Net Zero Energy Housing - Lessons Learned

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ABSTRACT
A review was carried out of a select group of Net Zero Energy Houses (NZEH) constructed in Canada and the United States to identify best practices and lessons which could be learned. Half a dozen NZE houses were studied in detail using published information supplemented with detailed discussions with their designers and builders. From this emerged general trends, observations and conclusions which have direct relevance for future Net Zero Energy Houses.

Perhaps most significantly, mechanical system complexity was identified as a major issue faced by almost all NZE house designers. Most systems were too complex, too unreliable and too difficult to maintain in a residential environment.

The analysis also questioned the economic viability of passive solar energy given that a unit area of window costs roughly 2 to 10 times as much as an equivalent area of exterior wall yet provides only a marginal energy benefit. Likewise, the economics of using thermal mass as an energy saving measure was questioned. Overheating was also identified as a concern although this was sometimes an issue in a single room or zone within the house as opposed to the overall structure. Reduced output from photovoltaic and solar thermal systems due to snow cover and adjacent shading was also noted by some of the designers. Likewise, some houses experienced problems finding adequate roof area to mount these systems, particularly in an urban environment.

INTRODUCTION
Net Zero Energy Houses (NZEH) represent the ultimate development of low energy housing technology. Defined as a house whose annual energy consumption is equal to, or is less than, the energy generated on-site using renewable energy systems, NZE houses are generally net consumers of energy during the heating season and net producers of energy during the non-heating season.

OBJECTIVES
The objective of the work described in this paper was to prepare a "Lessons Learned" analysis of recent NZE house design and construction experiences to discover what worked, what did not work, what designers and builders would change if they could and, as best as could be determined, how much things cost.

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SCOPE
Six, recently completed NZE houses (five in Canada and one in the United States) were studied in this project. Four were constructed as part of the EQuilbrium™ Home Program delivered by Canada Mortgage and Housing Corp. Since most were still in their monitoring phases, only limited performance data was available. However, the focus of this work was to capture the qualitative, rather than quantitative, lessons.

DESCRIPTION OF THE HOUSES (Tables 1 to 5)
Factor 9 House - Constructed in Regina in 2007, the Factor 9 House was not designed to achieve net zero status, rather, its goal was to use 90% less energy per square metre of floor area than a conventional Saskatchewan home. It was one of the first projects to use what is now known as "Net Zero-Ready" construction in which the building envelope, mechanical systems are other features are designed the same as they would be for a NZE House - except the renewable energy system is not installed. Since the latter typically represents 50% to 80% of the incremental cost of a NZE house, a Net Zero-Ready House can achieve about 90% of the energy savings at a fraction of the cost. The house is an architecturally conventional structure with 297 m^2 (3196 ft^2) of useable floor space (including the basement). Insulation levels are high: walls RSI 7.2 (R-41), attic RSI 14.1 (R-80), basement walls RSI 7.7 (R-44), measured airtightness is 1.2 ac/hr_{50}, passive solar energy is well utilized and active solar energy is used to provide part of the DHW and space heating loads.

EcoTerra™ - Constructed near Eastman, Quebec in 2007 as part of CMHC's EQuilibrium™ Homes Program, the EcoTerra™ House is a two-storey, 268 m^2 (2884 ft^2) (including basement) pre-manufactured, detached home. The RSI 6.6 (R-37) walls were built using SIPS panels while the roof uses RSI 6.6 (R-36) and the foundation RSI 6.6 (R-37). The house uses a Building Integrated Photovoltaic/Thermal (BIPV/T) system which recovers heat from the backside of the PV array and uses it for space and DHW heating (only about 12% to 18% of the solar radiation which strikes a PV panel is converted into electricity while the rest ends up as heat - which is normally wasted), (CMHC, 2010).

Inspiration Ecohome™ - Another EQuilibrium™ Home, this two storey 328 m^2 (3529 ft^2) structure (including basement) was built just outside of Ottawa in 2008. It uses double-wall construction with RSI 7.2 (R-41) walls, RSI 11.0 (R-62) attic and RSI 7.0 (R-40) basement walls. Space heating is provided by a 98% AFUE gas water heater supplemented by an active, hydronic solar space heating system (complete with 908 l, 200 I.G. thermal storage). Strong emphasis was placed on utilizing passive solar energy. A rainwater collection system is also used. Emphasis was also placed on natural ventilation to eliminate the need for air-conditioning.

