Multi-Objective Optimal Design of a Near Net-Zero Energy Solar House

ABSTRACT

This paper presents a multi-objective redesign case-study of an archetype solar house based on a near net-zero energy (NZE) demonstration home located in Eastman, Québec. Using optimization techniques, pathways are identified from the original design to both cost and energy optimal designs. An evolutionary algorithm is used to optimize trade-offs between passive solar gains and active solar generation using two objective functions: net-energy consumption and life-cycle cost over a thirty year life-cycle. In addition, this paper explores different pathways to net-zero energy based on economic incentives such as feed-in tariffs for on-site electricity production from renewables. The main objective is to identify pathways to net-zero energy that will facilitate the future systematic design of similar homes based on the concept of the archetype that combines passive solar design, energy efficiency measures including a geothermal heat pump and a building-integrated photovoltaic system. Results from this paper can be utilized as follows: (1) systematic design improvements and applications of lessons learned from a proven NZE home design concept, (2) use of a methodology to understand pathways to cost and energy optimal building designs, and (3) to aid in policy development on economic incentives that can positively influence optimized home design.

Keywords: net-zero energy, solar building, optimization, energy, life-cycle cost

INTRODUCTION

ASHRAE envisions a future of net-zero energy (NZE) buildings, or buildings which produce as much energy as they consume over a year (ASHRAE, 2008). There are many indicators of a growing market. The European Union has mandated that all member states build to NZE building standards by 2020 (EU Parliament, 2010). Analysts suggest that the NZE building market could grow to $1.3 trillion by 2035 (Pike Research, 2012). An international task-force responsible for establishing international NZE building definitions, simulation approaches and examining case-studies in different climates is nearing completion (IEA/ECBCS, 2013). In Canada, the NSERC Smart Net-zero Energy Buildings strategic Research Network (SNEBRN) envisions the widespread adoption of solar-optimized NZE buildings in key regions of Canada, by 2030 (SNEBRN, 2013).

NZE buildings offer many technical benefits: (1) they require an energy balance which offsets primary energy use for construction and operations while eliminating their embodied energy and greenhouse gas emissions over the life-cycle (Berggren et al., 2013), (2) low operation costs and the potential for a positive investment opportunity if generated electricity is purchased, (3) lower peak electrical demands relative to other buildings which reduces the need for future grid expansion (Sadineni et al., 2012), and (4) with additional smart-grid technologies, distributed generation makes the electrical grid more resilient to blackouts (IEEE, 2012).

In Canada, detached homes are ideal candidates to reach NZE since they have a large envelope surface area for installation of building-integrated photovoltaic panels and relatively low energy use intensity compared to other building types (NRCan-OEE, 2009).

Designing a NZE building requires an integrated approach involving passive solar design, improved envelope insulation and air-tightness, renewable energy generation, and control strategies to regulate solar gains. The process of balancing passive solar with energy efficiency and renewable energy generation involves many interacting design aspects. This process can be facilitated using a systematic optimization approach using energy simulation tools.

The approach proposed in this paper is complementary to the approach used by the Building Energy Optimizer (BEOpt) development team. The BEOpt team utilized a deterministic sequential search technique which identified all intermediate designs starting from a reference building to a cost optimal design and eventually a NZE home (Christensen et al., 2004). Sequential searches operate on a single representation to incrementally find variable changes which result in the largest cost-to-savings gradient. Emphasis is placed on energy conservation strategies until renewable energy installations are cost competitive, so cost-optimal pathways to net-zero energy homes are identified. In this paper, multi-objective trade-offs are quickly identified using specialized optimization techniques, then steepest-descent searches are used to better understand pathways to optimal solutions.

An archetype based on the Écoterra home design is used for the optimization study is discussed in the next section. The method describes the annual net-energy consumption and life-cycle cost objective functions as well as the optimization approach. The main objective is to identify pathways to net-zero energy that will facilitate the future systematic design of similar homes based on the concept of the archetype that combines passive solar design, energy efficiency measures including a geothermal heat pump and a building-integrated photovoltaic system. The results and conclusion discuss different pathways to achieve NZE by optimally combining energy efficiency and passive design measures with building-integrated photovoltaics that cover a complete south-facing roof surface.

ÉCOTERRA HOUSE: EXISTING DESIGN

ÉCOTERRA™ is a detached near NZE home located in Eastman, Québec, see Figure 1. This home was one of the winners of the Canadian Mortgage and Housing Corporation Equilibrium Net Zero Energy Home competition and the first demonstration house built under this program (CMHC, 2008). The primary goal of the house design was to be cost competitive with other pre-fabricated homes, while greatly reducing energy intensity compared to the Canadian building stock.

Figure 1: ÉCOTERRA House.

