IDENTIFYING AFFORDABLE NET ZERO ENERGY HOUSING SOLUTIONS

A REPORT PREPARED FOR

ALEX FERGUSON
SUSTAINABLE BUILDINGS AND COMMUNITIES (HOUSING GROUP)
CanmetENERGY
NATURAL RESOURCES CANADA

by

GARY PROSKIW, P. Eng.
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SECTION 1
INTRODUCTION

1.1 BACKGROUND

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 using on-site renewable energy systems, NZE houses are usually net consumers of energy during the heating season and net producers of energy during the non-heating season. To appreciate how this technology evolved, it is interesting to briefly review the history of low-energy housing technology in Canada.

Research and development on low-energy housing began in the 1970's and went mainstream about a decade later with the introduction of the R-2000 Standard into the marketplace by Energy, Mines and Resources Canada (now Natural Resources Canada). Introduced (and maintained ever since) as a voluntary program, the R-2000 Standard represented an evolutionary improvement over contemporary housing. Yet it incorporated all the key ingredients of what is now regarded as a low energy house: airtightness, higher levels of thermal insulation, quality mechanical ventilation systems, high efficiency space and water heating systems, passive solar design and a quality control program which went far beyond what was required by building inspectors. And, it used a performance target for energy consumption rather than the prescriptive approach normally found in building codes. But the improvements in energy performance were relatively modest compared to conventional houses with overall energy savings of 20% to 40%. Since its introduction, the R-2000 Standard has undergone a number of updates to reflect changing technologies, evolution of the conventional housing product and changes in the cost of energy. To date, well in excess of 10,000 R-2000 houses have been built across the country.

In the early 1990's, Natural Resources Canada introduced the Advanced House Program which used a similar format and design as the R-2000 Standard except that the performance-based energy target was set at one-half that of the R-2000 Standard. Although only about a dozen Advanced Houses were built, they provided a glimpse into the future. In fact, in most respects - such as overall design, insulation levels, airtightness and mechanical system performance - they were almost identical to the Net Zero Energy Houses of today. The one major difference was that renewable energy sources, specifically photovoltaic (PV) systems, were too expensive and hence were only used sparingly in a few Advanced Houses. Today, while photovoltaic systems are still expensive relative to conventional energy sources, their price is much more affordable and their performance is superior to the product of 20 years ago. Further, they are now net producers of electricity - when the embodied energy required to manufacture them is considered - whereas earlier products actually consumed more energy to produce than they generated over their projected life.

The final development which made NZEH possible was introduction of electronic control systems that permitted a photovoltaic system on an individual house to be connected to the electrical grid in such a manner that the PV system was able to use the grid as a giant battery. When the PV array produces more electricity than the house can use, it is pumped into the grid through a reversible electrical meter which runs backwards when the house is exporting power to the grid. This eliminates the need for on-site battery storage. When the house's electrical demands exceed the array's output, power is drawn from the grid in the conventional manner. While conceptually simple, the critical issue is power quality - specifically the energy exported by the house has to exactly match the voltage and frequency of the grid at the point where the house is connected. Fortunately, with developments in modern electronics, this is not only possible but reasonably affordable. With this final step, all the critical components necessary to design and build Net Zero Energy Houses were in place.

The next major development took place in 2006 when Canada Mortgage and Housing Corporation (CMHC) launched their EQuilibrium™ Sustainable Housing Demonstration project which provided financial assistance to builder-or-developer-led teams to design and construct houses whose annual energy consumption was zero and which met stringent environmental criterion. In addition, the homes had to be kept open for public tours for a minimum of six months after completion and also had to be subjected to detailed performance monitoring for a minimum of one year. Since inception, 13 EQuilibrium™ houses have been constructed across the country. At the time of writing, most of these are now in their monitoring phases and generating initial performance data.

While NZEH construction is still quite expensive relative to conventional practices, it is at least technologically feasible. Further, the cost of photovoltaic systems and the power they produce, has been dropping significantly over the last several years. In the last ten years, the cost to install one kilowatt of PV capacity has dropped to roughly $6,500/kW.

Finally, while we may have understood for some time the technical steps necessary to design and construct a NZE house, we are now developing a much better appreciation of how to optimize the design, not just from a technical standpoint but also from a cost perspective. This report has been prepared to further that process.

1.2 OBJECTIVES

The objective of the work described in this report was to propose a starting point for market-feasible NZEH designs. To achieve this, the report has been designed to:

- Identify best practices in current Net Zero Energy House designs in Canada and abroad, and
- Propose appropriate technology suites for the next generation of NZE houses.

The first objective was basically to prepare a "Lessons Learned" analysis of recent NZE house design and construction experience 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. The second objective was to take this knowledge and combine it with our existing understanding of low energy house design practice to propose a collection of technology suites (comprising envelope measures, mechanical system features and renewable energy packages) which were geared to the marketplace.

1.3 SCOPE

The field of Net Zero Energy Housing is evolving very rapidly with new information, understanding, products and approaches appearing on a regular basis. This creates a bit of a dilemma for studies of the type described in this report. For example, most of the NZE houses discussed in this report were completed within the last two years and in some cases had not been fully completed when this report was prepared. Most were still in their monitoring phases (given their novelty and cost, virtually all NZE houses are subjected to fairly intense monitoring for periods of at least a year). As such, their performance data (particularly the energy data) was incomplete and no attempt was made to write a final commentary on the quantitative performance of the houses or their components. However, this is not a problem since that topic will be handled in more depth by others. The current project is focused on the design and construction experiences which designers and builders had with these houses. Future monitoring results may temper the conclusions but are not expected to significantly alter them.

The reader will notice that this report contains many anecdotal observations and experiences obtained during interviews with builders, designers and others. Ideally, more comprehensive information sources would have been preferred but the development of NZEH technology is simply not that advanced. In simple terms, there are barely more than a dozen Net Zero Houses in Canada and all of these have been constructed within the last few years. In many cases, anecdotal information is all that exists. In addition, some information sources are unreferenced in this report to protect the privacy of the sources since they often provided a "warts and all" insight.

1.4 METHODOLOGY

The project was divided into three major phases:

Task 1) Review Of Cold Climate NZEH Projects

An initial list of 12 candidate NZEH projects was prepared by Natural Resources Canada. Ten of the houses were built in Canada and two in the United States. Using published reports, internet searches and various other sources of information, a small research file was created on each project to assemble information on the house design, construction, monitoring and (where available) performance. The houses used a variety of technologies and design approaches and were constructed in a number of different climates (an important point acknowledging how dependent house design is on climate).

Task 2) Follow-Up With NZEH Builders And Designers

Following the initial review, a sub-set of six of the original 12 houses was selected for more detailed study and review. Their builders and/or designers were then contacted and interviewed to capture their experiences, thoughts and what they felt they had learned about NZEH design and construction. Although only six houses were included in this group, the builders and designers had been involved in at least twice that number of NZEH projects and all had extensive experience with low-energy house practices.

Task 3) Preparation Of Market-Feasible Technology Suites

Using the information collected in the first two Tasks, three technology suites were designed based on the following criteria:

- Affordability
- Reliability
- Ease of installation
- Availability of service personnel
- Suitability for non-expert (homeowner) operation
- Production ready

Each suite consisted of three components: envelope measures, mechanical system features and renewable energy systems. Basically the intent was to use the knowledge and insight gained from the design and construction of the NZE houses studied in this project to identify the major design features for a market-feasible NZE house. Further, since different design approaches/philosophies were used for most of the houses, a different design strategy was proposed for each suite based on its underlying philosophy.

1.5 REPORT ORGANIZATION

Section 1 provides an introduction to the project while Section 2 gives a brief description of the six NZEH houses studied in the project. Using this information, Section 3 discusses the major lessons learned about the design, construction and operation of Net Zero Energy Houses - particularly within Canada. In some instances, these were singular lessons which resulted from specific experiences in a particular house while in other cases they represent the distillation of years of experience from a number of different NZEH structures and other low energy houses.

In addition, this project offered the opportunity to ponder what types of specific products, systems and practices could, and perhaps should, be developed to improve both the performance of NZE houses and their affordability. Some thoughts on this subject are contained in Section 4.

Finally, Section 5 combines these lessons to propose three groupings of technologies which could form the core of a market-feasible Net Zero Energy House. Each is designed around a separate design philosophy and combines technologies on the basis of performance, function and - perhaps most importantly - cost-effectiveness.

SECTION 2
DESCRIPTION OF THE SURVEYED HOUSES

2.1 INTRODUCTION

The six Net Zero Energy Houses used as the primary sources of information for this project are summarized in Tables 1 to 5 and a brief description is provided below.

2.2 DESCRIPTION OF THE SURVEYED HOUSES

Factor 9 House - Constructed in Regina in 2007, the Factor 9 House was not designed to achieve net zero status (at least using a strict definition of the term). Rather its intended goal was to use 90% less energy per square metre of floor area than a conventional Saskatchewan home and 50% less water. In fact, the Factor 9 House was one of the first to introduce what is now known as Net Zero-Ready construction in which the building envelope, mechanical systems and other features are designed the same as they would be for a NZE House - except the renewable energy system (photovoltaics) 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 90% of the energy savings at a fraction of the cost. Further, as the costs of PV systems decline, they can always be installed at a later date - hence the term "Net Zero-Ready".

The house itself is an architecturally conventional structure with 297 m^2 (3196 ft^2) of floor space (including the basement). Insulation levels are very 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 parts of the DHW and space heating loads. Some novel ideas were included in the mechanical system (such as a ground-coupled cooling system). Energy efficient lighting and appliances as well as various water conservation technologies were also included.