Riverdale NetZero - Completed in 2007 in Edmonton, this 254 m^2 (2733 ft^2) EQuilibrium™ home is a semi-detached duplex located on an inner city lot. Given the climate, emphasis was focused on building a very well insulated, airtight envelope. The exterior walls use double wall construction with blown-in cellulose insulation to produce a thermal resistance of RSI 9.9 (R-56) while the attics and basement use RSI 17.6

(R-100) and RSI 8.8 (R-50), respectively. Perhaps the most interesting feature is that it uses a 17,000 l (3744 I.G.) water tank to store heat collected by the solar thermal collectors during the non-heating season for use by the space heating season during the winter. Thermal mass in the form of a large masonry wall in the living room and concrete countertops, as well as very efficient windows, are also included. The house also uses a non-heat pump ground-coupled cooling system which transfers surplus summer heat to the ground using 96 m (315') of ground piping. It is designed to produce a net surplus of 500 to1000 kWh_e/yr.

Avalon Discovery 3 - This EQuilibrium™ house was built in Red Deer, Alberta in 2007. It is a 1½ storey slab-on-grade structure which features a very well-insulated building envelope. The walls use a novel RSI 12.3 (R-70) double-SIPS arrangement while the ceiling and foundation floor are insulated to RSI 15.3 (R-87) and RSI 10.6 (R-60), respectively. The heating system uses solar thermal heating with an electric back-up and a radiant heating system in the floor. An interesting concept is that 15.3 m^2 (165 ft^2) of flat-plate solar collectors are mounted vertically on the south wall rather than on the roof. This facilitates installation and maintenance and also reduces energy production from the collectors during the summer when there is excess capacity (the collectors are used for DHW heating). For summer cooling, the house uses 91 m (300') of ground-coupled piping mounted below the foundation insulation.

Metro Denver Net Zero - The only non-Canadian NZE house in the project sample, this bungalow was completed in 2006 in Denver, Colorado. Also unique was that the house was designed by the National Renewable Energy Laboratory (NREL) and constructed by Habitat For Humanity using largely volunteer labour. Although constructed in the mildest climate of the six project houses, it used comparable insulation levels for the building envelope. The exterior walls used double-wall construction insulated to RSI 7.0 (R-40) while the ceiling was insulated to RSI 10.6 (R-60). Perhaps the most innovative feature of the design process was that the energy conservation and renewable energy features were designed with the aid of BEopt - building optimization software developed by NREL.

LESSONS LEARNED

Overall Design

NZE houses are extremely unique creations which represent a major departure from conventional practice. This applies both to the design of the building and to the design process. For example, all of the houses in the survey used large and extensive design teams which included individuals who would not normally be involved in the design of houses. The time period between the first meeting of the design team and groundbreaking was typically one to two years. One individual observed that they had more analysts than designers on their team. This introduces another problem: too many cooks spoiling the soup. NZE houses have a tendency to become complicated and unique since the design team is usually starting from a blank piece of paper whereas most house designs are usually modest variations from earlier designs. One lesson from this study is that every effort should be made to keep the design as similar to conventional construction as possible while still meeting the NZEH objectives. This can translate into such basic measures as using standard window sizes rather than unique sizes which are more expensive and have longer delivery times. Another lesson was that the design objectives should be established in writing, in advance, so that everyone involved in the design process understood what they were trying to accomplish. Endless design tangents and "design-creep" were noted by several respondents.

Construction Scheduling Of Innovative Design Features

One problem which often occurs with innovative construction techniques is that it usually takes the builders and sub-trades time (or iterations) to work out all the scheduling and coordination issues. Obviously, a NZE house will be especially vulnerable since they routinely employ new ideas and design features. For example, one house used a novel space cooling system which circulated water through lines cast into the foundation piles. While conceptually simple, this required careful coordination between the foundation and mechanical system sub-trades - trades who normally do not have contact with each other. As one of the designers on this project put it: "Sequencing of the cooling lines into the piles was not plug and play".

BUILDING ENVELOPE

Foundations

Other than their unusually high insulation levels for both the walls and floors, most NZE houses use relatively conventional foundations. Interior insulation schemes were common (since the interior was usually finished) although exterior insulation was often added to control thermal short-circuiting of heat from the soil through the concrete wall to the outdoor air. Exterior insulation also has the benefit of creating a capillary break between the soil and the foundation thereby keeping the foundation dryer.

Exterior Wall Systems - Various types of wall systems have been used in NZE houses ranging from relatively standard frame construction with insulated exterior sheathing, to Structurally Insulated Panel System (SIPS) all the way to double walls. Insulation levels typically range from about RSI 5 to 12 (R-28 to R-70). For the most part, all of these wall systems work (or can be made to work). Over the last 25 years, various research studies have examined their performance from an energy perspective as well as from the standpoints of air leakage, moisture performance and durability. Perhaps the biggest issue with wall systems is cost. We have the means to significantly reduce both conductive losses and air leakage through walls but the cost of upgrading a wall from conventional 2x6, RSI 3.52 (R-20) construction ranges from about \$20 to \$70 per square metre (\$2 to \$7/ft^2) of wall area. Given that conventional wall systems are relatively well insulated, the benefits of higher insulation levels can be moderate.