The ÉCOTERRA design has a heated floor area of 211.1 m^2 (2,272 ft^2) and a heated volume of 609.1 m^3 (21,510 ft^3). The house is heated and cooled using a well-tied ground source heat pump (GSHP). Domestic hot-water (DHW) energy consumption is offset using a desuperheater and thermal energy collected from an open-loop solar thermal collector on the roof surface. The design features an innovative dual-energy roof system which uses 6% efficient amorphous silicon photovoltaic (PV) panels and an air-channel to simultaneously collect thermal and electrical energy.

The ÉCOTERRA home was the first pre-fabricated home design with a customized building-integrated photovoltaic/thermal (BIPV/T) roof linked to a hybrid thermal energy storage system (Chen et al., 2010a,b). This technology combined with passive solar design strategies resulted in an annual net-energy consumption less than $50 kWh/m^2$ (4.6 kWh/ft^2), or one fifth of the average national energy consumption or one half of the R2000 standard, see Figure 2 (Doiron et al., 2011). R2000 is a voluntary standard which promotes cost-effective energy-efficient building practices and technologies in Canada.

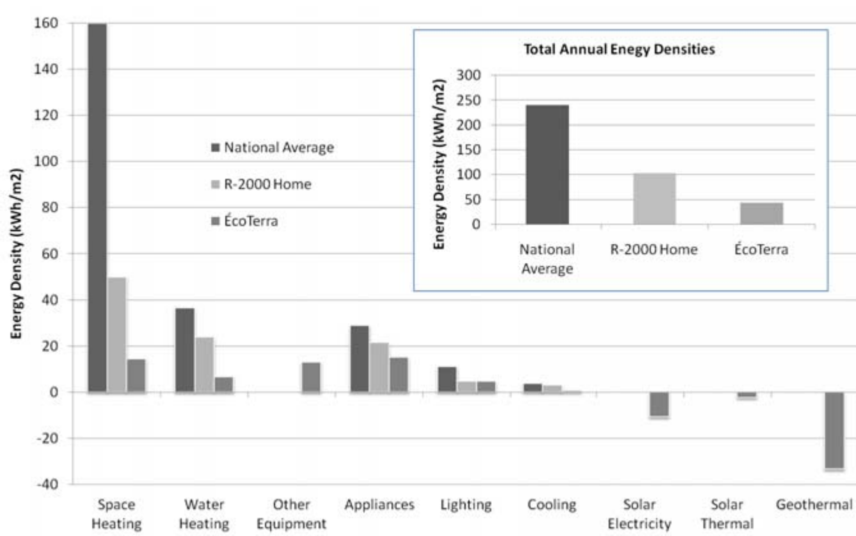

Figure 2: ÉCOTERRA annual energy consumption (Doiron et al., 2011).

Approximately 40% percent of the gross heating demand is met through passive solar gains. Some thermal energy is offset by the roof integrated 2.84 kWe BIPV/T system, which can produce up to 10 kW_p of useful heat (Candanedo et al., 2010). The remaining auxiliary heating is provided by a GSHP. The thermal energy from the BIPV/T is delivered directly through an open-loop air system to a concrete slab in the basement or to a DHW pre-heat tank through an air-water heat exchanger, see Figure 3 (Chen, 2009). The slab serves as an active charge/passive discharge storage device.

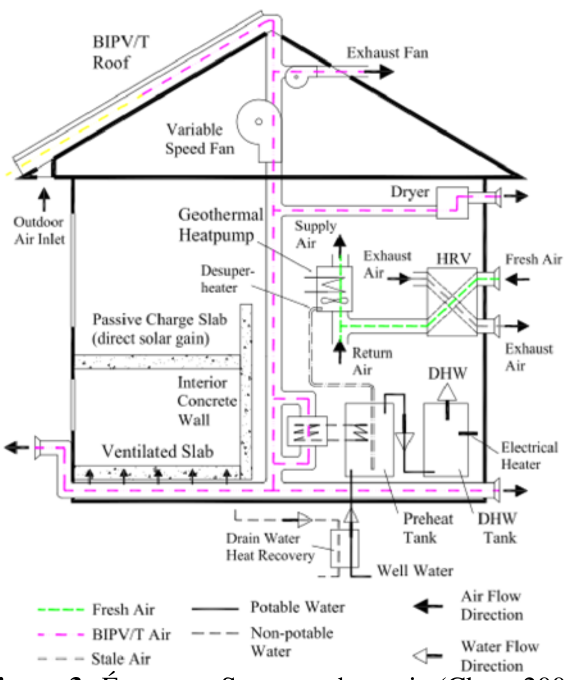

Figure 3: ÉCOTERRA System schematic (Chen, 2009).

