C) and 72˚F (22° C) in the hallway, the bedrooms would reach equilibrium at a temperature of 5° F to 10° F (3° C to 6° C) below the temperature of the directly heated space. In practice, a prolonged period of outdoor temperatures below 5°F is extremely unlikely in these climates. Most of the time, the equilibrium temperature difference will be less than those extremes calculated above, and bedroom doors will not be closed for sufficient time for the rooms to reach equilibrium. The builder at one point considered installing an air distribution system to equalize temperature between rooms. Calculations indicated that such a system would need to be prohibitively large in order to significantly change the temperature distribution.

In the fall of 2010, the authors installed data collection equipment in one occupied house. This house has three bedrooms on the second floor, a 1-ton (12,000 Btu/hr; 3.5 kW) ductless split heat pump in the second floor hallway, and a 1-ton ductless split on the first floor. Sensors were installed that measured temperature and relative humidity in each bedroom, the hallway, and the first floor; additional sensors measured duty cycles for both mini splits, and times at which the bedroom doors are opened and closed.

From these data the authors expect to learn how much the bedroom temperature deviates from the hallway temperature when the bedroom doors are closed, and by how much this exceeds the temperature difference with doors open. Logging the operation times of the heat pumps will reveal the lag between operation and bedroom response. These sensors will also provide general information about the house performance, notably the warmest temperature at which heat is required (balance point), and the temperature at which full capacity is required. Data from this monitoring will be collected at the end of the heating season.

Ventilation Systems

As discussed previously, earlier houses were built with an HRV exhausting from and supplying to single points (bathroom and second floor hallway). However, the builder became concerned that this system did not distribute the ventilation air, and in particular did not direct outdoor air to the bedrooms, where the highest pollutant concentrations typically occur. The bedrooms have air transfer grilles above the doors, and the doors are cut at least ½” (1.3 cm) above the carpet. These measures permit air to enter or leave the room; however, the lack of mechanical air supply means that there is no driving force. One possibility considered was to install a separate fan with ductwork to draw air from the hallway and supply it to the bedrooms. However, this represents a substantial duplication of materials and expense. The preferred option was to eliminate the HRV, and use the distribution system to draw air from outside directly.

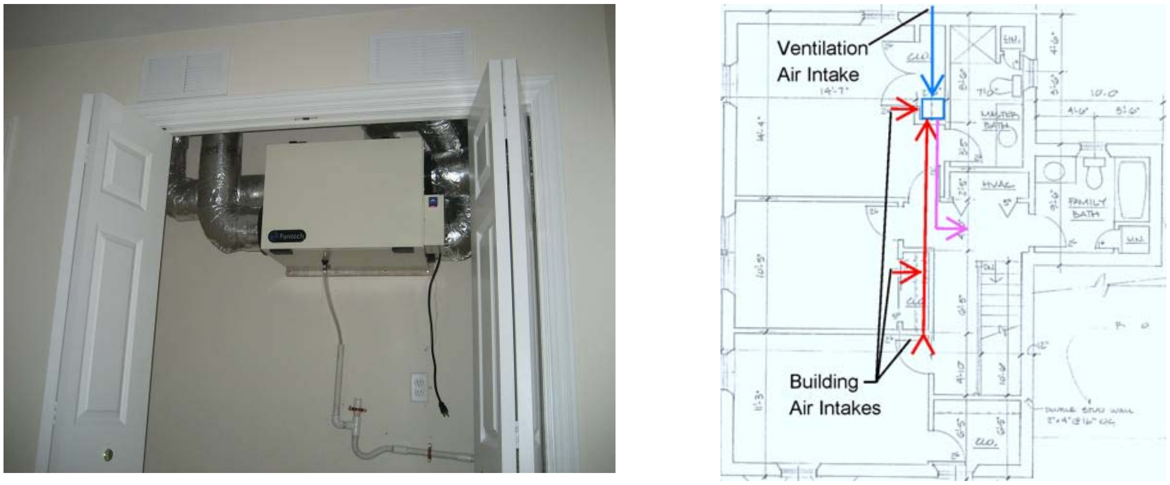

Figure 3 *Installed HRV (left) and schematic of proposed supply-only system (right)*

In this ventilation system, a small fan is used to draw air from outside and from the three bedrooms, and deliver the mixed air to the hallway. This ensures air movement between the bedrooms and the rest of the house; and by mixing (at roughly 25% outside air) avoids the extremes of supply temperature. Supply ventilation systems are preferred to exhaust systems because the air entering the house comes from a known location, distant from the garage or other pollutant sources. The fan is substantially less expensive than a reasonably efficient HRV, and the ductwork is much less than a system designed to also provide space conditioning.

ASHRAE Standard 62.2 (ASHRAE 2007) calls for 50 CFM (24 L/s) of ventilation air, supplied continuously, for 2000 square foot (190 m^2) houses with three bedrooms. However, anecdotal evidence suggests that when air is well distributed, most occupants are comfortable at rates 1/3 this. This reduced ventilation rate is easily achieved by operating a 50 CFM system for 20 minutes out of each hour (33% duty cycle). Assumptions about ventilation rate can significantly affect cost effectiveness of ventilation system upgrades.