Roofs - Conventional roof trusses restrict the amount of insulation which can be installed at the truss ends. This can reduce the effective, overall RSI-value of the ceiling by as much as 50% and can increase the probability of ice-damming and even mould infestations on the ceiling perimeter since it operates at a lower temperature than the rest of the ceiling. This problem is most pronounced with hip roofs (since the entire perimeter is vulnerable to reduced insulation coverage), low-slope roofs (since more of the perimeter area is affected) and small roofs (since a larger percentage of the total roof area is affected). The most effective solution is to use High Heel Trusses since they allow extra insulation to be installed right to the roof edge. Depending on the ceiling area and the type of truss, their incremental cost is about $500 to $1000.

Windows - Another lesson from this project was that window selection may be a much more contentious issue for NZE houses than previously thought. Historically, the goal of most NZEH designers has been to use the most technologically advanced window available (i.e. most energy efficient). However, selecting the best window is more complicated than selecting the best wall system or HRV since window performance is a function of two major variables (thermal resistance and Solar Heat Gain Coefficient, or SHGC) whereas the performance of almost all other house components is a function of a single variable (typically R-value or efficiency). Further, while it is usually desirable to have both high thermal resistance and high SHGC values, they generally move in opposite directions - as the thermal resistance increases the SHGC usually decreases, and vice versa. Window selection is further compounded by the fact that they are one of the most expensive components in the house, costing (on a unit area basis) 3 to 7 times as much as an equivalent amount of wall area. Another complication is that window analyses often assume unfettered access to the sun with no shading created by adjacent vegetation or buildings. However, this is usually not the case - which can have a major impact on window selection since shading increases the relative importance of the unit's thermal resistance and decreases the significance of the SHGC.

Window Economics - The issue of window economics needs to be explored in more detail to fully appreciate the costs and energy benefits which they provide. Using some basic costing and performance data, two basic scenarios can be explored.

a) Adding Extra Glazed Area - This is a question which arises in the design of every NZE house; should additional window area be added to increase solar gains and reduce the space heating load? To answer, consider the incremental costs and benefits of adding a south-facing window to a NZEH located in (say) Winnipeg. Using a hypothetical 167 m^2 (1800 ft^2) NZE house, a HOT2000 analysis was conducted with the house in its original configuration and with an extra 1 m^2 of south-facing window area. The house used RSI 7.75 (R-44) exterior walls and had a south-facing window area/floor area ratio of 6%. This ratio (6%) has been used in Canada for many years as an unofficial guideline for determining the maximum south-facing window area which can be installed without creating overheating problems in energy efficient houses.

Based on discussions with builders, the cost of constructing 1 m^2 of conventional RSI 3.52 (R-20) exterior wall is roughly \$100/m^2 (\$10/ft^2),retail. Using information from Proskiw (2009), the incremental cost of upgrading this wall to RSI 7.75 (R-44) is about \$70/m^2 - giving a total wall cost of \$170/m^2. Depending on the type of window, the cost of purchasing and installing 1 m^2 of window will range from about $300 to $700 (retail). The window used in this example was a triple-glazed picture window with one LowE film, argon fill and insulated spacers. Its estimated retail cost was \$488/m^2.

Therefore, the net cost of adding this 1 m^2 window to the house is equal to the cost of the window minus the cost of the wall area displaced. Using these costs and the results of the HOT2000 analysis gives us...

Incremental cost: $488 - $170 = $318

Annual energy consumption:
- Without additional 1 m^2 window: 1462 kWh/yr
- With additional 1 m^2 window: 1443 kWh/yr
- Saving: 19 kWh/yr, worth $1.90 /yr (based on a utility rate of $0.10 /kWh)

This gives a simple payback period of 167 years. Given that the life expectancy of an Insulated Glazed Unit (IGU) is about 25 years, it is clear that inclusion of the extra 1 m^2 of south-facing window area can never be economically justified. Of course, this is a just a single example and different results could be obtained using different house designs, insulation levels, thermal mass levels, locations, etc. However, these results are typical of those produced by this type of incremental window analyses. From a design perspective, these results indicate that increasing the amount of window area in a NZE house, *as an energy saving measure*, has to be examined extremely carefully since it is unlikely to be economic *relative to other available options*.

b) Upgrading Windows - The other window issue which designers face is selecting the type of window to use. Employing the same NZE house and process to that described above, the impact of upgrading the same 1 m^2 of south-facing window from a conventional triple-glazing unit to a more energy efficient model (triple-glazed unit with one Low E coatings, two argon fills and an insulated spacer) was explored. The cost of the conventional triple-glazed window was estimated at $360/$m^2$, while the high-performance unit was estimated to cost $488/$m^2$. Energy savings were calculated with the 1 m^2 south-facing window area in its original triple-glazed configuration and in the upgraded configuration...