Data was recorded from early 2008 until 2012 using over 100 temperature sensors distributed within the roof, slab and thermal zones. The PV generation, DHW and heat pump electrical demand of the home was monitored separately. This information permits the study of each design parameter and offers a unique opportunity to evaluate the present operation as well as to assess the impact of design improvements.

The proposed redesign case-study revisits the original design using a multi-objective optimization approach. The main objective is to identify pathways to net-zero energy that will facilitate the future systematic design of homes similar to the ÉCOTERRA archetype design. The following section describes the methodology used in the paper.

METHOD

Two redesign approaches were used in the paper: (1) identify minor upgrades that could help ÉCOTERRA reach NZE or reduce life-cycle costs without significant design modification, and (2) perform a full redesign with significant design modifications and a feed-in tariff to reduce operational costs.

For the first redesign approach, upgrades were restricted to simple renovations and control strategies modifications. These included modifying envelope insulation, air-sealing, and fine-tuning control strategies. Geometry, orientation, roof area and slope were fixed. Adding more PV panels was allowed if a similar PV product was used to match the aesthetic and electrical characteristics of the existing PV strings.

In the second redesign approach, the complete design was reconsidered including all aspects of passive solar design, renewable energy generation and control strategies. Changes to the rectangular shape were allowed only if the same floor area and number of floors were used. A feed-in tariff created revenue from on-site PV generated electricity. Including an incentive shows how economics can influence optimal building design approaches.

An exhaustive list of design variables used for optimization studies and the original ÉCOTERRA design are presented in Table 1. Note that glazing types and window to wall ratios (WWR) were considered as separate design variables for all four walls. The last six variables in Table 1 were used only for the second redesign study.

Table 1: Definition of Optimization Variables used for the ÉCOTERRA Redesign Study

VARIABLE	UNITS	MIN.	MAX.	NO. STEPS	ECOTERRA	DESCRIPTION
wall_ins	m^2K/W	3.50	12	8	5.89	Effective resistance of wall insulation
	ft^2 °Fh/Btu	20	68	8	20	
ceil_ins	m^2K/W	5.6	15	8	8.2	Effective resistance of ceiling insulation
	ft^2 °Fh/Btu	32	85	8	46	
base_ins	m^2K/W	0	7	8	5.2	Effective resistance of basement wall insulation
	ft^2 °Fh/Btu	0	40	8	30	
slab_ins	m^2K/W	0	2.32	4	1.32	Effective resistance of slab insulation
	ft^2 °Fh/Btu	0	13	4	7	
ovr_south	m	0	0.45	4	0	Width of southern window overhangs
	ft	0	1.5	4	1.1	
pv_area	%	0	80	8	50	Percent of PV area on roof
GT_s	–	1	4	1	4	Glazing type (also N, E, W)
FT	–	1	2	2	2	Window framing types (ex. 1:Wood, 2:Vinyl)
wwr_s	%	1	80	8	35	Window to Wall Ratio South (also N, E, W)
heating_sp	°C	18	25	4	22	Heating setpoint
	°F	64	77	4	72	
cooling_sp	°C	25	28	4	26	Cooling setpoint
	°F	77	82	4	79	
slab_th	m	0.1	0.35	8	0.1	Concrete slab thickness
	in	4	14	8	4	
vwall_th	m	0	0.35	8	0.1	Concrete wall thickness
	in	0	14	8	4	
zone_mix	L/s	0	400	4	200	Air circulation rate between thermal zones
	cfm	0	840	4	425	
infil	ACH	0.025	0.179	8	0.047	Envelope air-tightness (natural infiltration rate)
roof_slope[a]	degrees	30	50	8	33	South facing roof/PV slope
pv_area_e[a]	%	0	50	8	0	Percent of PV on east facade
pv_area_w[a]	%	0	50	8	0	Percent of PV on west facade
pv_eff[a]	%	6	15	8	6	PV efficiency
azi[a]	degrees	-45	45	16	0	Building orientation/azimuth
aspect[a]	–	0.7	2.2	16	1.3	Aspect ratio (south facing width to depth ratio)

a: value used only for the complete redesign case-study

An energy model, cost model, database and optimization algorithm were necessary for the optimization redesign study. Figure 4 presents the integration of an energy simulation tool with an optimization algorithm.