For instance, several of these houses feature a small HRV, which provides 50 CFM of actual ventilation (1x each supply and exhaust; 70 CFM (33 L/s) nominal rating). Table 2 compares this HRV to the supply system described in the preceding paragraph, using a fan with the same gross efficacy (CFM/W). It also shows installed cost.

Table 2. Ventilation Systems

System	Gross Airflow (CFM ; L/s)	Outdoor Air (CFM ; L/s)	Power (W)	Installed Cost
Supply-Only Ventilation	200 / 94	50 / 24	80	$900
Balanced Ventilation (HRV)	100 / 47	50 / 24	40	$1,500

Table 3 compares the total energy cost of the two ventilation systems, at 33% and 100% of the ASHRAE 62.2 rate. This cost includes both the fan energy for the ventilation system and the energy required to condition the ventilation air, at an average COP of 2.5; this analysis accounts for the thermal recovery of the HRV. It should be noted that energy costs were dominated by the fan energy costs of the system. The electricity rate is assumed to be $0.16 kWh in this analysis, typical for Massachusetts.

Table 3. Ventilation Energy Cost

System	33% Runtime	100% Runtime
Supply-Only Ventilation	$45/year	$130/year
Balanced Ventilation (HRV)	$20/year	$65/year

In both cases, the HRV saves energy. Reducing the ventilation rate, however, saves substantially more energy. Moreover, the reduced fan runtime casts the cost effectiveness of the HRV into doubt. With continuous operation, the simple payback of the HRV upgrade is 11 years. At 33% runtime, the payback is 30 years, substantially longer than other building features described, and possibly greater than the service life of the equipment.

The authors do not propose a single value of payback period above which upgrades should be rejected. Longevity of the system and its non-energy benefits such as occupant health, comfort, and building durability are often equally or more important. In this case, the supply ventilation system is expected to require less maintenance, and to deliver better air quality through improved mixing. The $600 upgrade cost would be better spent on other areas of the building offering better returns.

Pressurizing interior spaces in cold climates can drive moisture into enclosure elements and reduce building durability. In this case, the risk is small. The 50 CFM (24 L/s) airflow creates a typical pressure difference of 1.6 Pa across the enclosure, based on tested airflow at 50 Pa and an assumed flow exponent of 0.67. This is below the pressure differences due to stack effect and wind. In these houses, the wall framing cavities are filled with spray foam. Remaining exfiltration will occur largely at windows, bypassing the vulnerable oriented strand board sheathing.

Renewable Energy and Fuel Selection

All of these houses have roof-mounted photovoltaic arrays; the array size was typically limited by roof area. With current polycrystalline efficiencies of roughly 15%, this corresponds to a rated capacity of 7.6 kW_p for most house plans. Monocrystalline panels were also considered, but the lower cost per watt makes financing easier for polycrystalline modules.

Home buyers in these communities are given a choice between purchasing the solar arrays outright as part of the mortgage, or allowing a third party to own and operate the array. In the latter case, the power generator sells the electricity and the Solar Renewable Energy Credits, while the homeowner receives a 10% discount on purchased electricity.

Under the Massachusetts Renewable Portfolio Standard Solar Carve-Out Standard (DOER 2009) electric utilities across the state are required to include a total of 34 GWh (156 TJ) from solar in their electricity mix. The state is operating a solar renewable energy credit (SREC) market to support this requirement, and a "Clearinghouse Auction" which supports multi-year assured payments to the photovoltaic system owner above $250 per MWh ($70 per GJ). This helps to account for the ease of financing solar power.

Some designers have preferred to eschew gas combustion appliances, believing that the advantage they provide in reaching a net zero target will disappear as grid electricity is increasingly produced from non-fossil, renewable sources. The houses described in this paper participate in this trend both on the supply side (by producing electricity from solar radiation) and on the consumption side (by using electric heat pumps rather than on-site combustion). The builder has built some homes without gas service, and plans to do so in one upcoming development where the cost of installing gas mains is prohibitive.

The authors calculated the net annual cost of substituting electricity for gas in cooking, water heating, and clothes drying, assuming that space heating is being accomplished with electricity in both cases. Deru and Torcellini (2007) report national average source (primary) energy multipliers of 3.365 for electricity and 1.095 for natural gas. In Massachusetts, electricity costs roughly three times as much as natural gas per unit of energy, making price a good proxy for source energy content. However, the cost for gas should also include monthly minimum charges or connection fees, typically $8/month, which can be saved if all gas appliances have been eliminated. Based on Building America Benchmark assumptions of hot water and appliance use (Hendron 2007), using gas saves more than $350 per year relative to resistance heating. Roughly two-thirds of this savings is in water heating, while the other third is evenly divided between cooking and clothes drying.

