Assessing Qualitative Criteria in the Design of Cost-Optimal, Cold-Climate, Net-Zero Energy Homes

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Abstract

This paper presents a methodology for assessing qualitative aspects and addressing barriers to implementing energy conservation measures and renewable energy technologies in optimizing the design of net-zero energy homes (NZEH).

Recent demonstration projects have proven that net-zero or near-zero energy homes are technically feasible in Canadian climates. However, projects to date have used custom-engineered, complicated, and sometimes unreliable advanced energy systems that occupants do not understand and contractors often can not support. Furthermore, the incremental costs to build these homes have ranged from $90-120k or more above the cost to build a conventional home. A study seeking to reduce first costs to build NZE homes by developing a framework to apply optimization to the design process has been carried out. This paper focuses on the development and application of a "soft optimization" process to ensure cost-optimal design solutions are highly constructible and compatible with consumer expectations. Building on a best-practice review study including interviews with designers of existing NZE homes, the authors convened an Industry Advisory Committee to identify the necessary qualitative design criteria for consideration in addition to cost and energy performance. Industry needs identified through this work include: system simplicity; durability; minimized occupant impact; sufficient industry capacity to install and support; and minimized uncertainty. The quantitative performance of various technologies is assessed by determining the specific cost to conserve or produce a unit of secondary energy ($/kWh).

The "soft-optimization" methodology follows a pseudo-design process similar to that used in the design of many low-energy homes. For each energy-related building component, various efficiency measures are applied to a base 225m^2, single, detached archetype house. These are modelled using HOT2000 and contrasted in terms of their installed first cost to conserve a unit of energy. Simultaneously, the qualitative criteria are assessed for each technology. Using a scoring matrix, the most cost-effective technologies that meet each of the qualitative criteria are selected.

Using the technology pathways defined through "soft-optimization," an initial specification set for achieving NZE performance will be defined for the archetype house. "Fine-optimization" will be carried out using ESP-r for energy performance simulation, and

GenOpt optimization software to determine the lowest first cost at which NZE performance is achieved.

1 Introduction

A Net-Zero Energy House (NZEH) balances energy use and production over the course of a year. NZE represents a pinnacle in building energy performance and perusing NZE will help to reduce the energy and resource intensity of the Canadian housing sector.

The recent EQuilibrium^{TM} homes have proven technical feasibility. However, to date these projects have used custom-engineered, complicated, and sometimes unreliable advanced systems that occupants may not understand and contractors often can not support. Furthermore, the incremental costs to build these homes have proven prohibitive.

Reducing these high incremental costs becomes largely a design issue. Designers are faced with two major challenges: the need to specify the most cost-effective pathways to achieve net-zero level performance; while ensuring that the technologies they specify will meet performance expectations and are available, durable, safe, and simple to install. This paper presents a methodology for augmenting the design process to consider such qualitative criteria.

This work began with a comprehensive review of recently built net-zero and high performance houses in Canadian and northern US climates. From this review, it appears that the NZEH community is converging on a consensus on the general approach to the design process. The highest priority considerations (Proskiw, 2011) identified are:

1. Use energy efficient lighting and appliances;
2. Minimize heat loss through good architectural design, minimizing thermal bridging, super-insulating and ensuring air-tight construction;
3. Maximize passive-solar gains;
4. Select appropriately sized, efficient mechanical systems;
5. Use renewable energy systems for balance of energy requirements.

However, it is apparent from the review that the designer's strategies for addressing items 3-5 have historically diverged. No single mechanical system, magic rule for glazing ratios or guidelines on the using of solar thermal energy exist. However, several prominent design philosophies are apparent. Each philosophy emphasizes different building components and represents a unique approach and technology pathway for achieving net-zero. The authors have categorized these different approaches into three philosophies. These are:

1. *The "simple and durable" approach*

   Designs emphasize simplicity of construction, ease of installation, minimal maintenance and longevity. Capital investments are weighted towards building envelope.

2. *The "solar-energy" approach*

   These designs look to maximum amounts of solar energy generation and use on site (including passive solar, active solar thermal for space and/or water heating and solar electric generation)

3. *The "advanced systems" approach*

   Emphasizes the use of highly efficient, relatively expensive mechanical components.

According to these overarching philosophies, this paper discusses three distinct technology pathways derived through a technology screening and selection process. The objective is not to determine which philosophy is best but to contrast the technologies that each pathway relies upon and to determine cost-optimal pathways to reach net-zero according to the three philosophies. Each philosophy has its own merits and advantages and may be more attractive in certain contexts or for reasons other than energy performance. For example, the "simple and durable" approach emphasizes investments in envelope components, many of which will last for the life of the building. On the other hand, builders constrained with tight lots may prefer to specify relatively thin walls to reduce the loss of living area. For this group, a higher investment in ultra-efficient mechanical systems may be necessary to compensate for the higher space heating loads.