As shown in Figure 4, upper and lower limits of design variables are first defined. These limits define the entire possible set of designs available to the optimization algorithm. Once algorithm and design variables are defined, the op-

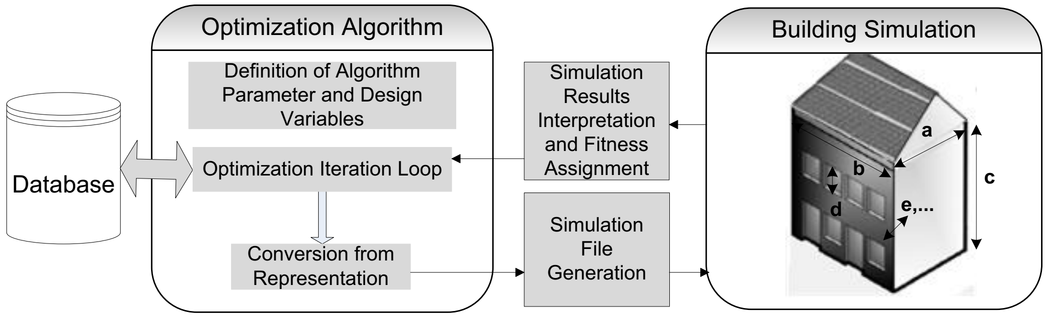

Figure 4: Integration of energy simulation with an optimization algorithm.

timization process can be initiated. Design representations created by the optimization algorithm are converted into simulation files. Simulation files are evaluated using a building simulation tool to determine the performance of each design in question. Simulation results are post-processed to determine net-annual energy consumption and life-cycle costs before reentering the algorithm. Databases are used by the optimization algorithm to store relevant simulation information. Building representations in the algorithm are improved upon until a terminal criterion is satisfied.

The following sections elaborate on the energy and cost models and the optimization algorithm.

Energy Objective Function

The first objective function is the net-energy consumption described by equation 1 which was evaluated using the EnergyPlus building simulation software (EnergyPlus, 2011). The energy model was calibrated using monitored data from the existing ÉCOTERRA home (Doiron, 2010; Doiron et al., 2011).

$$f(\mathbf{x}) = Q_{heat}/COP_H + Q_{cool}/COP_C + E_{elec} - E_{PV} \tag{1}$$

where: $\mathbf{x} = (x_1, x_2, \cdots, x_N)^T$ is a design variable vector. Table 1 shows the discrete variables and step-sizes used in the optimization analysis, $f(\mathbf{x})$ is the annual net-electricity consumption of the building (kWh), COP is the average annual coefficient of performance of the GSHP in heating and cooling mode, 3.77 and 2.77 respectively, Q is the annual heating and cooling load of the house (kWh), E_{elec} is the gross annual electricity consumption in lighting, domestic hot-water, appliances and plug-loads (kWh) and, E_{PV} is the electricity generated by the roof-top PV (kWh). NZE is achieved when $f(\mathbf{x}) \leq 0$ implying an annual energy balance. The combined coefficient of performance (COP) of the GSHP including circulation fans, pumps and auxiliary heaters was specified from seasonal-averages of monitored data. Since the heating system uses a GSHP, the COP does not vary significantly over an annual period. Electric lighting ensured that a minimum illuminance of 200 lx was present in all occupied spaces regardless of the window-to-wall ratio. A heat recovery ventilator with an efficiency of 60%, taken from manufacturer specifications, maintained the ventilation rate at 0.3 air-changes per hour in all occupied spaces. Roller shades were automatically deployed if exterior solar radiation on the exterior window surface exceeded 150 W/m^2 (14 W/ft^2) and if exterior temperature on the window exceeded 20 °C (68 °F). These values ensured that blinds were closed if there was potential for zone overheating (O'Brien, 2011).

Life-cycle Cost Objective Function

The second objective function is the incremental net-present value (NPV) of materials and operational energy costs over the life-cycle, see equation 2. Materials were scheduled for replacement based on an expected serviceable life-time (RSMeans, 2013). A marginal electricity rate of 7¢ with an escalation rate of 2.0% was used (Hydro-Québec, 2010). Life-cycle costs were calculated over a 30 year time horizon using a minimal acceptable rate of return (MARR). Note that all monetary amounts refer to Canadian dollars.

$$g(\mathbf{x}) = C_{NPV} + E_{NPV} + R_{NPV} - S_{NPV} - I_{NPV} \tag{2}$$

where: C_{NPV} is the capital costs of materials and equipment, E_{NPV} is the operational energy costs, R_{NPV} is the replacement cost for materials and equipment, S_{NPV} is the salvage or residual value using a linear depreciation method, and I_{NPV} is the income generated through incentives such as feed-in tariffs.

If $NPV = 0$, the investment is cost neutral over the considered life-cycle. For this paper, $NPV < 0$ is a profitable opportunity for a given MARR, and if $NPV > 0$, the investment is considered unprofitable over the evaluated life-cycle period. The goal of the cost optimization study is to minimize NPV.