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) detached home. The RSI 6.6 (R-37) walls are built using SIPS panels while the roof uses RSI 6.6 (R-36) and the foundation RSI 6.6 (R-37). A unique aspect of its construction is that it is a pre-manufactured house with all major components constructed in a factory and then assembled on-site. Another interesting feature is that 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).

EcoTerra™ also makes extensive use of thermal mass including a 15 cm (6") thick concrete slab covered with ceramic tiles (which receive direct solar radiation) as well as some concrete interior walls. The primary heating system uses a Ground Source Heat Pump (GSHP) with supplemental solar heating; the GSHP also provides DHW heating.

Inspiration Ecohome™ - Another EQuilibrium™ Home, this two storey 328 m^2 (3529 ft^2) structure (including basement) was built 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 is placed on utilizing passive solar energy. An interesting feature of the home is that it uses an "all-off" switch that turns off all lights, computers, cable boxes and other phantom load devices and can be activated when the homeowners leave the house. A rainwater collection system is also used. Emphasis is 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 of the house 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. The house is designed to produce a net surplus of 500 to 1000 kWh_e/yr.

Avalon Discovery 3 - This EQuilibrium™ house was built in Red Deer in 2007. It is a 1½ storey slab-on-grade structure which features a very well-insulated building envelope. The wall system uses a rather 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 with an electric back-up and includes a radiant floor heating system. One 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 uses insulation levels comparable to the Canadian houses. The exterior walls use double-wall construction with RSI 7.0 (R-40) insulation while the ceiling is 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 BOpt - building optimization software developed by NREL. This is intended to aid the designer in selecting quantitative values for thermal insulation values, equipment efficiencies, window types, etc. using a formal optimization process.

Table 1 - Study Houses, Basic Data

House	Designer	Builder	Built	Location	HDD	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 (Nominal R-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 Low E, argon, I/S	0.77	
Inspiration Ecohome	11.0	7.2	7.0	2.6	Double-stud wall with sandwiched 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	n/a	10.6	Double SIPS	T/G, 2 Low E, argon, I/S		
Metro Denver Net Zero	10.6	7.0		5.3?	Double wall	D/G, Low		

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

House	Glazing System			Heating System			
	Glazing/Floor Area Ratio	South Glazing/Floor Area 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	Renewable Energy Systems				Dedicated Thermal Mass	Lighting & Appliances	Water Conservation
	Type	Application	Notes	Est. Energy Production (kWh/yr)			
Factor 9 House	Active solar	DHW	20.4 m^2		2350 l storage for space heating	CFL lighting, Energy Star appliances	Rain & snow collection, 9,500 l water storage, Reduced water landscaping
	PV-ready	Future electrical generation		0			
	Airtight wood stove			1000 (est.)			
EcoTerra	Active solar			5291	15 cm concrete floor Two, 0.3 m thick, 1 m high concrete walls	Emphasis on natural lighting	
	PV array	Electricity & DHW	Uses waste heat from PV array	3480 (including DHW preheating)			
Inspiration Ecohome	Active solar	DHW	3.0 m^2		None	Emphasis on natural lighting, CFL & LED lighting	
	PV array	Electricity	6.2 kW	8166			
Riverdale Net Zero	Active solar	DHW			Concrete counter tops, Concrete pillars, Masonry wall		Low flow fixtures, Water conserving, appliances
	Active solar	Space					
	PV array	Electricity	5.6 kW, 33 m^2	6600			
Avalon Discovery 3	Active solar	DHW			None		
	Active solar	Space					
	PV array	Electricity	8.3 kW	9569			
Metro Denver Net Zero	Active solar	DHW	8.9 m^2			CFL lighting, Energy Star appliances	
	PV array	Electricity	4.0 kW	5756			

Table 5 (con't) - Study Houses, Renewables and Other Data

House	Net Energy Consumption (kWh/yr m^2)		EGH Rating	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		98	HOT2000	Partial data: $15,000 Building envelope $5,000 Windows $35,000 Mechanical system $5,000 Thermal mass
Inspiration Ecohome	-0.20		100	HOT2000 RETScreen	
Riverdale Net Zero	-1.50		100	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		101	HOT2000	Partial data: $50,000 SIPS panels
Metro Denver Net Zero				BEopt	

SECTION 3
LESSONS LEARNED

3.1 INTRODUCTION

The main component of this project consisted of numerous discussions held with NZEH designers and builders as well as various other individuals working in the field of low energy housing. In addition, extensive background research was compiled from published documents, technical reports, conference proceedings, presentations, journals, etc. This information was compiled and studied to identify common themes, observations, problems and insights which might be of value to others. This section summarizes these lessons.

The discussion begins with the design and optimization process and then moves on to discuss each major component of the house: building envelope, mechanical systems, renewables, etc. Comments are also offered on some of the occupant considerations.

3.2 DESIGN AND OPTIMIZATION

3.2.1. Design Optimization Of Net Zero Energy Houses

In this report, "design optimization" refers to the qualitative and quantitative selection of conservation and renewable energy measures best suited to the house. It does not include the conventional engineering or architectural design decisions which would still have to be performed if the house were a conventional structure.

The importance of design optimization for NZE housing can be expressed by two simple, yet critical observations: a) designing a NZEH is easy but b) doing it at the lowest possible cost is very difficult. Contrary to what some may believe, there are no significant technical impediments to the design and construction of such houses, the issue is simply achieving the desired performance at a lower cost than is now occurring. The incremental cost of upgrading a conventional house to NZEH levels is significantly higher than the cost of upgrading the same house to low energy standards (such as the R-2000 Standard). For example, the average incremental upgrade cost for a NZE house currently ranges from about $50,000 to $150,000 whereas the corresponding value for R-2000 houses is about $5,000 to $10,000. Therefore, while identifying the optimum R-2000 upgrade package is certainly important to the overall economic success of the design, identifying the optimum NZEH upgrade package is absolutely critical. Without careful consideration of the costs and performance of all available design options, tens of thousands of dollars can easily be wasted. As a result, design optimization of NZE buildings is paramount.

Over the last decade, considerable experience has been gained with NZEH design and construction and a general consensus has evolved among most designers (particularly those with the most experience) of the overall design philosophy which should be used:

1. Minimize envelope heat loss by using a simple architectural layout, massive amounts of insulation and a high degree of airtightness.

2. Select the most efficient types of space and water heating, ventilation and cooling systems.

3. Use energy efficient lighting and appliances.

4. Maximize passive solar gains (while still respecting the 6% rule -discussed later).
5. Use renewable energy systems to provide the balance of the energy requirements.

Historically, Net Zero Energy Houses have been designed using a combination of the designers' experience coupled with a semi-formal analysis of the costs and benefits of various conservation and renewable design options. Typically, this process consists of modelling the initial house design (with conventional conservation features and no renewable components) to determine the annual energy consumption. Various design options (such as increased insulation levels, airtightness and improved mechanical systems) are then modelled to determine the corresponding energy savings. The incremental upgrade costs of each option is then estimated and compared to the corresponding energy savings to arrive at some type of cost/benefit metric. This process continues until the incremental energy savings are judged to be too small relative to the attendant cost. At this point, the remaining energy deficit is met with the addition of renewable energy systems (almost always photovoltaics). As the designer's experience grows, refinements and improvements can be fed back into this process. For example, the incremental cost of the first three Net Zero Houses in Edmonton - all designed and constructed by the same team - declined from $110,000 to $70,000 (Howell, 2011)

With one exception, all of the houses surveyed in this study used this method. While it works, it is very dependent on the experience and skill of the designers and the amount of time they have to invest in the process. Generally, NZEH designers have reasonable competence at modelling houses to assess energy performance so their estimates of individual measure energy savings should be reasonable. However, the corresponding cost data tends to be more problematic. Since Net Zero Energy Houses have to push conservation measures to the extreme, the designers may be costing measures with which they have little, if any, direct experience. Further, sub-trades and suppliers, who generally supply costing data to builders may also be operating outside their experience envelope. This introduces the opportunity for significant errors in the costing information and the resultant cost-effectiveness of individual measures as well as the overall design. In addition, the designers may not have modelled all possible measures due to time or experience constraints. So in summary, the traditional design process works - but its level of success is totally dependent on the designers, their experience and skill.

The one house surveyed in this project which did not use this process was the Denver Net Zero House. It was designed by the National Renewable Energy Laboratory in the U.S. who developed and used a new software tool called BEopt (Building Optimization) to assist in the detailed selection of conservation and renewables measures. Basically, BEopt operates by automating the process described above. It takes the basic house design and evaluates the energy impact of various design upgrades. It then accesses an internal data base of costing information and calculates a corresponding cost-effectiveness metric for each measure. This process is repeated for large numbers of conservation and renewable options such that the lowest cost pathway through the available options can be identified. While conceptually very similar to the more familiar process, BEopt has the advantage that, from an experienced user's perspective, much of the analysis is simplified. Further, there is a better likelihood that all the necessary measures which should be evaluated will be evaluated. Nonetheless BEopt has some limitations. Perhaps the most significant is that designers may be too willing to accept its conclusions without a critical assessment of their applicability and appropriateness for the house or its climate. There is also an issue with the costing data. As mentioned, the uncertainty associated with costing data is significantly greater than it is for energy performance data since the latter can be calculated as an output function of the design parameters (R-values, envelope areas, mechanical system efficiencies, etc.) while the former is an input. Someone has to decide how much more it costs to build (for example) an RSI 7.04 (R-40) wall instead of an RSI 3.52 (R-20) wall. Costs cannot be "calculated" from first principles like energy consumption can. Still, BEopt is the only piece of software currently known to exist which offers the possibility of automating the optimization process for NZEH.