2 Background

In 2006 the Canada Housing and Mortgage Corporation (CMHC) with technical support from Natural Resources Canada (NRCan) launched the EQuilibrium™ Sustainable Housing Demonstration Initiative. The resulting construction projects have shown that it is technically feasible to build Net-Zero Energy (NZE), or near-NZE homes in Canada using integrated design, novel technologies and innovative building practises. While EQuilibrium™ homes confirm the prospect of near-NZE or NZE performance in Canada, they also illustrate challenges to the continued adoption of NZE homes. These include:

- Incremental costs to build the EQuilibrium™ homes have proven prohibitively expensive, ranging from $90-120K (Parekh, 2011) or more above conventional costs;
- Custom-engineered mechanical and renewable energy systems that are not commercially available and require on-site design and assembly;
- Reliance on occupants to correctly operate, monitor and schedule maintenance and service on advanced energy systems. To date, the homeowners have demonstrated little understanding or concern for these tasks;
- Residential energy simulation and design tools have proven limited in their capacity to predict the impact of advanced wall system thermal bridges, thermal mass and performance of advanced mechanical and renewable energy systems.

Incremental construction costs are perhaps the most significant barrier to adoption of NZE housing. In a recent survey by the Canadian Net-Zero Energy Home Coalition, (Winkelmann, 2011) the majority of responses indicated that cost (37%), industry capacity (22%) and public awareness (22%) were the most significant issues; only 6% chose technical barriers as the biggest challenge.

For builders to adopt new technologies and building approaches, it must be demonstrated that they can cost-effectively increase the home's quality and value, without negatively affecting construction time, occupant comfort or increasing risk of call-backs.

This study was undertaken with these needs in mind. Through best-practice reviews, consultation with industry, careful analysis and computer optimization, the objective was to reduce first costs associated with net-zero construction using technologies and building approaches that are both familiar to industry and ready for application in production homes.

In this work, the need for a robust framework for optimizing Canadian cold-climate net-zero energy homes was recognized. With few exceptions, most NZE houses built to date were designed with subjective cost analysis (Proskiw, 2011). Though all the EQuilibirum projects benefited from the experience of academic and private researchers, few had the resources or access to comprehensive optimization tools necessary to explore the cost-benefits of different technologies.

3 Methodology

The authors undertook a study using a two part (coarse and fine) optimization approach to define cost-optimal technology pathways for NZEH which also satisfy a series of qualitative criteria such as durability, simplicity and occupant impact. This paper describes the "coarse optimization" methodology used to consider these qualitative criteria and summarizes the findings. The course optimization results are the inputs to the ongoing "fine optimization."