Equation 3 specified the minimal acceptable rate of return used for net-present value calculations.

$$a = (1 + r)(1 + i) - 1 \tag{3}$$

where: r is assumed bank rate, a 2.14% return from a 10 year guaranteed investment certificates from 2002 to 2012 (Bank of Canada, 2009), i is the Canadian annual inflation rate, 2.0% (Bank of Canada, 2009), a is the calculated minimal acceptable rate of return, 4.18%.

Evaluation of initial costs included the following terms: (i) cost of wall, ceiling, basement and slab insulation; (ii) cost of windows based on glazing area; (iii) incremental cost of additional roof framing beyond 30 degrees slope; (iv) cost of overhangs; (v) cost of concrete walls and slab for passive thermal storage; (vi) cost of PV panels and inverters; and (vii) incremental cost associate with tighter envelopes. These costs were specified from RSMeans data (RSMeans, 2012, 2013). A price point of $4,000 per kW was used for the PV system.

Including replacement costs creates a potential problem—the possibility that costs are incurred just before the end of the life-cycle which results in a misleadingly large NPV (Anderson et al., 2006). Thus, salvage values were associated with each material. This is especially important for equipment, such as PV panels and inverters, where costs varied significantly from design to design depending on the array size. Salvage values were incorporated using a linear depreciation method (Doty and Turner, 2012).

At the end of the specified life-cycle period it was assumed that materials had residual value. In some instances this can be related to a real resale value, such as PV panels, whereas in other instances, such as insulation replacement, salvage values are strictly used to compare different life-cycle periods. The time horizons for replacement costs are summarized in Table 2. A dash indicates that the replacement costs for this material were not considered.

Table 2: Replacement Period of Materials

Material Category	Replaced?	Replacement Period, yr
Cellulose insulation in Walls	✓	25
Cellulose insulation in Attic	✓	25
Spray insulation in Attic/Basement	✗	–
Rigid insulation under Slab, exterior wall	✗	–
Windows	✓	40
Shingles on Roof	✓	25
Inverters	✓	15
PV Panels	✓	40
Miscellaneous PV array costs	✗	–

To accelerate the adoption of renewable energy systems, a PV feed-in tariff was implemented. Feed-in tariffs for renewable energy generation have been available since 2009 in Ontario. Peak electricity consumption in large Canadian cities, such as Toronto, is directly correlated with summer cooling (Toronto Hydro, 2011). Cooling loads associated with high solar gains and could partially be offset using PV generated electricity. To create a disincentive for electricity use during peak periods, some provinces in Canada have implemented time-of-use electricity charges. This paper examines the effect of a time-of-use feed-in tariff. Since electricity is sold at a higher rate during peak periods, logically, so too should it be purchased by the utility at a cost premium. Utilities benefit since they do not require expansion of centralized generation to meet peak electricity demands and PV system owners generate additional revenue during the equipment's expected lifetime. Table 3 shows the implemented time-of-use feed-in tariff. Note that peak electricity purchase rates are based on the microFIT program offered in Ontario (OPA, 2013).

Table 3: Time of use Feed-in Tariff

FIT Schedule	Hours	Peak?	Incentive, ¢/kWh
Summer Weekdays	21:00–07:00	off-peak	40
	07:00–11:00	mid-peak	60
	11:00–17:00	on-peak	80
	17:00–21:00	mid-peak	60
Winter Weekdays	21:00–07:00	off-peak	40
	07:00–11:00	on-peak	80
	11:00–17:00	mid-peak	60
	17:00–21:00	on-peak	80
Weekends and Holidays	00:00–24:00	off-peak	40

Multi-Objective Optimization Algorithm

This section describes the multi-objective evolutionary algorithm used in the paper. The goal of the multi-objective analysis is to find optimal trade-off curves which minimize both net-energy consumption and life-cycle cost. In a minimization study, the goal is to find a design variable vector, $\mathbf{x}$, such that:

$$min\{f(\mathbf{x})\} \tag{4}$$

where: $\mathbf{x}$ is the design variable vector $\mathbf{x} = (x_1, x_2, \cdots, x_N)^T$, in design space $\mathbf{X} \subset \mathbb{R}^N$, the objective or fitness function, $f()$, evaluates set of design variables onto an objective vector $\mathbf{y} = (y_1, y_2, \cdots, y_M)^T$ where $f_i \in \mathbb{R}^M$, $y_i = f_i(\mathbf{x})$, $f_i : \mathbb{R}^N \to \mathbb{R}^1$ for $i = 1, 2, \cdots, M$, describes the objective or solution space $\mathbf{Y} \subset \mathbb{R}^M$, $min\{f(\mathbf{x})\}$ is subject to L constraints $g_i(\mathbf{x}) \leq 0$ where $i = 1, 2, \cdots, L$, the feasible design vectors set $\mathbf{x}|g_i(\mathbf{x}) \leq 0$ form the feasible design space $\mathbf{X}^*$, and corresponding objective vectors set $\mathbf{y}|\mathbf{x} \in \mathbf{X}^*$ form the feasible objective space $\mathbf{Y}^*$, for a minimization problem, a design vector $\mathbf{a} \in \mathbf{X}^*$ is Pareto optimum if no design vector $\mathbf{b} \in \mathbf{X}^*$ exists such that $y_i(\mathbf{b}) \leq y_i(\mathbf{a}), i = 1, 2, \cdots, M$.