A very similar, albeit less comprehensive, approach was developed by Proskiw (2008). Rather than attempting to identify every possible conservation and renewable design option, HOT2000 software was used to evaluate the energy savings of approximately 50, relatively popular energy conservation measures. The analysis was performed for four Canadian locations with three house types and two heating fuels thereby creating 24 sets of recommendations. This information was coupled with costing data developed using Canadian experiences to create a cost-effectiveness metric termed the "ECM Value Index" defined as:

$$\text{ECM Value Index} = \frac{\text{incremental cost of the measure}}{\text{energy savings}} \tag{1}$$

A similar costing metric was also developed for renewable energy systems called the "PV Value Index which has a very similar form to Eq. (2):

$$\text{PV Value Index} = \frac{\text{PV system cost}}{\text{energy savings}} \tag{2}$$

Notice that both Eqs. (1) and (2) have the same units ($\$/\text{kWh}_e \cdot \text{yr}$) and both represent the extra cost required to save 1 kilowatt-hour per year. Several hundred HOT2000 simulations were then performed to evaluate the ECM Value Indices for each ECM/location/house type/fuel type combination. Finally, the ECM Value Index was compared to the PV Value Index to determine the cost-effectiveness of each ECM relative to the photovoltaic option. All of this information was then assembled into a series of ECM Upgrade Priority lists. Using this process, design guidelines were established for each of the 12 house/location combinations. These guidelines can then be used by designers to create a first draft of the energy-related, design features of the house. Once these have been identified, the actual, proposed house design can be modeled and the design fine-tuned. Also, the Value Index data can be modified to reflect local costs. Basically, this approach represents a middle-ground between the basic, semi-unstructured approach used by most NZEH designers and the high-level method employed by BEopt.

3.2.2 Design Constraints

Several, if not most, NZEH projects surveyed in this project had to contend with various design constraints, beside the obvious dictate of having to be "net zero". Some were created by site conditions, or financial constraints, or in several cases the availability of specific products or systems which the owners wished to be included. This observation is mentioned because it often forced the design team towards a final design which was not optimized from an energy perspective. In other cases, these constraints were self-imposed by the design team. Still, design is the art of compromise so constraints have to be recognized as an integral component of any NZE house design.

a) Cost - Cost will be an obvious constraint with any NZE house since considerable investment has to be made in technology which a more conventional house would not need to incorporate. However, NZE houses are also at the cutting edge of low energy house development so they are often pushing the design envelope in terms of innovation. This raises the issue of how "innovation" should be budgeted. For example, all construction budgets contain contingencies to deal with unforeseen problems. Cost estimators will establish a contingency, usually expressed as a percentage of the total construction budget. However, these values are based on conventional construction which does not carry the same risk as NZE housing. A suggestion made by one designer was that NZEH designs should include a second contingency fund specifically for innovation. Its magnitude could be established based on the level of perceived risk - such as the number and types of technologies included in the design. Obviously, given the limited amount of experience with NZEH design and costs, this would be an inexact process but would still offer the benefit of forcing the issue of technological risk to be explicitly addressed as a cost issue.

b) Commercial Availability - One project team decided to only use products which were readily commercially available, both to insure the availability of maintenance personnel as well as spare parts. This had the biggest impact on the mechanical system since some state-of-the-art technologies could not be included since they had not advanced sufficiently in commercial development.

c) Orientation - The optimum orientation for a NZE house is generally assumed to be due south. In several cases, the lot chosen for the house did not provide that opportunity - particularly in urban locations with existing street layouts. One designer reported that one of his other NZE houses (not part of this study) had no south-facing glazing because of shading from vegetation and other buildings.

d) Adjacent Buildings - While the classic image of a NZE house may be a solitary structure in a relatively open space, the reality is that adjacent structures or vegetation are often present and cannot be easily eliminated. In some cases, such as a NZEH forming part of a row house, the attached structures affected window placement. Obviously, this was most commonly encountered in urban locations.

e) Integration With The Adjacent Architecture - Once again, this was predominately an urban constraint and occurred when the NZE house was planned for an existing neighbourhood and there was a desire to match the existing architectural vocabulary. This constraint can affect the size and placement of glazing, the placement of photovoltaic arrays and solar thermal collectors as well as the general appearance of the building.

f) Homeowner-Imposed Constraints - Several homeowners insisted upon inclusion of specific technologies or products they wished to have in their homes. In one instance the homeowners wanted an in-floor radiant heating system for comfort purposes even though it increased costs and likely provided only marginal improvement in comfort since a tight building shell and highly insulated envelope should have created a very comfortable, indoor environment. In another case, the homeowner wished to have an active, thermal storage system included as part of the mechanical system, partially because he had access to a large, used storage tank. Further, the tank size was not optimized, from a thermodynamic perspective, for the rest of the system.

g) Ground Source Heat Pumps - These systems form part of the "conservation toolkit" available to designers. However, they are also, in most cases, the most expensive option in the toolkit. A typical GSHP system designed to supply the space heating load and possibly the DHW load (if a desuperheater is included) will cost $20,000 to $30,000. In contrast, a conventional electric forced air heating system and electric DHW tank (complete with a Greywater Heat Recovery System) would cost about $10,000. Therefore, if a design decision is made to use a GSHP, it could impose cost constraints on the rest of the design due to its significant incremental cost relative to more conventional alternatives. Another designer reported that most GSHP equipment was sized for houses with more conventional energy performance. Finding a system small enough to work in a NZE house, with its greatly reduced space heating (and possibly) DHW load, was an issue.

h) Desire For Modular Construction - In one case, the builder used factory production of components rather than conventional site construction techniques. Therefore, all their houses were designed for modular production, transportation and erection on site. This imposed some modest constraints on their NZEH design.

i) Air-Conditioning Not Permitted - In one instance, the builder was a non-profit charitable organization who - as a general policy - did not provide air-conditioning with any of their houses. This created considerable concern about the possibility of overheating and the design team paid special attention to insure it was addressed through other means.

3.2.3 Overall Design

NZE houses are extremely unique creations which, when constructed, 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. To be fair, this simply reflects how different a typical NZE house is from conventional practice. Given the considerable extra cost, such investments are probably justified. However, 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 departures or variations from earlier designs. This creates a tendency to introduce non-standard design features, dimensions and layouts.

One lesson which can be taken 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. For example, one of the house builders insisted that the overall layout should be as conventional as possible. This translated into such simple measures as using standard window sizes rather than more unique sizes which could only be purchased as special orders, were more expensive and had longer delivery times. It is interesting to note that the R-2000 Standard had similar experiences in its early days. Some of the early R-2000 houses were quite architecturally unique and visibly different from their neighbours. However, within a very short period, most builders realized that an R-2000 house should be as indistinguishable as possible from its neighbours. This reduced costs and made it easier to market the product.

Another point which came apparent in the interviews was that the design objectives for the house 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.

3.2.4 Little Problems Turning Into Major Costs

Although this can occur with any construction project, NZE houses are particularly vulnerable to small problems creating major cost issues. Part of this is because NZE houses are at the cutting edge of design practices. In addition, the complexity of most designs (particularly the mechanical systems) leaves them very vulnerable to this problem. Commenting on the performance of four NZEH houses in Florida, Sherwin et al noted that "One recurring lesson from the projects is that small changes matter, and the overall success of the project will depend on the cumulative integrity of individual parts" (2010).

3.2.5 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, NZE houses 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 put it: "Sequencing of the cooling lines into the piles was not plug and play".

3.3 BUILDING ENVELOPE

3.3.1 Foundations

Other than their unusually high insulation levels for both the walls and floors, most NZE houses use relatively conventional foundations although with much higher insulation levels. Interior insulation schemes are common (since the interior is usually finished) although exterior insulation is 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.

The Urban Ecology NZE House (not one of the survey houses) used Insulated Concrete Forms (ICF) for the foundation insulated to RSI 7.04 (R-40). ICF's have been in use in Canada for a number of years and have proven to be very successful. Although somewhat more expensive than conventional cast concrete foundations, they combine all the components into one assembly. One advantage of this approach is that the insulation level can be increased simply by using a different form (the concrete volume remains the same). For example, RSI 10.57 (R-60) forms are now available from one supplier - which should be adequate for most NZEH construction.

3.3.2 Exterior Wall Systems

Wall System Costs - 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 air leakage, moisture performance and durability standpoints.

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 are often more modest than expected.

Increased wall thickness can consume living space. For example, increasing the wall thickness by 15" (6") on a 149 m^2 (1600 ft^2) house would reduce the useable floor space by about 5%, assuming the extra thickness were accommodated on the interior. If the additional insulation is placed on the exterior, property taxes could be impacted.

Excessive Air Leakage Through SIPS Panels - One of the study houses which used Structural Insulated Panels for the exterior walls reported excessive air leakage around the panel perimeters. The problem was further aggravated at the grade beam foundation since it was not as flat as required. The builder solved the problem with supplemental caulking.

3.3.3 Ceilings, Attics and Roofs

Reduced Thermal Resistance At Roof Perimeter - 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 entire ceiling surface since it operates at a lower temperature. The problem is most pronounced with hip roofs (since their 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 employed, the incremental cost is about \$500 to \$1000.