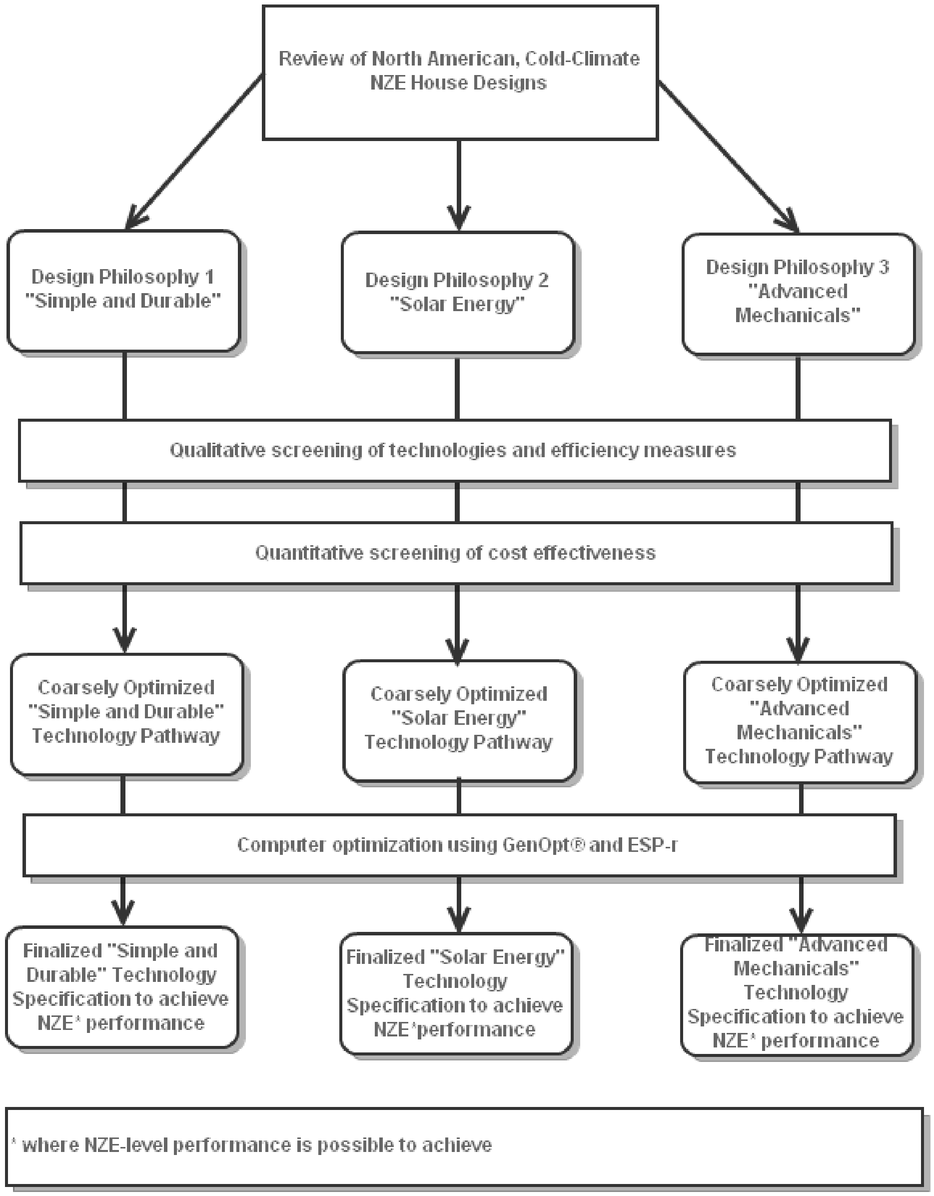

Figure 1: Optimization Process

A base archetype home was developed, representative of common tract-built housing in the target market. The design was defined using criteria identified in a market feasibility study conducted for the region, and reflects common architectural elements and consumer expectations prevalent in Southern Ontario tract built housing.

The Greater Toronto Area was used as the geographic location for this study, as it encompasses nearly 25% of all housing starts in Canada (Canada Mortgage and Housing Corporation, 2011). The base case efficiency measures and mechanical equipment were specified according to a prescriptive package stipulated in Ontario Building Code supplementary standard SB-12 (Ontario, 2011) which came into effect in January 2012. The base case home as modelled with HOT2000 version 10.51 and achieved an EnerGuide Rating System score of 79[1].

The base archetype is a single detached, two story home of approximately 225 m^2 (2400 ft^2) living area (exclusive of basement). The house was assumed to be situated on a typical 15x26m (50' by 85') "wide and shallow" lot. Most detached homes in this market are built on conventional 16x33m "narrow and long" lots (i.e. 38' by 110'); however, "wide and shallow" lots are gaining popularity. Citing the house on such a lot will afford more flexibility in building form, solar access, south-facing roof area, and passive solar gains in order to achieve NZE performance on a constrained suburban lot.

The coarse optimization process was developed to define technology pathways according to each of the three design philosophies. In this stage, the merits of different technologies and building approaches are weighed against each other.

For this coarse optimization, a set of selection criteria was developed based on feedback received from builders and designers of North America's first generation of NZE and Near-Zero energy homes. Inclusion of a technology was based on both quantitative and qualitative criteria. This generic coarse optimization framework is not particular to any one project and can be applied in the design of any net-zero or high performance house.

The qualitative criteria considered were:

- *Simplicity:* Complex systems have proven more prone to failure, and require high occupant awareness to operate / maintain. These have proven to be key barriers in the adoption of net-zero homes. Simple solutions were sought.
- *Durability:* Durability and longevity were key criteria, especially for more expensive systems. Although lifetime estimates and replacement costs were not considered in the analysis, there was recognition that systems must be durable.
- *Occupant impact:* Technologies that burden occupants or require significant intervention by the occupants to achieve design performance have faired poorly in high-performance homes. Impact on occupant lifestyle and comfort, including effects such as overheating and loss of living space to thicker wall construction was also considered.
- *Industry familiarity:* Technologies and methods that are merely extensions of existing industry practice are more readily adopted than new concepts and systems. Familiarity of new practices and concepts with industry was considered, and where possible, technologies that are extensions of existing practice were preferred.
- *Uncertainty:* Many of the technologies contemplated in the three design philosophies are new to the housing industry. Each bears some uncertainty about its cost, performance and availability. In this study, market-ready solutions were selected over nascent technologies. Where possible, solutions with too much uncertainty about cost and performance were avoided.