One approach to solve the above problem is a systematic algorithmic approach using pseudo-evolution. The functionality of this algorithm was described in a previous publication (Bucking et al., 2013). The inclusion of multiple objectives is accomplished in the EA by modifying the parent selection operator. The elitist non-dominated sorting genetic algorithm (NSGA-II) was selected as a parent selection operator for multi-objective optimization as described in Deb (2001, chap. 6.2). This selection operator preserves elite individuals through non-dominance and explicitly maintains population diversity using crowding distances. The advantage of NSGA-II over other techniques is that it uses a computationally efficient crowding strategy (Deb et al., 2002).

Back-tracking Searches to Identify Pathways to Optimal Designs

This paper proposes a back-tracking search to identify pathways to optimal designs. Optimization of building design is a well-explored research area where optimal combinations of design aspects are identified. However, few algorithms show pathways from typical designs to the optimal design. Pathways refer to a sequence of design variables changes on the path from a reference individual to an individual with improved performance. The proposed back-tracking search finds steepest objective function gradients from a known optimal design, or reference design, to a known initial design. This search is performed after the optimization algorithm by varying relevant input parameters and conducting additional simulations to identify steepest gradients to optimal solutions. Figure 5 shows a back-tracking search using a simplified example.

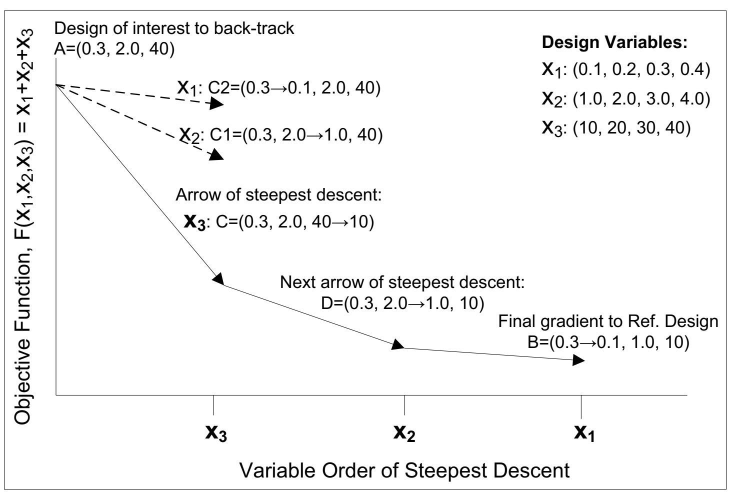

Figure 5: Simplified back-tracking search.

A back-tracking search identifies the order in which each variable should be changed to result in the steepest objective function gradients from a selected design, *A*, to a known reference design, *B*. In Figure 5, starting from the initial design, A, three potential variable changes are tested. The variables, x_1, x_2, x_3, are changed from the value found in the selected design to the value known in the reference design. Thus three new intermediate designs, C, C_1, C_2, are created and evaluated using the objective function. The variable x_3 resulted in the steepest change in the objective evaluation and is identified as the variable with the highest importance as listed in the x-axis. The objective function gradient from design A to design C is recorded. Now, the variable x_3 can be excluded from the remaining back-tracking searches. Starting from the intermediate design, C, the variable x_2 with the next steepest gradient is identified for design D. This process is repeated until all variables of design A are back-tracked to design B.

For this paper, the reference design is the optimal design identified by the optimization algorithm. The design which we are back-tracking from is the original ÉCOTERRA design. Thus, the proposed back-tracking search identifies the most significant improvements to the existing ÉCOTERRA design to achieve the discovered optimal design. Both objective functions, life-cycle cost and net-energy consumption will be used in separate back-tracking analyses.

The next section presents results and a discussion.

RESULTS AND DISCUSSION

Recall that two redesign approaches were used in the paper. The first was to redesign ÉCOTERRA reach NZE. The second was to perform a full redesign and utilize a feed-in tariff. The first redesign study is shown in Figure 6.