Excessive Ceiling Insulation Weight - Although most types of attic insulation are quite light, problems can occasionally arise when very heavy amounts are used. For example, OSB had to be installed on the underside of the roof trusses in the Urban Ecology Equilibrium™ House because the weight of the R-14.1 (R-80) loose fill insulation would have caused excessive sagging of the ceiling drywall (Hockman, 2011).

3.3.4 Window and Doors/Passive Solar

Window Selection - One realization which emerged from this project is 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 decreases, and vice versa. So, selection of the non-optimum window can have a significant cost impact on the design. And, designers are becoming increasingly aware of this fact. Some houses selected different windows for different orientations, putting high SHGC-value windows on the south orientation and high R-value units on all other orientations.

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. There are also major differences between the incremental costs of the various window technologies (insulated spacers, low E films, gas fills, insulated frames, etc.). Further, each of these components is available in multiple variations from their manufacturers (who supply the window manufacturers). This issue is discussed below in more detail below (see "Window Economics").

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 increased shading increases the relative importance of the unit's thermal resistance and decreases the significance of the SHGC. Within HOT2000 (the most common design software used for NZE houses in Canada), this variable is termed the "curtain shading factor" and has an input value from 0 (complete shading) to 1 (no shading).

A common "problem" reported by a number of builders is that their projects were locked in with one window manufacturer because of the historical relationship between their two firms or to secure a pricing advantage. While this makes sense commercially and from a marketing perspective, it does not necessarily result in selection of the best window for the house. Another issue, encountered with the Riverdale NetZero House, was that the quadruple-glazed windows were too heavy for one person to handle which increased installation costs (CMHC, 2010).

As a result of these issues, window selection is one of the more problematic aspects of NZEH design. There is uncertainty about which window type to use (or more specifically which window technologies to use) and there is uncertainty about whether additional window area even makes sense given the relative unit costs of windows compared to walls.

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, the two scenarios previously mentioned can be examined using an "incremental analysis of cost and benefits". Also, the "Value Indices" (either ECM or PV) described in Section 3, will be referenced. Recall that this is a simple metric for comparing conservation measures and renewable energy options. The lower the Value Index, the more cost effective the option. It will be used in Section 5 for comparing the economic performance of window area and window type, relative to other options.

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 illustrate how this problem can be approached, consider the incremental costs and benefits of adding a south-facing window to a typical NZEH. Using a hypothetical 167 m^2 (1800 ft^2) NZE house in Winnipeg as an example, a HOT2000 analysis was conducted with the house in its original configuration and with an additional 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%.

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 Low E film, argon fill and insulated spacers. Its estimated retail cost is \$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 this cost data and the results of the HOT2000 analysis gives us...

Incremental cost: \$488 - \$170 = \$318

Annual energy consumption:
- Original configuration: 1462 kWh/yr
- With additional 1 m^2 window: 1443 kWh/yr
- Saving: 19 kWh_e/yr, worth \$1.90 /yr (based on a utility rate of \$0.10/kWh)

Value Index
- Value Index = (Incremental cost) / (Annual energy savings)
  = \$318 / 19
  = 16.7

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 just a single example and different results would 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 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 described above, the impact of upgrading the same 1 m^2 of south-facing window from a relatively conventional triple-glazing unit (with an insulated spacer to control condensation) to a more energy efficient model (triple-glazed unit with one Low E coating, two argon fills and an insulated spacer) was explored.

The cost of the original the conventional triple-glazed window was estimated at \$360/m^2, while the high-performance unit was estimated at \$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 window: 1451 kWh/yr
- With T/G, 1 LowE, 2 argon fills, window: 1443 kWh/yr
- Saving: 8 kWh/yr, worth \$0.80 /yr (based on a utility rate of \$0.10/kWh)

Value Index
- Value Index = (Incremental cost) / (Annual energy savings)
= \$128 / 8
= 16.0

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

These results may appear surprising but they are very consistent with our 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 significantly larger and the economics much more favourable.

Recommendations For Windows - The preceding discussion used the incremental analysis of costs and benefits 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. A more rigorous analysis, using a wider range of windows, houses, locations, etc. would yield similar results in most cases. 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 and is designed to offer a rational process for selecting windows (Proskiw, 2008). One by-product of this work has been the recommendation that window selection focus on two issues: a) picking a "good" window (from an energy perspective) although not necessarily the best unit and b) 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 often be better spent on improving the energy performance of some other conservation or renewable energy option. In other words, window selection cannot be based simply on the available window options, but rather on the basis of options which may be 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 reduction in the energy load than would be produced by upgrading the foundation (for example), then the investment should be directed towards the foundation - not the windows.

The problem with 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. In fact, the National Building Code contains specific requirements to control condensation on windows in Article 9.7.3.3. (2010).

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. Canadian Standards Association A440.1 "User Selection Guide to CSA Standard Windows A440" defines the Temperature Index as:

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

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. Unfortunately, many window manufactures do not publish information on their products, likely because there is little demand for it. Using the indoor and outdoor design temperatures and the indoor design relative humidity, the Temperature Index allows the condensation resistance of different windows to be compared.

On a practical level, the following procedure is recommended for selecting the type of window and the window area for a Net Zero Energy House, based solely on economics:

1. Select a window which meets the minimum condensation resistance requirements of Article 9.7.3.3. of the National Building Code. This will mean complying with either the maximum U-value requirements or the minimum Temperature Index requirements of

Article 9.7.3.3. Further, restrict the south-facing window area to no more than 6% of the floor area of the house.

2. Once all, or most, of the house's other energy specifications have been identified (such as R-values and mechanical system efficiencies), determine the Value Index of the last conservation measure added to the design (i.e. the measure with the highest Value Index).

3. Conduct an incremental analysis of the costs and benefits of alternative window types and areas using the procedure illustrated in Section 3.3.4. If the Value Index of the window alternatives is lower than that of the last conservation measure added, then the window alternative can be justified. If the Value Index is larger than that of the last conservation measure, then the window options can not be justified on an economic basis.

4. If necessary, modify the window area to reflect aesthetic or functional requirements of the house.

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. As such, south-facing glazing area should be restricted to 6% (to control overheating) and total window area should also be limited to that required for functional and aesthetic considerations.

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 need to be carefully re-examined and likely challenged.

Overheating - Due to their very low heat loss, NZE houses are obviously prone to overheating problems if care is not taken in the design stage. Several designers and builders expressed concern about possible overheating problems. However, 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 NZE house, two west-facing garden doors caused localized overheating in the room containing the doors until the homeowner retrofitted a solar-blocking glazing film. In another case, one of the design constraints was that air-conditioning could not be included in the final design making the issue of overheating a pure comfort, and not an energy, issue. In retrospect, one of the designers felt that a large exhaust fan could have been installed to provide some cooling capabilities during the summer. This is particularly important if the house is in a location where security is an issue since it may not be wise to leave windows open for ventilation purposes, particularly at night.

The Avalon Discovery 3 NZEH used retractable window shades for some windows in an effort to control overheating. As of this writing, no information is available on their performance.

One non-mechanical option available to combat overheating, not used on any of the study houses, is removable exterior window screens. These consist of a quasi-opaque mesh, similar to insect screen but with lower light transmission, mounted on a metal frame which is installed over the exterior of the windows during the cooling season. This requires the homeowner to install (and remove) them once a year which may prove unacceptable to some. Second storey windows would be a particular problem.

Depending on the weave density selected, they will block one-quarter to one-half of the incoming solar radiation before it reaches the window. Curiously, they have been used in commercial construction with some success but have only been employed in a handful of residential applications.

3.3.5 Airtightness

Although only limited, measured airtightness data was available for the study houses, some general observations can be made, which are supported by similar experiences with low-energy housing:

1. **Focus on the big leaks** - Most air leakage in a house occurs at the joints, intersections and penetrations through the building envelope where the 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 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 differentials 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 and sealed.

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 system, main wall intersection)
    - Suspended basement floors
    - Duct penetrations, especially those for solar air-based systems

Some houses made extensive use of spray-applied, two-component polyurethane foam (PUF) for both its insulating and sealing capabilities. However, its cost is several times that of batt insulation. One designer, who used it as the primary insulation system, reported that they would be much more selective with its use in the future restricting it primarily to locations where air sealing was critical or where space constraints dictated a product with a very high thermal resistance per unit thickness.

3.3.6 Thermal Mass

One of the more popular features of 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 Riverdale NetZero team estimated the incremental cost of adding a large masonry concrete wall on the basement and floor levels at $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. Historically, buildings were often constructed using heavy masonry or large dimension timbers which provided significant mass. 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. Excessive temperature fluctuations would be viewed by many homeowners as undesirable.

Another problem with thermal mass is that it is most effective when the sun is able to shine directly on its surface so that solar radiation is directly absorbed. If the thermal 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. Good interior design is essential if thermal mass is to be used. This also suggests that the practice of placing drywall scraps in partition walls to increase the thermal mass may not be an effective strategy. A good example of effective utilization of mass would be a masonry floor located in a room with a large expanse of south-facing glazing such that the sun is able to shine directly onto the floor for several hours per day during the heating season. Or, a masonry fireplace located such that the sun is able to shine on it could also be a workable solution. However, as discussed below, both of these examples assume that the "mass" (masonry floor or fireplace) was not installed as an energy conservation feature but for other reasons (functionality or aesthetics).

One of the problems with analyzing the performance and cost-effectiveness of thermal mass strategies is the difficulty of evaluating savings since they cannot be directly measured but must be inferred from modelling software or other means. For this reason, there is considerable debate about the value of adding thermal mass to a NZE house.