Incremental cost: $488 - $360 = $128

Annual energy consumption:
- With T/G, I/S test window: 1451 kWh/yr
- With T/G, 1 LowE, 2 argon fills, test window: 1443 kWh/yr
- Saving: 8 kWh/yr, worth $0.80 /yr (based on a utility rate of $0.10/kWh)

This gives a simple payback period of about 160 years - better than the case for adding window area but still hopelessly uneconomic.

These results may appear surprising but they are very consistent with our growing understanding of the behaviour of NZE housing. The reason the two window upgrades faired so poorly, from an economic perspective, is that the space heating load in a NZE house is very small compared to any other type of house. By adding window area, or upgrading window performance, the space heating load is reduced but it is already so small that there is little opportunity for further savings. Had these two upgrades been applied to a conventional house, with a much larger space heating load, the energy savings would have been larger and the economics more favourable.

Recommendation For Windows - The preceding discussion was used to illustrate the economics of adding glazed area and of upgrading windows in a Net Zero Energy House. Although it used single examples, the process could be easily used for other windows in other houses. Given this, what recommendations can be offered to NZEH designers and builders about window selection and sizing? A methodology for window selection in NZE houses has been proposed based on the cost-effectiveness of the product and that of other conservation options (Proskiw, 2008) and is designed to offer a rational process for selecting windows. One product of this work has been the recommendation that window selection focus on two issues: picking a "good" window (from an energy perspective) although not necessarily the best unit, and condensation resistance. The rationale for the first criteria is predicated on the argument that since windows and their upgrade options are so expensive, the investment would be better spent on improving the energy performance of other conservation or renewable energy options. In other words, window selection cannot be based simply on the available window options, but rather on the basis of options available for any other parts of the house - including those not associated with the windows. If the investment necessary to upgrade the windows produces less energy savings than would be produced by upgrading the foundation (for example), then the investment should be directed towards the foundation - not the windows.

The limitation of this approach is that a certain minimum level of window performance is still required to control condensation. For most conventional houses, and probably all NZEH designs, the weakest thermal link in the building envelope will be the windows (typically around the perimeter of the Insulated Glazed Unit where the spacer bars have the greatest influence). Since condensation resistance is a by-product of energy efficiency (primarily the type of spacer and the design of the window or sash frame), it means that some minimum level of energy performance will be required. While the need for condensation resistance is well known, few are aware that there is an explicit metric which has been developed that describes a window's condensation performance. AAMA/WDMA/CSA 101/I.S.2/A440-08 "Specification for Windows, Doors, and Skylights (AAMA/WDMA/CSA, 2008) defines the Temperature Index as:

$$I = [T - T_c] / [T_h - T_c] \times 100 \quad (3)$$

where:
I = Temperature Index
T = the coldest temperature on the inner surface of the window (glazing or frame)
T_c = outdoor temperature
T_h = indoor temperature

The Temperature Index can be determined by modeling, measurement or a combination of the two.

So, to summarize: From an energy perspective and based on the incremental costs and energy savings, window selection should be based solely on the need to control condensation. Further, the window area should be limited to that necessary to meet the functional and aesthetic needs of the building. South-facing glazing area should be restricted to 6% (to control overheating) and total window area should also be limited to that required for non-energy reasons. On a broader level, these results indicate that our long-held belief in the merits and value of passive solar energy as a key component of Net Zero Energy House design needs to be carefully re-examined and likely challenged.

Overheating - Due to their very low heat loss, NZE houses are prone to overheating if care is not taken. Several of the designers and builders expressed concerns about this issue. Depending on the design and operation of the air-handling system, overheating can occur throughout the house or can be concentrated in one or two rooms. In one house, two west-facing garden doors caused localized overheating in that room until the homeowner retrofitted a solar-blocking glazing film.