The large energy and monetary savings due to avoiding resistance heating generally support installing gas appliances wherever it is at all feasible. However, some home buyers report gas consumption of less than 2 therms (211 MJ) per month, which is less than 20% of what was predicted. It has not yet been determined whether this is due to occupant behavior or can be attributed to features of the building which are likely to apply regardless of occupants. If the non-space heating requirements are in fact this low, electricity is less expensive (when including gas monthly fees) as well as more convenient (for installation and the construction process).

While gas remains the most efficient option, heat pump water heaters considerably narrow the gap. Commercially available units have rated energy factors (EF) of 2 or greater. Notably, water heater COP considerably lags space heat COP. These units rely on drawing heat from their immediate surroundings for water heating; in these houses, the water heater is typically located in the basement or in a mechanical closet on the first floor (for homes without a basement). In warmer regions, this incidental space cooling is a direct benefit. However, in heating-dominated climates, this is a matter of some concern, especially considering that the water heating load is of the same order as the annual space heating requirement in these low-load houses.

A simple spreadsheet model was used to estimate the hours during which water heating would increase the space heating load or reduce the cooling load. The water demand schedule was taken from the Building America Benchmark Definition (Hendron 2007). Hourly heating and cooling loads were calculated by a DOE-2.1E-based software package (Energy Gauge USA, Parker et al. 1999). COP for space and water heating were calculated by the simulation software from rated HSPF and EF. With these assumptions, water heating adds 330 kWh/yr (1190 MJ/yr) to electricity use for space heating, and reduces cooling energy use by 70 kWh/yr (250 MJ/yr). The net increase of 260 kWh/yr (940 MJ/yr) is roughly 10% of total space conditioning energy.

Of course, the efficiency of a heat pump water heater would be a function of (among other factors) ambient temperature. A water heater in a semi-conditioned basement will certainly experience cooler temperatures than one located in a closet adjacent to conditioned spaces. The mechanical closet is also likely to cool substantially during extended hot water draws; additional ventilation/airflow would likely be required. In addition, preliminary analysis of data collected at another project shows that the in-service energy factor can be much lower than rated when daily use is lower than average. More accurate information about the real world performance of these appliances will be helpful in deciding whether they are superior to gas water heaters in particular buildings.

Net Zero Performance

Close to one year of utility bills have been collected for one house, which has a 6.4 kW_p photovoltaic array, and is all-electric. Net annual energy consumption was 1000 kWh (3600 MJ). 22 months of solar production data are available: in the earliest 12-month period, 8450 kWh (30.4 GJ) were produced; in the most recent period, 8950 kWh (32.2 GJ). Normalizing these values gives better than 1.3 kWh per nominal W per year production from the photovoltaic array, which is slightly more than predicted. ggkq

Several upgrades made to the more recently constructed homes will further reduce net energy consumption. The builder has increased the photovoltaic array size from 6.4 kWp to 7.6 kWp. Extrapolating from the measured output, this is expected to produce an additional 1560 kWh per year (5600 MJ). The data below include energy for heating water with electrical resistance . Newer houses use either heat pump water heaters or gas- or propane-fired tankless heaters. The heat pump is expected to save between 1000 kWh and 1200 kWh per year; the gas options save even more energy on a source energy basis. Finally, mini-split space heating technology has improved in the last several years, especially regarding output and efficiency at low outdoor temperatures.

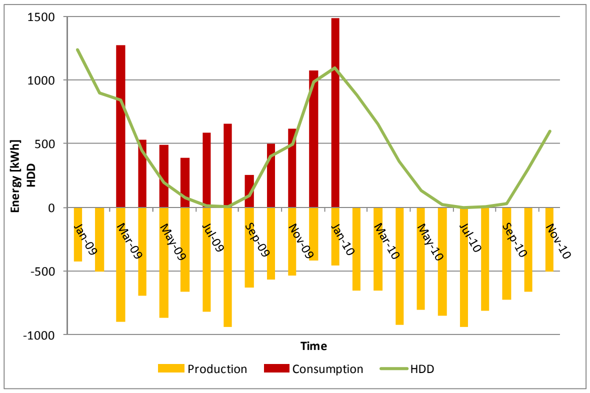

Figure 4 *Electrical consumption and production; Heating Degree Days 2009-2010*

CONCLUSION

Annual bills for a home in Massachusetts indicate that net-zero homes can be built in a cold climate. The builder has further demonstrated that this can be done on a production basis, at competitive market rates. Reducing mechanical system cost, especially through minimizing ductwork, is critical in controlling building cost. Ductless split heat pumps contribute to this objective. Alternative financing options allow photovoltaics to be deployed on residential roofs, and hence near the point of use, without increasing homeowner mortgage debt. Combustion appliances can be cost-effective energy saving measures, but are not necessary in order to reach net-zero

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About this Report

This report was first presented at the 2011 ASHRAE Annual Conference in Montreal, Quebec, Canada.

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