Some of the study houses incorporated additional thermal mass into their designs as an energy saving measure. Some of the designers, in hindsight, felt that this was a good decision while others were critical of its value.

One theoretical assessment of thermal mass was carried out using HOT2000 with four different levels of thermal mass in NZE houses (Proskiw, 2008). The study found that 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. Even then, maximum savings could only be achieved if upgrading from conventional, light weight stick framing to very heavy concrete construction. 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 (such as those in the U.S. and Europe) 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. Further, the houses modelled used relatively modest overhangs (0.6 m or 2') and were assumed to be completely unshaded by adjacent buildings or vegetation - which this study has found to often not be the case. Also, it was found that the benefits tended to plateau fairly quickly as the mass level was increased.

3.4 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 new technologies. In some cases, the controls did not work properly, in other instances they were judged as too complicated by the builder (particularly if they were designed for commercial buildings where extra complexity is more acceptable) or customers complained about the difficulty of using them. Several designers expressed concerns about delivering a product to homeowners which they might not be able to operate. Mechanical control systems targeted for the residential market have to be simple, reliable and obvious in terms of their use. One should not have to read a manual to change the temperature.

Dehumidistat controls, used to activate or increase the flow rate of the ventilation system, were also noted as a cause for concern due to malfunctions or generally poor control over indoor humidity levels (which was also reported as a problem by some homeowners).

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 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 use additional 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 this project.

On a related issue, builders felt that it was very important that all the mechanical systems should be available from a single supplier to ease maintenance and warranty issues, particularly for the homeowners. This can be a problem for NZE houses since they push the state-of-the-art which may dictate purchasing components from more than one supplier to maximize performance.

The issue of mechanical system complexity was recognized by most, if not all, of the design teams and some even used it as the rationale for simplifying their systems. One NZEH design team had planned to use earth tubes to preheat incoming ventilation air but abandoned the concept once they considered the costs (high), benefits (marginal) and potential secondary effects (life forms growing in the ventilation system).

3.4.1 Space Heating Systems

Excessive Floor Space Required For The Mechanical Systems - Most NZE houses use mechanical systems which are much more complicated and contain more components than equivalent systems in conventional houses. This results in a system which occupies significant amounts of floor space. Several designers reported that 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. A related problem can occur if extra ductwork, beyond that normally found in a house, is required for the mechanical system. For example, Building Integrated Photovoltaic/Thermal (BIPV/T) systems 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 which provides a very comfortable, uniform indoor environment. They are often found in high-end homes, as well as some NZE houses. 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 for some consumers.

However, there applicability in NZE houses was questioned by some designers and builders. Since these houses use highly insulated building envelopes with very airtight construction, high quality windows and mechanical systems, the indoor environment tends to be well controlled and not subject to drafts or cold spots - as is commonly found in some houses, such as older houses. Given the cost of radiant heating systems, this criticism appears to have merit. 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.

3.4.2 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 used in the survey houses were Greywater Heat Recovery Systems which 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.

3.4.3 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 - the only exception being when the windows are open. 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 the Avalon Discovery 3 house which employs 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 would be saved and the life expectancy of the HRV increased.

Lack of Available Energy Efficient HRV Motors - Most HRV's are equipped with standard, less-efficient PSC (Permanent Split Capacitor) electric motors while some are available with energy efficient ECM (Electronically Commutated Motors) motors. In some instances, the make and model of HRV selected by the designers was only available with a PSC motor.

3.4.4 Space Cooling Systems - Some might argue that a cooling system should not be included 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.

Some of the survey houses used ground-coupled cooling systems rather than a standard vapour compression cycle, air-conditioning system. The Factor 9 house used a series of water lines installed in the concrete piles as a heat dump. A water-cooled fan coil installed in the ductwork system extracts heat from the house air and transfers it to the cooling fluid which circulates it through the pile-embedded lines. This system can provide about 0.5 tons of cooling (1.76 kWh_e/hr or 6,000 btu/hr). Conventional residential cooling systems typically provide 2 to 3 tons of cooling so the Factor 9 system is undersized in comparison. However, if the house is carefully designed with attention to summertime shading and minimizing extraneous heat gain from base loads, this may be adequate.

3.5 RENEWABLE ENERGY SYSTEMS

3.5.1 Solar Thermal Systems

Cost and Complexity of Solar Domestic Hot Water Heating - Solar thermal DHW systems tend to be a common feature of most NZE houses. On the surface, they appear to offer a good solution to the problem of heating hot water. 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 (and many more conventional structures). Measures such as energy efficient water heaters, greywater heat recovery systems, low-flow fixtures, etc. all help to reduce the DHW load. Since these are usually very effective and, in many cases, very economical they are generally the first features designed into the DHW system in a NZE house. Collectively, these measures can reduce the DHW load by 25% to 50%. However, this minimizes the potential savings which a solar DHW system can generate since the net DHW load is now smaller than it otherwise would have been. 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. The occupants' behaviour has a very large, if not the dominant, impact on the payback of solar (thermal) DHW systems. In NZE houses with low DHW consumption (due to the lifestyle of the occupants or the performance of the hot water system), 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). In another case, Christian and Dockery reported on the TVA Dollar-a-Day research home and found that the solar water heater had the worst payback of all the technologies selected for the house (2010). Finally, since the cost of solar thermal systems is rising while the cost of PV systems is dropping, a point may be reached in the next few years where PV systems evolve into the ultimate competitor for solar DHW systems.

Glycol-based systems use a small pump to circulate the glycol. This typically consumes a few hundred kilowatt-hours of electricity per year (depending on the efficiency of the motor and pump) thereby detracting slightly from the overall energy performance of the house.

Maintenance is also an issue. Although commercially available systems are normally fairly reliable, the systems operate in a hostile environment and regular maintenance is essential.

Monitoring solar DHW systems can be a problem since they rarely include meters or other monitoring devices which would permit the homeowner to evaluate their performance - in contrast to PV systems which can be easily metered. Unlike electricity which is quite easy to monitor, solar DHW systems require more complicated monitoring systems since the temperatures of both the inlet and outlet streams to the collectors have to be measured to calculate the energy production of the collector, and these temperatures can change on a minute-by-minute basis. In summary, solar DHW systems can be complex to design, model, install, commission, monitor and maintain (CMHC, 2010).

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 or how it relates to predicted 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 or arrays, 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, which used 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. This issue has not been researched in great detail but anecdotal observations suggest that it needs to be addressed. Some houses have used snow traps at the bottom of solar collectors or modules to prevent roof avalanches. Unfortunately these also served to trap snow in front of the bottom modules.

Vertical Integration of Solar Panels Into Exterior Walls - One problem with solar panels is their appearance. By integrating the panels into a section of exterior wall, a potential eyesore is removed. If it also reduces the cost of cladding, the cost savings may counter the reduced output from the panel due to its non-optimum, vertical orientation. This approach was used with success on the Factor 9 House (Dumont, 2011).

3.5.2 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 south-facing lots (2010). This effectively increases 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, and 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. Although the total roof area was usually larger than that required for the solar energy systems, a portion 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 officials insisted on a flat roof, in part to manage falling snow. As a result, the designers used 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.

Curb Appeal of PV Arrays - Depending on one's tastes, a photovoltaic array located on the family home may or may not enhance the house's aesthetic appeal. Undoubtedly, some would see it in a negative light. Fortunately, since PV modules are relatively thin they can be partially hidden. The Avalon Discovery 3 house integrated the PV arrays into the roof design on both the house and attached garage, and then used a shingle colour similar to that of the arrays, thereby camouflaging the system onto the house.

3.5.3 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 DHW heating. Experiences 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_e annually - not including the fan energy required to run the system. Further, this ignores the lost electricity which would have been generated by the array without the BIPV/T system since PV output decreases as the array temperature increases., By enclosing the backside of the array, its average temperature is increased and electrical output is reduced. Despite this modest energy production, the reported cost of the system was $15,000. On another house, the cost of a BIPV/T system was estimated at $20,000 (CMHC, 2010).

3.6 THE OCCUPANTS

3.6.1 Homeowner Understanding Of House Operation - This issue was reported by a number of the survey respondents. Given the complexity of some of the systems used in the houses, concerns were raised about the homeowners comprehension and whether they would be able to operate the house properly. This is not surprising and is typical of what occurs when people purchase a house which contains features they have never encountered. Many early R-2000 houses experienced this problem with components such as HRV's since, at the time, these were new products which few buyers had any experience with. However, NZE houses are more complex than R-2000 houses so problems may be more pronounced. This can manifest itself with simple issues. For example, one of the survey houses (not equipped with a mechanical cooling system) proved vulnerable to overheating problems. The designers had anticipated that significant free cooling could be provided by judicious operation of the windows (keeping the windows closed during the day and opening them at night when the outdoor temperature is lower). However, this was not understood by the homeowners, who operated the windows opposite to the intended manner (open during the day and closed at night). This did not work well.

Occupant Lifestyle - Purchasers of Net Zero Energy House may not operate the house in the most efficient manner. That is not a "problem" in the sense that any house must be designed to meet anticipated loads, but is rather a reminder that design assumptions may not be realistic. One NZEH purchaser installed a high-output electric garage heater to keep the garage at a comfortable temperature, another replaced CFL fixtures with halogens while others operated their homes at higher than anticipated temperatures or installed more appliances than the designers had expected.