Airtightness

Although only limited, measured airtightness data was available for the houses, some general observations can be made:

1. **Focus on the big leaks** - Most air leakage in a house occurs at the joints, intersections and penetrations through the building envelope where major components meet. Minor leaks through obscure pathways can often be ignored.
2. **Concentrate on the upper part of the building** - During the heating season, the upper part of the building envelope is subjected to the strongest positive pressure differentials which causes air exfiltration, moisture transport and potentially interstitial moisture deposition.
3. **The importance of air leakage control increases with building height** - Since pressure differentials increase with building height, the taller the building the greater the pressure differential and hence air leakage.
4. **Draw out complicated details** - If you can't draw it, you probably can't build it.
5. **Check every building for air leakage -** Although every NZE house receives an airtightness test for compliance purposes, in many cases the greatest value of the test is that it permits air leaks to be quickly identified.
6. **Avoid, or plan around, problem areas, such as:**
    - 1½ storey floor/kneewall intersections
    - Attached garages, especially those under heated rooms
    - Cantilevers
    - Recessed ceiling fixtures (pot lights)
    - Irregular-shaped protrusions
    - Fireplace chases

- Three-sided intersections (such as the basement wall, floor, main wall intersection)
- Suspended basement floors
- Duct penetrations, especially those for solar air-based systems

Thermal Mass
A popular feature in many NZE houses is thermal mass, particularly for houses located in the United States and Europe. The basic principle is straightforward - as the house's indoor temperature cycles between day and night, excess heat generated during the day by passive gains or parasitic losses from appliances and people is stored as sensible heat within the building's mass and then released at night as the house's temperature falls. The greater the mass, the more energy can be stored. The most common materials used are concrete, masonry and water. Unfortunately, these tend to be fairly expensive except for water which, while cheap, needs to be stored in secure containers - which are expensive. For example, the estimated incremental cost of adding a large masonry concrete wall on the basement and floor levels in one of the study houses was $2400 (CMHC, 2010).

Ideally, the storage material should have a high Specific Heat to increase the amount of sensible energy which can be stored. Once again, most construction materials have relatively low specific heats - with the exception of water. However, the storage capacity is a direct function of the temperature differential through which the mass cycles. This creates a conflict with modern control strategies which emphasize the controllability of the indoor environment. Another problem with thermal mass is that it is most effective when the sun is able to shine directly on the mass surface so that the solar radiation is absorbed directly into the surface. If the mass is not exposed to direct solar radiation, and has to rely upon convective heat transfer from the surrounding air, its usefulness will not be fully realized thereby further eroding its economic viability.

One theoretical assessment of thermal mass was carried out using HOT2000 with four different levels of thermal mass in NZE houses (Proskiw, 2008). This study found that the impact of increasing thermal mass produced relatively modest energy savings - typically between 100 and 700 kWh_e/yr which represented about 2% to 7% of the space heating load and about 1% to 2% of the house's total energy consumption. The study concluded that while these savings were obviously beneficial, thermal mass should not be viewed as a panacea for NZE houses designed for Canadian conditions. Unlike more temperate climates which experience diurnal temperature variations more amenable to utilizing thermal mass, most Canadian locations simply cool off in the fall and do not warm up significantly until spring. ***Basically, if mass and materials are being added to the house for architectural, aesthetic or other purposes, then a secondary energy benefit can be expected. However, it is difficult to justify significant, additional monies for thermal mass as an energy savings strategy.***

MECHANICAL SYSTEMS
Mechanical System Complexity - One of the most common problems (both observed and reported) with Net Zero Energy Housing has been the complexity of the mechanical

systems (space heating, domestic hot water heating, ventilation and cooling). "While there may be a temptation to use every thermodynamic opportunity to maximize performance, the reality is that complex mechanical systems almost always prove to be problematic, expensive and far too unreliable. Perhaps the most trouble-prone example has been seasonal heat storage systems which attempt to capture and store large amounts of energy between seasons. While technically feasible, such systems are usually extremely expensive, produce nominal savings and may require the homeowners to adopt a full-time repairman as a live-in family member" (Proskiw, 2008). Controls for mechanical systems were a particular source of frustration for some of designers, especially those using advanced and new technologies. In some cases, the controls did not work properly, in other instances they were judged as too complicated by the builder or customers complained about the difficulty of using them.

In fact, the need to simplify mechanical systems was arguably the most consistent comment offered by designers during the interview phase of this project. For example, one designer had used a solar thermal system in conjunction with a Greywater Heat Recovery (GWHR) system and a desuperheater on a heat pump - three separate technologies to heat water. Overall, he found the solar thermal system to be leak-prone and not as effective as originally hoped. In retrospect, he felt that it would have been preferable to simply add photovoltaic capacity in place of the solar thermal system since most of the DHW heating was provided by the geothermal and GWHR systems. ***Perhaps the issue of mechanical system complexity was best captured up by one NZEH designer who summed up his approach: "Just say no!". It should be noted that this was also one of the most experienced NZEH designers encountered in the project.***

Excessive Floor Space Required For The Mechanical Systems - Most NZE houses use mechanical systems which are physically larger than equivalent systems found in conventional houses. This results in a system which occupies significant floor area. Several designers reported this was an issue with their houses, some noting that if one considers the cost per square metre of new construction, then the cost of providing additional room for the mechanical system amounts to a hidden cost of several thousand dollars, particularly if extra ductwork is required for the mechanical system. For example, if a Building Integrated Photovoltaic/Thermal (BIPV/T) system is used, it will require fairly large ductwork between the roof-mounted PV array and the mechanical room. If the latter is in the basement (the most common arrangement), floor space will have to be provided on each floor for the ductwork runs and their presence may complicate the interior design of the space.