Although it is possible to explore grouping of data in Figure 6, this paper focuses on results of potential candidate solutions. Raw optimization data plotted in the Figure aid in understanding the diversity of near-optimal solutions and

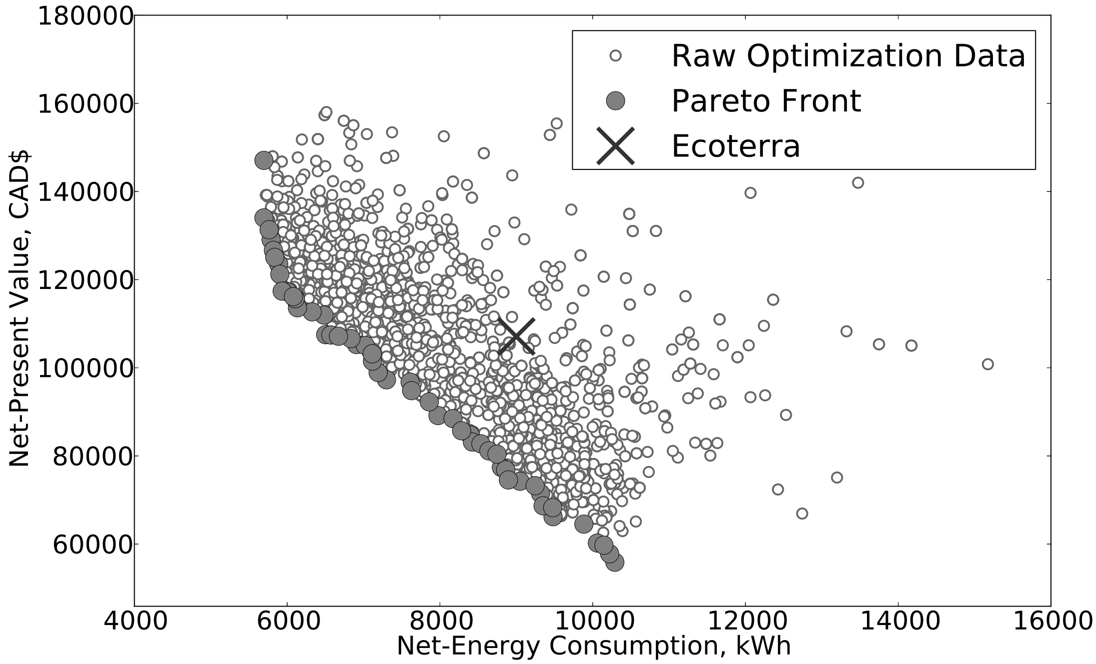

Figure 6: Multi-objective constrained redesign of ÉCOTERRA home.

the number of energy simulations to identify Pareto fronts. We select the energy optimal design since the goal was to redesign to achieve NZE. The best design found had a net energy consumption of 5700kWh, a decrease in energy intensity from 50 kWh/m^2 (4.6 kWh/ft^2) to 27 kWh/m^2 (2.5 kWh/ft^2). Important changes included adding PV to the remaining area of the roof and modifying the heating and cooling dead-band limits, resulting in a combined net-electricity consumption reduction of 3500kWh. Of the redesign opportunities identified, none required significant changes to the passive solar design of the house. For example, fine tuning the thermal storage (slab and basement wall), increasing the slab and wall insulation levels, increasing the southern window area to 50%, increasing air tightness to 0.5 ACH at 50Pa (0.025 ACH at ambient pressure) from 0.8 ACH at 50Pa (0.047 ACH at ambient pressure), cumulatively amounted to only 500kWh of annual electricity savings. This indicates that the ÉCOTERRA design was near a local optimum with regards to passive solar design.

Figure 7 shows results for the second part of the redesign case-study. In this part, all variables were reconsidered including PV panel efficiency, roof-slope, orientation and geometry. Note that all designs were compliant with local building codes. The diversity in results shows that there significant opportunity to better improve energy codes and reduce energy consumption and life-cycle cost of residential homes in Canada.