SECTION 4
IMPROVING THE PERFORMANCE AND AFFORDABILITY OF NET ZERO ENERGY HOUSES

4.1 INTRODUCTION

This project has provided a rare opportunity to study the current state-of-the-art of Net Zero Energy House design and to discuss the subject with some of the most experienced individuals in the field. This has made it possible to identify various products and technologies which currently do not exist but which would be very useful for future NZEH projects, as well as low energy houses in general. Some of these were suggested by individuals interviewed during this project while others were identified during the overall course of the project. These ideas are briefly discussed below in the hope that efforts will be directed towards their development.

4.2 IMPROVED DOMESTIC HOT WATER HEATING SYSTEMS

DHW systems were a source of frustration for a number of designers due to the difficulty of dealing with this load in a cost-effective manner. Although several supply and conservation options exist, none were able to adequately handle the load. For example, consider the water heater. Conventional electric water heaters are quite inexpensive, reliable and relatively efficient (around 90%, with some of the "lost" heat offsetting the space heating load during the winter). However, electricity is a high-grade energy source and, as the building envelope becomes increasingly better insulated and airtight, the DHW load represents an increasingly large percentage of the overall gross energy consumption of the house. Most types of natural gas, or propane, powered DHW heaters have very limited application in NZEH houses since they either cannot operate safely in a well-sealed house or are significantly more expensive with a relatively short life expectancy (approx. 10 years). Another option used in many NZEH houses are instantaneous, tankless water heaters. They reduce line and standby losses since there is no tank and the unit can be located close to the end use. However, they have comparatively large power draws when there is a call for hot water. A typical, electric instantaneous heater requires a 50 Amp breaker.

Other options for water heating include: Greywater Heat Recovery systems, solar thermal systems and heat pump water heaters. GWHR systems are commercially available, extremely reliable, but only save 15% to 25% of the DHW load and are not suitable for houses with slab-on-grade or crawl space foundations. Improved systems could theoretically overcome these limitations but no such products currently exist.

Solar thermal systems are a relatively mature technology but can still be problematic from a reliability perspective - particularly in harsh climates. Cost can also be an issue. Solar DHW systems are commonly used on NZEH houses. They appeal to the philosophical purity of the NZEH concept but their performance is climate dependent, reliability appears to be poorer than conventional DHW systems and their cost, relative to their load, is high. As previously mentioned, some of the surveyed designers who had used solar thermal systems for DHW heating stated that given the problems with reliability and performance, they would have replaced the system with a larger PV array and a (relatively) conventional electric DHW heater. Although the first costs would be higher, reduced maintenance concerns and more dependable performance were felt to be worth the extra investment.

Heat pump water heaters offer some intriguing possibilities. These devices extract heat from the indoor air and use it to preheat the domestic hot water. During the heating season, they do not offer any advantage since the energy they extract from the indoor air has to be replaced by the space heating system. However, during the non-heating season, they extract heat which would otherwise contribute to the cooling load or to overheating of the space. Therefore, the length of the non-heating season has a critical effect on their economic performance. However, as the house becomes increasingly more energy efficient, the length of the non-heating season is increased and the attractiveness of this type of system improves. This means that, all other factors being equal, a heat pump water heater should be much more economic in a NZE house than in a conventional structure.

Another issue which can arise, particularly with larger houses, is the time required for hot water delivery. If the fixture is physically remote from the heater, it can take 10 to 30 seconds for hot water to begin flowing at the fixture. One solution is to install a recirculation system which pumps hot water through a circulation loop thereby maintaining the water at a relatively hot temperature. Branch lines draw water off the recirculation loop so it can be supplied hot to the fixture with very little warm-up time. The limitation of this approach is that heat losses from the recirculation loop are significant. During the heating season, this is not an issue since the parasitic losses from the piping reduce the space heating load by an equivalent amount. During the non-heating season, which in a NZE house would be six to ten months per year, these losses serve no useful function. Further, the cooling load is increased by an amount equal to the parasitic losses. In general, DHW recirculation systems should be avoided in NZE houses. If the house is very large and a hot water fixture is located some distance from the water heater, other options should be explored such as installing a small, electric water heater close to the marooned fixture which is fed by a branch line from the main DHW heater.

In summary, a more rational and cost-effective approach to DHW heating needs to be developed. This could include both new products and a more rigorous examination of the costs and performance benefits of the various DHW options and conservation technologies.

4.3 IMPROVED GREYWATER HEAT RECOVERY (GWHR) SYSTEM

Most Net Zero Energy Houses now use some form of greywater heat recovery system to minimize the DHW load. The systems currently marketed operate using the "falling film" principle first used on the GFX GWHR system introduced in the 1980's. The falling film principle is a direct application of the Coanda effect first discovered in the 1930's. A fluid such as water has a natural tendency to adhere to the surface of any object which it is flowing over or through. GWHR systems exploit this principle by directing the house's greywater down a vertical pipe installed in the soil stack. Greywater flows down the pipe but since it does not completely fill the cross-sectional area, most of it will adhere to the walls rather than flowing down the open cavity. Since the greywater is in intimate contact with the pipe walls, heat transfer is maximized. Surrounding the stack is a tightly coiled copper pipe which is in thermal contact with the outer surface of the soil stack. Incoming mains water is directed into this outer coil before being plumbed to the hot water tank and/or some of the hot water plumbing fixtures. As a result heat transfer between the warm, outgoing greywater and the cold, incoming mains water is very good. These types of systems can typically reduce the DHW load by 15% to 25%, depending on the occupant's lifestyle. However, they have two major limitations. First, since they do not contain any thermal storage, the system only provides effective heat recovery when the greywater and cold water flows occur simultaneously, such as during a shower. When hot water is used for batch processes, in which the flows do not occur at the same time, heat recovery is dramatically reduced. Batch flows include baths, dishwashing and some other applications. The second limitation is that current systems have to be installed in a vertical configuration so the outgoing greywater can adhere to the pipe walls. If installed horizontally, their performance is dramatically reduced. For houses with basements, this is not an issue since the GWHR system is usually installed in the basement. However, for houses with crawl spaces or slab-on-grade construction, the GWHR option has limited application.

Therefore, what is needed for NZEH (and other) houses is a new type of GWHR system which a) can better utilize batch flows and b) can be installed in a horizontal configuration so it can be used for all house types. This may involve some type of thermosiphon system with a modest amount of thermal storage.

4.4 OVERHEATING SOFTWARE

A major issue for low-energy houses is the possibility of overheating. For NZE houses, with their emphasis on passive solar heating and a very well insulated building envelope, this issue can be acute. Net Zero Energy Houses have displayed a vulnerability to overheating.

At present, the dominant software used for energy modelling of houses in Canada is HOT2000. However, it has only a limited capability to deal with overheating. Although a mechanical cooling system can be simulated in HOT2000 and the cooling load predicted, this is merely a proxy for predicting overheating. Unfortunately, this is a difficult issue since, unlike heating loads, cooling loads (and hence overheating) are highly transient and are best addressed by hourly rather than monthly bin-based models such as HOT2000. HOT2000's ability to predict overheating is not well documented. However, one study reported on the predictive ability of a European, monthly bin-based model to estimate the performance of three near Net Zero Houses in Austria and concluded that a monthly model was sufficiently accurate for residential buildings (Bednar et al, 2010).

Obviously some tool, be it software-based or otherwise, is required to assist designers in determining the house's vulnerability to overheating. It should be able to account for the affects of overhangs, exterior shade devices (such as solar shade screens), small-capacity air-conditioners and, ideally, be able to accommodate varying levels of thermal mass.

One immediate application for this software would be a more extensive exploration of the so-called "6% rule" which states that the area of south-facing glass should not exceed 6% of the floor area of the house (this calculation usually ignores the basement floor area unless there is an air distribution system present which operates on a regular basis so excess heat generated on the main living levels can be distributed to the basement). This "rule", actually more of a guideline, has been used for at least 25 years although it was developed for low-energy, not NZE, houses.

Overheating problems were encountered in the Manitoba Advanced House since it was constructed without a dedicated cooling system. It had been hoped that cooling energy could be captured from the basement by operating the house's air circulation system. However, since the basement was extremely well insulated (RSI 7.04 on the walls and RSI 1.76 under the floor slab), there was little cooling capability available.

4.5 IMPROVED, SMALL CAPACITY AIR-CONDITIONING SYSTEMS

Given the previous discussion and the difficulty of accurately predicting the overheating threat, inclusion of an air-conditioning system in NZE houses seems prudent. However, most residential systems are relatively large and too big for a NZE house. An oversized system wastes energy, reduces system longevity (since the air-conditioner cycles more frequently) and impairs the dehumidification capabilities of the system. With respect to the latter point, an air-conditioner normally serves two functions - providing sensible cooling and providing dehumidification by condensing some of the water vapour out of the house air. When an air-conditioner starts, it initially provides only sensible cooling (thereby increasing the relative humidity of the conditioned air). Dehumidification begins once the evaporator temperature drops sufficiently below the dew point of the conditioned air. If the cooling system is oversized, dehumidification may not occur since the system cycles off before the evaporator temperature reaches the required level. Therefore, a small capacity air-conditioner should be used since it takes longer to meet the sensible load thereby allowing the evaporator temperature to drop sufficiently that dehumidification can occur. However, these may not be commercially available.