Radiant Floor Heating Systems - These systems deliver space heat by circulating a heated fluid through tubes embedded in the floor to provide a comfortable, uniform indoor environment. Radiant heating systems are sometimes promoted as energy saving devices - using the argument that by providing such a warm, comfortable environment to the occupants, the thermostat setting can be reduced thereby allowing the house to operate at a lower average temperature. Although this latter point is somewhat contentious (since field research has suggested that occupants maintain the same thermostat settings, CMHC, 2001), they are still popular systems. However, their applicability in NZE houses has to be questioned. Since these houses use highly insulated building envelopes, the indoor environment tends to be well controlled and not subject to drafts or cold spots. Basically, how much money can be justified to improve the quality of the indoor space when it is already high quality? And, remember that the primary obstacle to NZE housing is economics, not engineering.

Domestic Hot Water Heating

Unanticipated Interactions Between Mechanical System Components - One house used a solar thermal system for DHW preheating coupled with an electric, instantaneous stand-by heater. However, under certain conditions the preheated water from the solar energy system was warm enough that the stand-by heater did not activate resulting in "cool" hot water.

Greywater Heat Recovery Systems

One of the most common features encountered in the survey houses were Greywater Heat Recovery Systems. These recover a portion of the energy normally wasted by the DHW system to preheat the incoming mains water. Although they only reduce the DHW load by about 15% to 25%, they are extremely robust and reliable devices and also increase the "effective" supply of hot water, particularly for loads such as showering.

Mechanical Ventilation Systems

Ventilation During Unoccupied Periods - Since NZE houses are quite airtight, most of the required ventilation air will be delivered by the mechanical system. If the house is unoccupied, the ventilation rate can be reduced (although some low level ventilation may be required to control building-generated pollutants). This concept was used in one house which employed a motion sensor-activated control override to shut down the HRV when the house is unoccupied.

Appropriate Ventilation Rates for NZE Houses - Since NZE houses are normally designed with great attention to indoor air quality and material selection (to minimize off-gassing), it begs the question of whether lower mechanical ventilation rates can be safely used in such structures. For modelling and design purposes, current practice is to use an average air change rate of 0.30 ac/hr (consisting of the net air change rate from natural infiltration and mechanical ventilation although with a very tight building envelope, most of this would be provided by the mechanical system). If the total, and hence, mechanical air change rates are reduced, energy can be saved.

Space Cooling Systems - Some may argue that a cooling system is not required in a NZEH house, particularly in a cold climate like Canada's. However, this ignores the reality that the heating season in a NZE house is comparatively short relative to any other type of house and that overheating is a serious issue - particularly if extra south-facing glazing has been used. The requirement for cooling has to be considered.

RENEWABLE ENERGY SYSTEMS

Cost and Complexity of Solar Domestic Hot Water Heating - Solar thermal DHW systems are common features in most NZE houses. On the surface, they appear to offer a good solution to the problem of heating hot water in a house with a very small space heating load. However, experiences have been mixed to date. First, there is the issue of cost. Typical installed costs for a glycol-based system capable of providing 30% to 50% of the annual DHW load range from about $4,000 to $6,000. Since a regular water heater is still required, there are no capital cost savings. There is also an economic conflict with the types of conservation features commonly included in NZE houses. Measures such as energy efficient water heaters, GWHR systems, low-flow fixtures, etc. all help to reduce the DHW load. Since these are usually very effective and, in many cases, very economical measures they are generally the first features selected for the DHW system. Collectively, they can reduce the DHW load by 25% to 50%. However, this minimizes the potential savings which the solar DHW system can generate since the net load is now smaller. Likewise, if the occupants' hot water usage is less than planned, the economics of solar DHW are further eroded since a conserving lifestyle has the same effect on economic performance as a conservation measure. In NZE houses with low DHW consumption, the argument has been made that it would be more economic to eliminate the solar DHW system and replace it with additional photovoltaic array area (EDU, 2008).