The researchers developed a screening process to test candidate technologies and alternative building practises against these qualitative criteria. Each candidate technology or building approach (collectively referred to as systems) is individually scored against each of the five qualitative categories. A green, yellow or red scoring approach was used. A green

[1] The EnerGuide Rating is calculated based on standard operation assumptions so that the energy performance of one house can be compared against another. Performance is rated on a scale of 0 to 100. A rating of 0 represents extremely high energy consumption. A rating of 100 represents an airtight, well insulated, sufficiently ventilated net-zero energy home.

score indicates no significant concerns were identified, yellow representing some concern or uncertainty and red representing serious concern and/or uncertainty.

A matrix was used to track the findings and to aid in representing the coarse optimization analysis visually. An example of the matrix is presented in Figure 1, below:

Table1: Coarse Optimization Matrix

	QUALITATIVE					QUANTITATIVE
Component	**Simplicity**	**Durability**	**Occupant Impact**	**Industry Familiarity**	**Uncertainty**	**Cost-effectiveness**
						$/kWh-yr saved
System I						
System II						
System III						
System IV						

Once each system was scored against each of the qualitative criteria, they were assessed quantitatively in terms of cost-effectiveness in energy savings or generation. To determine this cost-effectiveness, a full specification for each system was developed including all necessary components for integrating the system into the base house. These specifications were then used to collect cost data. Quotes were sought from regional suppliers and contractors and included both materials and labour.

The quantitative performance of a candidate technology was assessed by contrasting cost effectiveness, with cost effectiveness defined according to Equation (1):

$$Cost\text{-}effectiveness = \frac{Incremental\ \cos t(\$)}{Incremental\ energy\ saved\ or\ generated\ (kWh)} \qquad (1)$$

Cost-effectiveness was based on incremental construction costs instead of life-cycle costing. Incremental cost data is far more available and reliable for off-the-shelf technologies. Also, life-cycling costing requires estimation of product lifetimes and introduces a large element of uncertainty. A builder considering building NZEH is most concerned with construction costs.

Each system was individually integrated into the archetype house, modelled in HOT2000 and the impact on the home's annual energy use was estimated. The total energy saved or generated was divided by the incremental installed cost to determine the cost-effectiveness of each system. At this stage, the intent was not to arrive at optimal performance levels, but to rule out technologies that were clearly less attractive than the alternatives. The analysis focused on the marginal benefits that each higher-priced technology option provided over a base case. At the end of the coarse optimization, each of the technology pathways were narrowed to a single envelope / mechanical / renewable design that will serve as a starting point of the fine optimization phase.

The most cost-effective systems with the fewest "yellow" concerns were then selected for each building category to be included in the "fine" optimization stage. Systems with "red" concerns were excluded from study.

In the fine optimization stage, dedicated software tools (i.e., code scripts) will be used to explore the optimal performance of each of the technology packages in detail. The fine optimization stage is ongoing work that will not be complete by time of publication. These tools will automate iterative simulation runs in ESP-r to examine the effect of varying wall thickness, changing glazing areas, and altering roof pitch within each coarsely optimized pathway. The results of this work will provide a detailed *cost-savings map* describing the optimal energy savings that can be achieved for each incremental dollar invested.

It is anticipated that the optimization tools will offer limited support for emerging and complex mechanical and renewable systems. In these cases, estimates will be developed for the performance and cost effectiveness of these technologies using a) measured data and b) additional modelling using other tools such as TRNSYS. These results will be integrated into the fine optimization results. For each technology that cannot be studied using the optimization tools, the cost and marginal energy saving will be estimated. The researchers will locate the point in the *cost-savings map* that corresponds to the same cost of marginal energy saved, and study the feasibility of integrating the emerging technology at this point.

4 Results and Discussion

The results of the coarse optimization are described and discussed below.

Based on preliminary modelling in HOT2000, notional starting points were developed for the three design philosophies (as described in table 2). These were based on the results of the best-practice review of existing homes. As expensive components such as windows and heat pumps were incorporated, envelope performance specifications decreased. The starting points will not preclude other solutions, but offer educated guesses to optimal pathways.

Table 2: Notional Starting points

Component		Simple and Durable	Solar Energy Approach	Advanced Mechanicals
South-facing glazing fraction	%	<6%	6-10%	<6%
Walls – thermal resistance	RSI (R-value)	>8.8 (R50)	7.1-8.8 (R40-50)	5.3-7.1 (R30-40)
Ceiling – thermal resistance	RSI (R-value)	>14.1 (R80)	>12.3 (R70)	10.6-12.3 (R60-70)
Foundation – thermal resistance	RSI (R-value)	>5.3 (R30)	3.5-5.3 (R20-30)	3.5-5.3 (R20-30)

Foundation Walls

Table 3 below is an example of the coarse optimization matrix as applied to the analysis of foundation wall systems.