4.6 LESS EXPENSIVE EXTERIOR WALL SYSTEMS

The most common exterior wall system used in conventional new homes in Canada is the traditional 2x6 wood frame wall with RSI 3.52 (R-20) fibreglass batt insulation. Depending on the geographic location, this wall system has been the norm for a quarter of a century or more. In NZE houses, higher R-values will be required. The 2x6 wall is effective, well understood, reasonably inexpensive and all its components are readily available. There are a few, inexpensive (or even money saving) measures which are available to improve thermal performance: the RSI 3.52 (R-20) batts can be replaced with RSI 3.87 (R-22) or RSI 4.23 (R-24) batts and Optimum Value Engineering (OVE) can be used to reduce the amount of framing material in the wall. Combined, these two measures will increase the wall's thermal resistance by about 18% to 25%. However, if better thermal performance is desired, then the cost increases rapidly since either exterior insulated sheathing, interior strapping or double wall construction is required. Thicker studs, such as 2x8's, are not an option because the effects of thermal bridging become so pronounced that most of the potential benefits from the thicker insulation are destroyed by heat loss through the framing members.

Depending on the amount of added insulation, insulated sheathing and interior strapping add roughly \$20 to \$40 per square metre (\$2 to \$4/ft^2) of exterior wall area to the retail cost of the house. Double wall construction is even more expensive costing about \$60 to \$80/m^2 (\$6 to \$8/ft^2). Since a typical NZEH house has about 200 m^2 (gross) of wall area, an upgraded wall system will add \$4000 to \$16,000 to the cost of the house. In fact, the exterior walls are often the most expensive envelope component to thermally upgrade.

What is needed is a less expensive exterior wall system which can provide R-values in range of RSI 5 to RSI 9 (R-30 to R-50). There are a few options which can be envisioned. One is to use a manufactured stud. For example, some European low energy houses use I-profile wood studs in place of the conventional studs (Langmans et al, 2010). These are similar to manufactured I-joists which use solid wood flanges and oriented strand board (OSB) webs and are commonly used as floor joists. The advantage of this approach is that incremental increases in wall thickness only require corresponding increases in the web width. The designers of the Urban Ecology Equilibrium™ NZE house attempted to use manufactured I-joists, normally used as floor joists, for the exterior wall system. However, the local building authority refused to permit their use since the manufacturer had not approved them for this application - even though a structural engineer had accepted them for use in the house.

A second approach is to use a modified double wall system in which the "studs" consist of inner and outer pieces of wood held together with metal rods. This system was used on the Manitoba Advanced House in the early 1990's to achieve an overall thermal resistance for the wall of RSI 8.1 (R-46) using blown-in cellulose and fibreglass insulation. Changing the finished wall thickness only requires a change in the wire length. The studs consisted of inner and outer pieces of dimensioned lumber and the small diameter metal rods were imbedded into both pieces of wood. The studs were factory-manufactured so quality control was good. Once the studs were delivered on-site, the wall was framed in much the same fashion as a conventional 2x6 wall

Notice that both of these wall systems permit any desired wall thickness, and hence R-value, to be achieved with only minor modifications to the stud manufacturing process and neither are overly affected by thermal bridging.

A third approach is that used in the Urban Ecology House which employed a double-wall assembly for the exterior walls except it was not constructed as a one-piece assembly as normally done. Instead, the "double wall" consisted of an outer, load-bearing 2x4 frame wall with a non-load bearing 2x4 interior wall which could be added after the building shell had been completed and the building made weathertight. Although this approach might complicate the air barrier detailing around the floor systems, it is a very fast way to close in the building while still permitting very high insulation levels to be attained.

4.7 BUILDING COMMISSIONING

The term "commissioning" refers to the practice of measuring, verifying and adjusting the key systems in a building to insure they are operating in compliance with the project's stated design goals. Although commissioning has traditionally been used in commercial buildings, it is becoming more common in residential construction. Commissioning practices in conventional houses are largely dependent on the builder and may range from simple verification that components are present and operable to detailed measurements and adjustments. Historically, the first inclusion of mandatory commissioning requirements for houses occurred about 25 years ago when the R-2000 Standard adopted requirements for airtightness testing and measurement of ventilation system flow rates. Over time, these were expanded to include detailed commissioning requirements for more of the mechanical system and now include measurements of main and branch air flow rates in forced air heating systems (and water flow rates in hydronic systems) plus various other parameters.

Since they often contain new and sometimes developmental equipment and systems, most Net Zero Energy Houses include various commissioning protocols to verify the house and its components are functioning properly. All of the houses in this survey benefited from this practice and problems were commonly uncovered which could be corrected. However, one theme which both the survey respondents and the general literature frequently mentioned was the need to properly commission the building and verify that all systems were working properly. In several cases, houses did not fully meet their anticipated performance because of small, sometimes even innocuous problems such as: excessive distribution losses, unexpected air leakage through the building envelope, premature failure of motion-activated lighting controls due to high cycling rates, etc. Obviously, these types of problems can, and do, occur in non-NZE housing but their impact is more pronounced in NZEH construction because of the attention focused on every aspect of the house's performance. Further, virtually all NZEH houses are prototypes, demonstrators or research houses so detailed predictions are made about the house's anticipated performance making it much easier for imperfections (even minor ones) to be noticed. Since most NZEH homebuyers have a keen interest in energy, they are also apt to be much more observant of the house and its performance - and be dissatisfied if the house does not meet their expectations. So, the lesson is that a thorough and comprehensive commissioning process must be undertaken on all NZE houses. As this type of construction becomes more of a mainstream product, it may be worthwhile to develop a formal commissioning protocol which specifies all the necessary steps involved, the types of measurements required and the corrective actions which should be undertaken to remedy any deficiencies.

SECTION 5
PROPOSED MARKET-FEASIBLE TECNOLOGY SUITES

5.1 INTRODUCTION

The preceding sections of this report have attempted to identify some of the key lessons learned about the first generation of Net Zero Energy Houses with a focus on the critical design and construction issues. Most of the buildings discussed in this report are, at the time of writing, only a year or two old and most are currently being monitored to determine their performance under real world conditions. Undoubtedly, as this monitoring data is collected and analyzed, much will be learned about their performance particularly with respect to energy. Nonetheless, the insight and understanding gained during this project can offer some clear direction for future NZE houses.

This section identifies three broad approaches to NZEH design, identified as "Technology Suites", and then uses the information from this project to provide recommendations on the critical design decisions to best achieve Net Zero status for each approach. Each Technology Suite consists of combinations of various energy conservation measures and renewable energy systems best suited to their particular application. The three Technology Suites are:

a) Lowest Cost Approach - This Technology Suite is designed to achieve Net Zero status at the lowest possible incremental cost relative to conventional construction. It is intended for the builder or designer who wishes to produce the most affordable NZE house possible while emphasizing reliability and durability. No preferences are given to specific technologies, nor is preference given to energy conservation measures over renewable measures or vice versa. Measures are selected solely on the basis of their cost-effectiveness and known technical performance.

b) Passive Solar Approach - This Technology Suite is geared towards those who wish to achieve Net Zero status while maximizing passive solar gains. While this may not be the most economical approach, it does reflect the desire of some designers to maximize the amount of glazing - which may be desirable for aesthetic or other reasons. The maximum amount of recommended glazing is increased (relative to the Lowest Cost Approach) to levels used in some of the NZEH discussed in this report - provided that the incoming solar radiation is able to shine directly on a portion of the thermal mass

c) Ground Source Heat Pump Approach - This Technology Suite is designed for those houses in which the decision has been made to use a GSHP. Since this is a relatively major investment, costing $20,000 to $30,000, its inclusion affects other design decisions for the house. This approach is not recommended for maritime climates since the space heating load is usually small.

Each of these three Technology Suites is summarized on the following pages which includes recommendations for insulation levels, glazing, airtightness, mechanical systems, etc. Quantitative guidelines, such as recommended insulation levels, have been developed using a quantitative cost-optimization analysis which considered the costs of various conservation measures and the cost of energy generated from photovoltaics (Proskiw, 2008). Since PV costs have been declining for the last several years, the recommendations have been updated using costing data effective to November, 2010 (for both PV and conservation measures).

TECHNOLOGY SUITE #1 - LOWEST COST APPROACH

Design Approach

This Technology Suite is designed to achieve Net Zero status at the lowest possible incremental cost relative to conventional construction. It is intended for the builder or designer who wishes to produce the most affordable NZE house possible while emphasizing reliability and durability. No preferences are given to any specific technology nor is any preference given to energy conservation measures over renewable measures or vice versa. Measures are selected solely on the basis of their cost-effectiveness and known technical performance.

Advantages

- Affordability is maximized.
- Few architectural changes are required from conventional construction.
- Maintenance concerns are minimized since off-the-shelf products are used.
- The mechanical system is relatively uncomplicated and does not require excess floor space.
- Overheating is less of an issue since the glass area is similar to that of conventional construction.
- Since glass area is not increased, orientation and shading are less critical design issues.

Disadvantages

- May miss some cutting edge technologies since only off-the-shelf products are used.
- May not conform to some designer's or consumer's concept of how a NZEH should look.

Instructions

- Select the design guidelines from Table 5.1 based on the house's geographic location.
- Note 1 - Select the window type and window area using the incremental cost and benefit analysis method described in Section 3.3.4.