Reduced Solar Energy System Production Due To Snow Cover - Since the houses researched in this project are still undergoing monitoring, no firm statements can be offered about their actual energy performance. However, one issue which has arisen is snow build-up on solar collectors and PV systems. Depending on the snow's thickness, its residency time on the collectors, and other factors, snow can have a significant impact on the overall energy production of these systems. In one instance, one of the project houses with a low pitch roof, was subjected to a heavy snow fall which remained on the roof for a month resulting in zero photovoltaic production for that period. Some houses have used snow traps at the bottom of solar collectors to prevent roof avalanches. Unfortunately these also served to trap snow.

Photovoltaic Systems, Shading and Orientation - Problems with shading and site orientation are issues for passive, active and photovoltaic-based solar energy systems. However, because of their very high cost the financial consequences are perhaps most significant for PV systems. Sherwin et al report on NZE houses in Florida which were constructed on lots with west-facing orientations - resulting in 15% to 20% reductions in energy production compared to a south-facing lot (2010). This effectively increased the cost of PV energy production by almost the same percentage (some fixed costs for inverters, controls, etc. do not change). The impact of shading can be similar. Sherwin described experiences in which existing shading issues on a lot were recognized but (ultimately) could not be corrected by removing the offending trees due to conflicts with city ordinance policies on tree removal, or with the developer.

Inadequate Roof Area For Solar Energy Systems - The large amount of area required for both photovoltaic arrays and active thermal systems often created space problems on the roof for designers. Although the total roof area was usually larger than the area required for the solar energy systems, a portion of it was often oriented in the wrong direction, was shaded or otherwise unavailable for use.

Zoning Restrictions - One team had planned to design their urban NZE house with a sloped roof to accommodate a PV array but the city officials insisted on a flat roof, in part to manage falling snow. As a result, the designers installed a large, expensive steel framework on top of the roof to support the arrays - although noting that this was functionally and aesthetically identical to a pitched roof. Fortunately, this created a lot of useable space under the array which could be useful for barbeques, etc. Unfortunately, the plumbing stacks were vented at eye-level on the roof and produced a pungent odour whenever the wind was blowing from the south.

Building Integrated Photovoltaic/Thermal Systems (BIPV/T) - This is a relatively new concept which uses a PV system to produce electricity but also recovers heat from the backside of the array which can be used for space and possibly DHW. Experience with these systems is quite limited so firm conclusions are premature but a few observations can be made. One system installed on a NZE house was reported as having produced less than 1000 kWh annually - not including the fan energy required to run the system or the additional electricity which would have been generated by the array (PV output decreases with increasing temperature, so by enclosing the backside of the array to create a flow channel, the average temperature of the array can be increased - which reduces electrical output). Despite this modest energy production, the reported cost of the system was $15,000. On another house, the cost of a BIPV/T was estimated at $20,000 (CMHC, 2010).

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REFERENCES

AAMA/WDMA/CSA. 2008. *AAMA/WDMA/CSA 101/I.S.2/A440-08 North American Fenestration Standard/Specification for Windows, Doors, and Skylights.* American Architectural Manufacturers Association (AAMA), the Window & Door Manufacturers Association (WDMA), and the Canadian Standards Association (CSA).

Canada Mortgage and Housing Corporation. 2001. "Thermostat Settings in Houses with In-Floor Heating". Technical Series 01-106.

Canada Mortgage and Housing Corporation. 2010. "Riverdale NetZero Passive Solar Design". EQuilibrium™ Housing InSight.

Canada Mortgage and Housing Corporation. 2010. "Avalon Discovery 3: Active Solar Heating". EQuilibrium™ Housing InSight.

Canada Mortgage and Housing Corporation. 2010. "Avalon Discovery 3: Building Integrated Photovoltaic System". EQuilibrium™ Housing InSight.

Canada Mortgage and Housing Corporation. 2010. "Monitoring Results for the Factor 9 Home". Research Highlight.

Proskiw, G., Proskiw Engineering Ltd. 2008. *Building Envelope and Mechanical System Technologies and Design Philosophies for Net Zero Energy Housing*. Draft report prepared for Natural Resources Canada.

Sherwin, J.; Colon, C.; Parker, D. and Martin, E. 2010. *Performance of Four Near Zero Energy Houses: Lessons Learned*. Buildings XI Conference. Clearwater Beach, Florida.