Table 3: Foundation Wall Coarse Optimization Matrix – Qualitative Criteria

Foundation System	Simplicity	Durability	Occupant Impact	Industry Familiarity	Uncertainty
Externally Insulated Foundation	+ simplifies air sealing + continuous insulation + mass is within thermal envelope -difficult transition details	+ protects foundation from freeze-thaw cycles by keeping foundation warm + reduces the potential for condensation on basement surfaces	+ no loss in floor space or room area for basement +natural drainage and capillary break means reduced moisture risk and IAQ problems - no attachment surface for drywall should occupant wish	- contractors may be unfamiliar with proper detailing procedures	

		- durability risk to foam above grade	to finish basement		
Hybrid External/ Internally Insulated Foundation	+ simplifies air sealing + continuous insulation + mass is within thermal envelope -difficult transition details where top of foundation wall meets above grade wall	+ protects foundation from freeze-thaw cycles by keeping foundation warm + reduces potential for condensation on basement surfaces - durability risk to foam above grade - interior wall may mask potential moisture leading to mold or rot	- Some loss in floor space +natural drainage and capillary break means reduced moisture risk and IAQ problems	- contractors may be unfamiliar with proper detailing procedures.	
Internally Insulated Foundation	+simple and affordable -more difficult to address thermal bridging - foams require fire-rated covering	-more likely to suffer moisture problems - may mask potential moisture in wall assembly leading to mold or rot	- basement floor space is lost -higher moisture risk may lead to IAQ problems	+ conventional approach	
Insulated Concrete Form	+simple to do form work -may be slower	+ Insulated forms produce stronger concrete in cold weather		-trades may be unfamiliar with installation	
Structural Insulated Panels	+ simple. Doesn't require concrete crew once footings are in + fast to install	-Good drainage is fundamental. Without free-draining soils, may be durability issues + Good resistance to seismic events		- unfamiliar to framing crews	- How will market respond to below-grade wood walls?

Table 4: Foundation Wall Coarse Optimization Matrix – Quantitative Criteria and Final Selection

Foundation Walls	**Unit Cost** **($/ft2)**	**Energy Saving** **(kWh/yr)**	**Value** **($/kWh)**	**Simple and Durable** **Target: R30+**	**Solar Approach** **Target: R20-30**	**Advanced Mechanicals** **Target: R20-30**
Externally Insulated (Rigid) Foundation Spec: 100mm XPS applied externally Assembly RSI 3.6 (R20.2)	10.63	699	2.73	Insufficient Insulation	Borderline insufficient insulation	SELECTED

Hybrid External/ Internally Insulated Foundation Spec: 2" XPS applied externally, 5" void, 2x4 wall, all filled with cellulose Assembly RSI 6.5 (R37.2)	13.77	2199	2.59	SELECTED	Excessive cost	Excessive cost
Internally Insulated (Rigid+Batts) Foundation Spec: cast foundation wall, 2x4 wall spaced 5" inside foam, all filled with cellulose Assembly RSI 4.8 (R27.5)	12.21	1089	3.09	Excessive durability concerns	SELECTED	Excessive cost
Insulated Concrete Form (R16-41) Spec: 4.5" EPS ICF Assembly RSI 2.8 (R16)	12.21	1303	2.92	Insufficient thermal resistance	Insufficient thermal resistance	Insufficient thermal resistance
Structural Insulated Panels RSI 3.4-6.9 (R19.2-39.4)		No quantified		Excessive uncertainty and durability concern	Excessive uncertainty and durability concern	Excessive uncertainty and durability concern

A minimum RSI of 5.3 (R30) was the notional starting point for foundation walls for the *Simple and Durable* technology pathway. For the *Solar Energy* and *Advanced Mechanical System* pathways, foundation wall assemblies with thermal resistances in the range of RSI 3.5-5.3 (R20 to R30) were sought. Five foundation systems were analyzed: externally insulated; internally insulated, hybrid external / internally insulated cast foundations, insulated concrete forms (ICFs) and structural insulated panels (SIPs). Table 3 summarizes the findings of the qualitative assessment. Externally insulated foundations and ICFs proved most attractive based on the qualitative assessment (the only concern identified with either system relates to lack of trade familiarity).

Next, several specifications for each system were developed, costs were estimated and the systems were modeled in HOT2000. The cost effectiveness of varying insulation levels was then compared and a system selected based on the combined findings of the qualitative assessment and quantitative cost-effectiveness.