Table 5.1
Technology Suite: Lowest Cost

	Maritime Climates	Prairie Climates	Eastern Climates	Northern Climates
Architectural Features				
Thermal Mass	Light or medium weight framing	Light or medium weight framing	Light or medium weight framing	Light or medium weight framing
South-Facing Glazing Area	6% of floor area (max.)	6% of floor area (max.)	6% of floor area (max.)	6% of floor area (max.)
Building Envelope				
Airtightness	Target: 0.50 ac/hr_{50} or as tight as possible	Target: 0.50 ac/hr_{50} or as tight as possible	Target: 0.50 ac/hr_{50} or as tight as possible	Target: 0.50 ac/hr_{50} or as tight as possible
Main Walls	RSI 5.28 (R-30)	RSI 10.57 (R-60)	RSI 8.81 (R-50)	RSI 10.57^{+} (R-60^{+})
Attic	RSI 10.57 (R-70), HHT	RSI 14.09 (R-80), HHT	RSI 14.09 (R-80), HHT	RSI 14.09 (R-80), HHT
Basement Walls	RSI 4.23 (R-24)	RSI 4.23 (R-24)	RSI 4.23 (R-24)	RSI 4.23 (R-24)
Basement Slab	Uninsulated	Uninsulated	Uninsulated	RSI 1.76 (R-10), Perimeter
Windows	See Note 1	See Note 1	See Note 1	See Note 1
Mechanical Systems				
Space Heating	Electric baseboards	Electric baseboards	Electric baseboards	Electric baseboards
Domestic Hot Water Heating	Conservation package, GWHR, DHW heat pump (possibly)	Conservation package, GWHR, DHW heat pump (possibly)	Conservation package, GWHR, DHW heat pump (possibly)	Conservation package, GWHR, DHW heat pump (possibly)
Ventilation	Mid or high-efficiency HRV	High-efficiency HRV	High-efficiency HRV	High-efficiency HRV
Cooling System	Efficient A/C, Target: SEER 18	Efficient A/C, Target: SEER 18	Efficient A/C, Target: SEER 18	Efficient A/C, Target: SEER 18
Base Loads	Target: 40% of R-2000 default values	Target: 40% of R-2000 default values	Target: 40% of R-2000 default values	Target: 40% of R-2000 default values
Renewable Energy Systems				
Photovoltaic System	Provide sufficient PV capacity to achieve NZEH performance			

TECHNOLOGY SUITE #2 - PASSIVE SOLAR APPROACH

Design Approach

This Technology Suite is geared towards those who wish to achieve Net Zero status while maximizing passive solar gains. While this may not be the most economical approach, it does reflect the desire of some designers to maximize the amount of glazing - which may be desirable for aesthetic or other reasons. This approach works best when appreciable amounts of thermal mass, such as a masonry floor or fireplace, are planned for the house (for aesthetic or other reasons) since this will help to control potential overheating problems.

Advantages

- Maximum use is made of passive solar energy .
- May provide certain aesthetic advantages relative to other approaches.

Disadvantages

- May not represent the most economical approach to achieving Net Zero Energy performance.
- Comfort issues may arise (cold chills in winter and overheating in summer).
- Requires a forced air heating system so passive gains can be better distributed around the house.
- Orientation and shading are more of an issue.

Instructions

- Select the design guidelines from Table 5.2 based on the house's geographic location.
- Note 1 - Select the window type and window area using the incremental cost and benefit analysis method described in Section 3.3.4.

Table 5.2
Technology Suite: Passive Solar

	Maritime Climates	Prairie Climates	Eastern Climates	Northern Climates
Architectural Features				
Thermal Mass	Medium weight framing; part of mass should be directly heated by sun	Medium weight framing; part of mass should be directly heated by sun	Medium weight framing; part of mass should be directly heated by sun	Medium weight framing; part of mass should be directly heated by sun
South-Facing Glazing Area	8% of floor area (max.)	8% of floor area (max.)	8% of floor area (max.)	8% of floor area (max.)
Building Envelope				
Airtightness	Target: 0.50 ac/hr$_{50}$ or as tight as possible	Target: 0.50 ac/hr$_{50}$ or as tight as possible	Target: 0.50 ac/hr$_{50}$ or as tight as possible	Target: 0.50 ac/hr$_{50}$ or as tight as possible
Main Walls	RSI 5.28 (R-30)	RSI 10.57 (R-60)	RSI 8.81 (R-50)	RSI 10.57^{+} (R-60^{+})
Attic	RSI 10.57 (R-70), HHT	RSI 14.09 (R-80), HHT	RSI 14.09 (R-80), HHT	RSI 14.09 (R-80), HHT
Basement Walls	RSI 4.23 (R-24)	RSI 4.23 (R-24)	RSI 4.23 (R-24)	RSI 4.23 (R-24)
Basement Slab	Uninsulated	Uninsulated	Uninsulated	RSI 1.76 (R-10), Perimeter
Windows	See Note 1	See Note 1	See Note 1	See Note 1
Mechanical Systems				
Space Heating	Electric forced air	Electric forced air	Electric forced air	Electric forced air
Domestic Hot Water	Conservation package, GWHR, DHW heat pump (possibly)	Conservation package, GWHR, DHW heat pump (possibly)	Conservation package, GWHR, DHW heat pump (possibly)	Conservation package, GWHR, DHW heat pump (possibly)
Ventilation	Mid or high-efficiency HRV	High-efficiency HRV	High-efficiency HRV	High-efficiency HRV
Cooling System	Efficient A/C, Target: SEER 18	Efficient A/C, Target: SEER 18	Efficient A/C, Target: SEER 18	Efficient A/C, Target: SEER 18
Base Loads	Target: 40% of R-2000 default values	Target: 40% of R-2000 default values	Target: 40% of R-2000 default values	Target: 40% of R-2000 default values
Renewable Energy Systems				
Photovoltaic System	Provide sufficient PV capacity to achieve NZEH performance			

TECHNOLOGY SUITE #3 - GROUND SOURCE HEAT PUMP APPROACH

Design Approach

This Technology Suite is designed for those houses in which the decision has been made to use a GSHP. Since this is a relatively major investment, costing $20,000 to $30,000, its inclusion affects other design decisions for the house. Due to the relatively small space heating load, this approach is not recommended for maritime climates.

Advantages

- Cooling and DHW heating can also be provided by the GSHP.
- Orientation and shading are less of an issue.

Disadvantages

- May not represent the most economical approach to achieving Net Zero Energy performance.
- May not be well suited to certain lots or situations.
- Requires a forced air heating system so passive gains can be better distributed around the house.
- Service personnel may not be readily available in remote or northern locaitons.

Instructions

- Select the design guidelines from Table 5.3 based on the house's geographic location.
- Note 1 - Select the window type and window area using the incremental cost and benefit analysis method described in Section 3.3.4.
- Ground Source Heat Pumps not recommended for NZE houses in maritime climates due to the relatively small heating load.

Table 5.3
Technology Suite: Ground Source Heat Pump

	Maritime Climates	Prairie Climates	Eastern Climates	Northern Climates
Architectural Features				
Thermal Mass		Light or medium weight framing	Light or medium weight framing	Light or medium weight framing
South-Facing Glazing Area		6% of floor area (max.)	6% of floor area (max.)	6% of floor area (max.)
Building Envelope				
Airtightness		Target: 0.50 ac/hr$_{50}$ or as tight as possible	Target: 0.50 ac/hr$_{50}$ or as tight as possible	Target: 0.50 ac/hr$_{50}$ or as tight as possible
Main Walls		RSI 10.57 (R-60)	RSI 8.81 (R-50)	RSI 10.57^+ (R-60^+)
Attic		RSI 14.09 (R-80), HHT	RSI 14.09 (R-80), HHT	RSI 14.09 (R-80), HHT
Basement Walls		RSI 4.23 (R-24)	RSI 4.23 (R-24)	RSI 4.23 (R-24)
Basement Slab		Uninsulated	Uninsulated	RSI 1.76 (R-10), Perimeter
Windows		See Note 1	See Note 1	See Note 1
Mechanical Systems				
Space Heating		Ground Source Heat Pump; Target COP = 3.0	Ground Source Heat Pump; Target COP = 3.0	Ground Source Heat Pump; Target COP = 3.0
Domestic Hot Water		Conservation package, GSHP desuperheater GWHR	Conservation package, GSHP desuperheater GWHR	Conservation package, GSHP desuperheater GWHR
Ventilation		High-efficiency HRV	High-efficiency HRV	High-efficiency HRV
Cooling System		GSHP	GSHP	GSHP
Base Loads		Target: 40% of R-2000 default values	Target: 40% of R-2000 default values	Target: 40% of R-2000 default values
Renewable Energy Systems				
Photovoltaic System		Provide sufficient PV capacity to achieve NZEH performance		

GLOSSARY

ac/hr - air changes per hour
ac/hr$_{50}$ - air changes per hour at a pressure differential of 50 Pascals
A/C - air-conditioning
AFUE - Annual fuel utilization efficiency
BIPV/T - Building Integrated Photovoltaic/Thermal
CFL - compact fluorescent lighting
COP - Coefficient of Performance
D**HW** - Domestic hot water
ECM - Energy conservation measure
ER - Window energy rating
GSHP - Ground-source heat pump
HDD - Heating degree-days
HHT - High-heel trusses
HRV - Heat Recovery Ventilator
ICF - Insulated concrete forms
I/S - Insulated spacer
kWh - Kilowatt-hour
kWh$_e$ - Kilowatt-hour, effective
LED - light-emitting diode
NZE, NZEH - Net Zero Energy House
OVE - Optimum Value Engineering
PSC - Permanent split capacitor
PV - Photovoltaic
PUF - Polyurethane foam
Q/G - Quadruple-glazing
R - Thermal resistance, imperial
RSI - Thermal resistance, metric
SEER - Seasonal Energy Efficiency Ratio
SHGC - Solar Heat Gain Coefficient
SIPS - Structural, Insulated Panel Systems
T/G - Triple-glazing

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