Table 1 - Study Houses, Basic Data

House	Designer	Builder	Built	Location	Heating Degree Days	Volume (m^3)	Floor Area (m^2)	Stories	Design Airtightness
Factor 9 House	Saskatchewan Research Council -led team		2006	Regina	5750	744	297	1	0.50
EcoTerra	Alouette Homes -led team	Alouette Homes	2007	Eastman	4800	671	268	2	1.00
Inspiration Ecohome	Minto Developments -led team	Minto Developments	2008	Ottawa	4600	820	328	2	0.65
Riverdale Net Zero	Habitat Studio & Workshop	Habitat Studio & Workshop	2007	Edmonton	5400	635	254	2	0.50
Avalon Discovery 3	Avalon Master Builders-led team	Avalon Master Builders	2007	Red Deer	5750	452	181	1.5	0.50
Metro Denver Net Zero	National Renewable Energy Laboratory	Habitat For Humanity	2006	Denver, USA	3491			1	

Table 2 - Study Houses, Insulation and Window Data

House	Nominal RSI-Values				Wall Type	Windows		
	Ceiling	Walls	Foundation Walls	Foundation Floor		Major Window Types	RSI Value	ER
Factor 9 House	14.1	7.2	7.7	2.0	SIPS with exterior, insulated cladding	T/G, 2 Low E, argon (N&E) Q/G, 2 Low E, argon (S)	0.93 1.05	-12 3
EcoTerra	6.3	6.6	6.6	1.3	SIPS	T/G, 2 LowE, argon, I/S	0.77	
Inspiration Ecohome	11.0	7.2	7.0	2.6	Double-stud wall with sandwhiched rigid insulation	T/G, 2 Low E, argon (N&E)		
Riverdale Net Zero	17.6	9.9	8.8	4.2	Double stud with blown-in cellulose	T/G, 2 Low E, argon (N&E) Q/G, 2 Low E, argon (S)	1.2-1.4 1.8	
Avalon Discovery 3	15.3	12.3		10.6	Double SIPS	T/G, 2 LowE, argon, I/S		
Metro Denver Net Zero	10.6	7.0			Double wall	D/G, LowE		

Table 3 - Study Houses, Window (con't) and Heating System Data

House	Glazing System			Heating System			
	Glazing/Floor Ratio	South Glazing/Floor Ratio	Shutters	Type	Distribution	Efficiency	Notes
Factor 9 House	8.8%	6.4%	No	Electric	Water	100%	
				Solar			2350 l water storage tank
EcoTerra	12.4%	7.8%	No	GSHP	Water		
				Solar	Liquid		
Inspiration Ecohome	8.9%	5.7%	No	Gas	Air	98% AFUE	
				Solar	Liquid		908 l water storage tank
Riverdale Net Zero	11.7%	6.7%	No	Electric	Fan coil forced air	100%	
				Solar	Liquid		17,500 l water storage tank (seasonal)
Avalon Discovery 3	11.3%	4.5%		Electric	Water	100%	Radiant heating system in floor
				Solar	Liquid		
Metro Denver Net Zero			No	Gas furnace	None	90%	
				Electric	Baseboards	100%	

Table 4 - Study Houses, DHW, Ventilation and Cooling System Data

House	DHW System			Ventilation System		Cooling System
	Type	Efficiency	Notes	Type	SRE	
Factor 9 House	Electric	94%	Instantaneous GWHR	HRV	77%/60%	Non-heat pump ground cooling c/w 4.5 m of piping in piles
	Solar thermal					
EcoTerra	GSHP			HRV		GSHP
	BIPV/T					
Inspiration Ecohome	Gas	94%	GWHR	HRV	80%/77%	
	Solar thermal					
Riverdale Net Zero	Electric	94%	Instantaneous GWHR	HRV	84%/72%	Non-heat pump ground cooling c/w 96 m ground piping
	Solar thermal					
Avalon Discovery 3	Electric	94%		HRV	79%/72%	Non-heat pump ground cooling c/w 91 m ground piping
	Solar thermal					
Metro Denver Net Zero	GSHP with desuperheater		GWHR	ERV		GSHP Solar curtains used on some windows
	Solar thermal					

Table 5 - Study Houses, Renewables and Other Data

House	Net Energy Consumption (kWh2/yr m^2)		Design Software	Approximate Incremental Cost Data
	Estimated	Actual		
Factor 9 House	30	33	HOT2000 RETScreen	$ 37,000 Total (12% extra, excluding land, for the energy & water conservation measures)
EcoTerra	-0.32		HOT2000	Partial data: $ 15,000 Building envelope $ 5,000 Windows $ 35,000 Mechanical system $ 5,000 Thermal mass
Inspiration Ecohome	-0.20		HOT2000 RETScreen	
Riverdale Net Zero	-1.50		HOT2000 RETScreen	$ 12,000 Building envelope $ 1,800 Electricity efficiency $ 2,400 Passive solar $ 36,700 Active solar (space and DHW) $ 54,000 Photovoltaics $ 1,750 Water efficiency $110,000 Total (approx.)
Avalon Discovery 3	1.49		HOT2000	Partial data: $ 50,000 SIPS panels
Metro Denver Net Zero			BEOpt	