When assessing the cost-effectiveness of each system it became apparent that the foundation wall systems that scored highest in the qualitative assessment (external insulation and ICF) did not yield a sufficient thermal resistance to meet the minimum requirements for the *Simple and Durable* approach of RSI 5.3 (R30). Consequently, a hybrid externally and internally insulated foundation wall was used for that philosophy. This foundation wall assembly featured 50mm (2”) of exterior XPS, a conventionally cast 200mm (8”) concrete wall and a 38x89mm (2”x4”) on 610mm (24”) centre interior standoff wall, spaced 125mm (5”) from the concrete, with the entire cavity filled with dense-pack cellulose. The effective thermal resistance of this wall is RSI 6.5 (R37.25). Such an upgrade was considered cost effective at $2.59 per annual kWh saved.

This approach facilitates air sealing and ensures continuous insulation, minimizing thermal bridging at the sill plate and rim joist. Insulating the exterior of the foundation also helps to protect against freeze-thaw cycles and reduces potential for condensation in the basement. Externally insulated foundations offer the benefit of a capillary break between the soil and the foundation, which reduces moisture risk. Proper detailing is critical and consideration should be given to protecting the foam above grade.

A conventional, cast foundation insulated on the interior was selected for the *Solar Energy* pathway. This approach is simple and affordable. However, the risk of moisture intrusion and damage is higher. Additionally, insulating the interior may hinder interior drying (Lstiburek, 2006). Interior insulation may also mask moisture in the wall assembly leading to mould or rot. Therefore, exterior moisture protection is critical with this approach. Most rigid and spray applied foams require a fire-rated barrier or covering. Finally, interior basement floor space is sacrificed by insulating the inside of foundation walls.

A conventional foundation insulated on the exterior with 100mm (4”) of XPS proved most feasible for the *Advanced Mechanicals* pathway. Formwork is simple, although it may take slightly longer depending on the crew’s familiarity.

The HOT2000 basement model uses regressed results from thousands of runs of a 2-D finite element analysis program called BASECALC (Beausoleil-Morrison, 1996).

Foundation Slab

Spray-applied expanding polyurethane insulation in thicknesses of 100mm (4”) and 50mm (2”) was selected for use under the slab for the *Simple and Durable* and *Solar Energy* pathways. Spray foam helps to ensure continuous insulation and vapour retarder. No under-slab insulation was specified for the Advanced Mechanicals approach.

Main Walls

The wall systems considered include externally insulated stick-framed walls, engineered truss walls, Structural Insulated Panels (SIPs), double stud walls, insulated concrete forms (ICF) and vacuum insulated panels (VIP).

For the *simple and durable* approach, a 400mm (16”) thick double stud wall insulated with dense-pack cellulose with an effective thermal resistance of RSI 9.1 (R51.6) proves most appropriate. Constructing double stud walls is time consuming, but technically simple and should be relatively easy for framing crews to pick-up. Municipal building code officials will readily understand these wall systems since they are similar to conventional stick built walls. The most significant drawback is the high profile, contributing to a loss of $24m^2$ (260 ft^2) of floor area.

For the s*olar approach*, a 38x140mm (2”x6”) an advanced framed stickbuilt wall with 100mm (4”) of externally applied type IV extruded polystyrene (XPS) was selected. The thermal resistance of this wall is RSI 7.0 (R40.0). This is a conventional advanced framed wall, readily understood by trades. It is important to check or consider the vapour permenace of rigid foams to minimize risk of condensation in the wall-assembly. Some rigid foam boards are fragile and can easily be damaged on a construction site.

For the a*dvanced mechanicals approach,* a 260mm (10-1/4”) expanded polystyrene (EPS) SIP wall was selected. The thermal resistance of this wall is RSI 6.2 (R35.5). Installation of SIP walls is simple and relatively quick. Care should be taken in storing panels outdoors for long periods as exposure to moisture can lead to durability problems. Many carpenters are unfamiliar with SIPs and wiring can be difficult. It is very important to ensure foundation walls are level so that SIPs butt evenly and a continuous seal and air barrier is maintained.

HOT2000 estimates the effective insulation (RSI/R) value of common framing situations but does not handle the thermal bridges created by fasteners and hangers used for SIP walls as well as thermal bridges created by the reinforcing members in some types of ICFs.

Exposed Floor

Strategies to insulate exposed floors (over the garage) include mineral wool batts, "flash and batt" spray-foam sealed cavities with batts, and spray foam filled joist cavities.

Two pound expanding polyurethane spray foam was selected for the *Simple and Durable* approach. Used with a 38x250mm (2x10") joist floor, 400mm (16") OC, this yielded a RSI 9.2 (R52.2) floor.

For both the S*olar* and *Advanced Mechanicals* philosophies, conventional mineral wool batt insulation was selected, yielding an effective RSI5.6 (R32) floor.

Ceiling

All of the ceiling systems consisted of raised-heal trusses with blown-in cellulose insulation. This is a simple approach and should not vary from industry practice. High levels of attic insulation may require additional reinforcement under the ceiling. One builder found that RSI 14 (R80) insulation in the attic caused excessive sagging in the ceiling drywall, and had to install OSB under the ceiling trusses (Proskiw, 2011)

The cost of extra cladding was included in the cost-effectiveness of increasingly taller trusses. A 530mm (21") heel truss with RSI 15.8 (R90) blown-in cellulose was selected for the S*imple and Durable* philosophy. RSI 12.3 (R70) blown-in cellulose in a 460mm (18") heel truss was selected for S*olar* and A*dvanced mechanical*s pathways.

Windows

In his review of best-practices, Proskiw noted that window selection was one of the most difficult aspects of NZEH design. Most of the designs specified very high performance glazing to maximize solar gains while minimizing heat loss, but Proskiw questions whether such windows are the most sensible area for investment. Shading effects of neighbouring buildings and landscaping can limit solar gains and many designers either overlook these issues or aren't equipped with tools to help estimate these impacts. Over-glazing (especially the South facing elevation) can easily lead to overheating.

Proskiw's design recommendation for glazing area is to limit south facing glass-to-floor area to a maximum of 6%. He also recommends that window selection should be based on the need to control condensation and not overall energy performance since the cost-effectiveness of most advanced window systems is poor compared to other energy conservation options readily available to the NZEH designer and builder.

For this study, vinyl framed windows were selected for all three design philosophies. Through coarse-optimization, durability concerns were identified with such windows. Vinyl has a higher coefficient of thermal expansion and therefore may not be as durable as fiberglass or wood. However, the costs of vinyl windows make them very attractive, especially to production builders who are likely already specifying vinyl.

Both the *Simple and Durable* and *Advanced Mechanicals* pathways include a maximum south-facing glazing ratio of 6%. The windows selected were double glazed units with a low-e coating, argon fill and insulated spacers (U-1.82, SHGC-0.5). The *Solar* pathway increased the south-facing glazing fraction (ratio of south-facing window area to total heated floor area) to between 7-8%. The windows selected for that case were argon filled, single low-e, triple glazed units (U-1.65, SHGC-0.51).

Optimum glazing fractions will be determined using simulation runs in ESP-r and optimization software. Increasing levels of thermal mass may provide sufficient thermal storage capacity to increase south-facing glazing fractions, but care will be taken to ensure occurrences of overheating conditions are minimized.

Space Heating Systems

The space heating systems considered included: ground source heat pumps, ductless mini-split air source heat pumps, cold-climate, central air source heat pumps, electric resistance heaters and, condensing gas furnaces and point source gas-fired air heaters. For all pathways, mechanical systems were kept as simple as possible. Considering that NZEH will have minimal space heating loads due to high envelope insulation, expensive, complex mechanical systems are rarely warranted. This is a common recommendation from the experienced designers and builders of advanced homes. Many of the advanced, integrated mechanical systems employed in the EQuilibirum™ homes were very expensive and required custom engineering and design work, have underperformed compared to expectations, and are poorly understood by homeowners. Furthermore, controls for such equipment are complex, unreliable and are often proprietary and thus do not integrate well with one another.

Consequently, the *Simple and Durable* pathway used electric resistance to provide space heating. Installation, maintenance and operation are very simple. The *Solar* pathway used an air source heat pump for space heating. A ground source heat pump was used for space heating in the *Advanced Mechanicals* pathways.

HOT2000 can not model some types of advanced systems that are often considered for advanced homes such as solar combi systems (i.e., combination solar hot water and air heating systems). Energy simulation tools generally fall short in this area because of all the combinations of heating/cooling system options and controls.

Water Heating Systems

Domestic hot water heating technologies considered included: electric and gas storage and instantaneous heaters, heat pump water heaters, solar thermal water heaters and drain water heat recovery devices. Consideration was made to avoid unintended negative interactions between various systems (for example solar domestic water heating with tankless systems)

The *Simple and Durable* pathway utilized an electric storage water heater for its simplicity and affordability. For the *Solar* pathway, solar thermal water heating was augmented with an electric tankless unit. The *Advanced Mechanicals* approach utilized a heat pump water heater or a desuperheater. All three pathways used drain water heat recovery units, which are durable and simple to install.

Ventilation

A high efficiency HRV or ERV with an ECM motor was specified for each of the design philosophies. Where a centrally-ducted space heating system was not used, the HRVs required dedicated duct work. The costs for such dedicated duct work were included in the coarse optimization.

Airtightness

Airtightness was evaluated using HOT2000. Limited data is available on the costs associated with air tight construction. Since achieving high levels of air tightness is dependent on experience and attention to detail, it is difficult to estimate labour requirements. However, the researchers surveyed experienced builders and solicited material and labour estimates to achieve certain benchmark air tightness data.

The base case air tightness is assumed to be 3.5 ACH@50Pa. Four upgrade scenarios were analyzed in the coarse optimization ranging from a final airtightness of 1.75ACH_{50} to 0.6ACH_{50}. Measures to improve air tightness included caulking framing connections, caulking the slab perimeter, upgrading to airtight electrical boxes and mechanical penetrations, rim joist sealing gaskets, and flash sealing of joist cavities with spray foam. These estimates were extrapolated and used to develop a function for estimating the cost of increasing airtightness. This function is assumed valid in the range of 0.6 to 3.57 ACH_{50}.

$$\text{Incremental cost (\$)} = 275(ACH_{50})^2 - 2410\,(ACH_{50}) + 5150 \qquad \textbf{(2)}$$

where:

ACH_{50} = the final measured airtightness (air changes per hour at 50 Pa)

Industry familiarity was identified as the largest barrier to tighter construction. However, this is one of the most cost effective of the measures considered (cost effectiveness of achieving 0.6ACH@50Pa was determined to be $0.81/kWh saved annually). For this reason, the target tightness for all three approaches was set at 0.6 ACH. It is important to note, at this air tightness, mechanical ventilation is required to maintaining indoor air quality.

Thermal Mass

Maximizing solar heat gain is a priority in net-zero energy housing design. However, overheating is a significant concern. Maintaining comfortable conditions for occupants is critical. The use of thermal mass (dense materials with high specific heat) within the heated space may act as a thermal battery to store solar gains and radiate heat back to the surrounding surfaces later in the day. This prevents or dampens air temperature spikes. Typical strategies to add thermal mass include extra drywall or gypsum, concrete topping applied to floors, masonry walls, floors or countertops. Key to using additional mass effectively is a) ensuring that it will be directly lit by sunlight and b) ensuring that the thermal mass physically has a high area-to-volume ratio. Phase change materials offer promise in this area.

As the south facing glazing fraction exceeds 6%, thermal mass may become important to control overheating. The qualitative criteria were applied to thermal mass options including concrete floor toppings, additional layers of gypsum on the walls and using a masonry “feature wall.” The simplest and likely most cost effective approach is using gypsum. Adding concrete to floors may have structural implications to the floor design. Furthermore, floors often get covered by area rugs and furniture, negating any mass benefits.

A challenge with thermal mass however, is predicating its storage capacity and effectiveness. To do this, simulation software that evaluates hourly heat gains and losses needs to be used. For that reason, HOT2000 which assumes steady-state conditions wasn’t used to evaluate cost-effectiveness of applying additional thermal mass. The effects of thermal mass will be examined in the fine optimization stage using either ESP-r or the next generation of HOT2000 – HOT3000, which is based on the ESP-r core.

Renewable Energy

Photovoltaic (PV) modules were selected for all three design pathways to generate the balance of the annual energy use to achieve net-zero performance. In the tract-built context, solar energy is the most predictable and unobstructed renewable energy source. Three PV systems were considered: standoff PV; building integrated PV and hybrid PV/thermal panels.

5 Conclusions

Technical barriers, while significant are no longer the biggest challenge to building marketable net-zero energy homes in Canada. The challenge lies in minimizing incremental construction cost. Design tools and methods to assist in cost-optimization will play a crucial role in finding cost-optimal building designs and approaches until prescriptive guidelines are made available for various markets and climatic regions.

Technology costs are market specific and are constantly in flux. Consequently, there's a high degree of uncertainty in pure cost estimation and optimization. Therefore, technology pathways that are simple, durable, proven and easily understood by trades and occupants ought to be prioritized. In addition to cost, these qualitative parameters should form the basis for selecting technology pathways. A quick method of comparing the cost effectiveness of different measures is described by simulating the energy impact using HOT2000. The quotient of the incremental cost divided by the quantity of energy saved (as per Equation 1) is computed and used as a comparator. Computer optimization and simulation can be used for further fine-tuning.

Several advanced mechanical and renewable energy systems are currently unsupported by simulation software that analyzes whole home energy performance. This study illustrates the need for easy-to-use residential energy simulation tools to better explore the effectiveness of thermal mass and solar thermal space heating systems such as solar combi systems.

Finally, uncertainties in technology performance, energy simulation and occupant lifestyle make guaranteeing NZE-level performance practically impossible. However, simulation including realistic assumptions concerning building loads augmented by a "coarse optimization" process similar to that outlined in this paper can aid a designer in selecting the most appropriate technology choices to achieve highly constructible, affordable net-zero energy home designs.

6 References

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