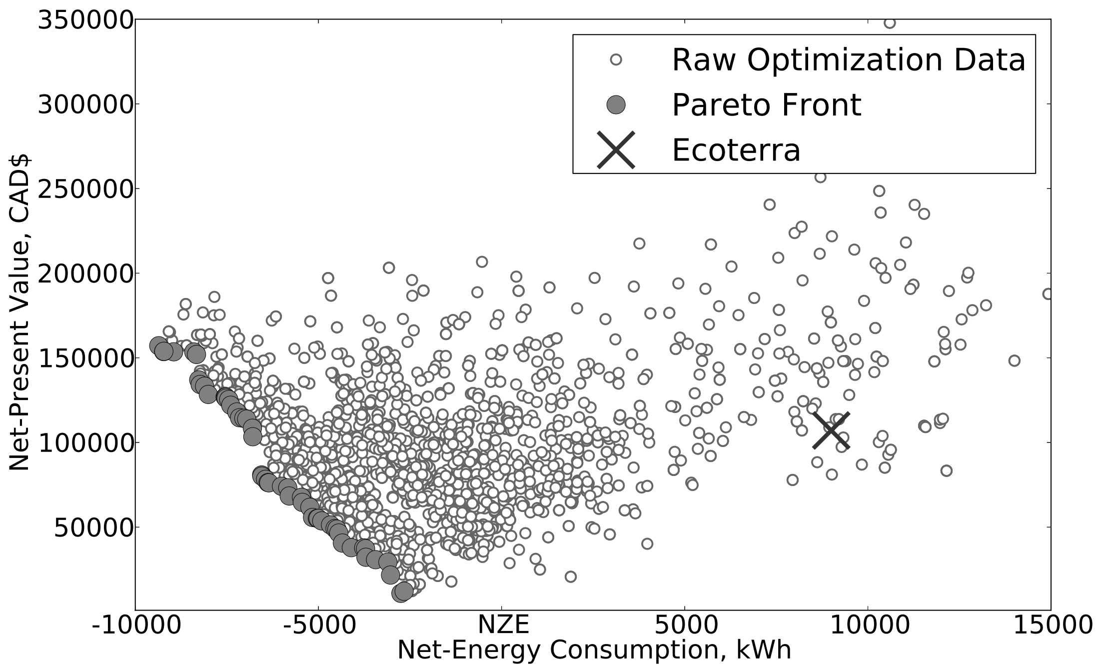

Figure 7: Multi-objective complete redesign of ÉCOTERRA home.

The primary inhibitor to NZE with the ÉCOTERRA design is the lack of renewable energy generation. More than doubling the PV efficiency from 6% to 15% alone would reduce net-electricity consumption from 5700kWh to 400kWh. A secondary inhibitor was high appliance loads which were measured from monitored data to be approximately 4000kWh/yr. Further research on implementing conservation measures on appliance, lighting, and DHW loads and their effect on occupant energy behaviour is recommended.

Although Figure 7 shows a spectrum of cost and energy savings, we shall consider a single optimal design to examine improvements. This design is shown in Table 4. The optimal design shown in Table 4 generated a net of 3150 kWh of electricity and cost $\$32,000$ over the life-cycle. To achieve this optimal design required integrated approach. A balance of passive solar strategies, such as: air-tight envelopes (0.025 ACH natural infiltration rate), sufficient wall envelope insulation values, RSI 8.56 (R49), sufficient south-facing glazing area (48% WWR), sufficient air circulation between zones to distribute solar gains, 133 L/s (280 cfm) and sizing of concrete floor thermal mass, 0.25 m (10 in.). Thermal mass allowed storage of solar gains and interacted with solar gain control strategies. Blind control strategies and exterior shading allowed for a larger window-to-wall fraction while maintaining acceptable visual comfort. The identification of trade-offs between passive solar design, energy efficiency and active solar electricity generation resulted in a sufficient improvement to achieve NZE.

Figure 8 shows the back-tracking search from the initial ÉCOTERRA design, to an optimal solution using the energy objective function defined in equation 1. The fraction shown in the Table represents the fraction of each parameter change with respect to the total objective function difference. Note that the first five parameters have the largest impact on fitness as they open new solution space landscapes. Other variables were less significant because they were either near optimal already, or were insensitive to changes in the vicinity of the solution space landscape.

Table 4: Optimization Results for Écoterra Complete Redesign

Variable	Description	Units	Optimal Values
azi	Building orientation/azimuth	degrees	12 (SSE)
aspect	Aspect ratio (south facing width to depth ratio)	–	1.4
wall_ins	Effective resistance of wall insulation	m^2K/W	8.56
		ft^2 °Fh/Btu	49
ceil_ins	Effective resistance of ceiling insulation	m^2K/W	10.57
		ft^2 °Fh/Btu	60
base_ins	Effective resistance of basement wall insulation	m^2K/W	5.08
		ft^2 °Fh/Btu	29
slab_ins	Effective resistance of slab insulation	m^2K/W	1.39
		ft^2 °Fh/Btu	8
pv_area	Percent of PV area on roof	%	90
pv_area_e	Percent of PV on east facade	%	0
pv_area_w	Percent of PV on west facade	%	0
pv_eff	PV efficiency	%	15
roof_slope	South facing roof/PV slope	degrees	45
wwr_s	Percent of window to wall ratio, south	%	48
wwr_n	Percent of window to wall ratio, north	%	10
wwr_e	Percent of window to wall ratio, east	%	10
wwr_w	Percent of window to wall ratio, west	%	10
GT_s	Glazing type, south (also N,E,W)	–	2
heating_sp	Heating setpoint	°C	18
		°F	64
cooling_sp	Cooling setpoint	°C	28
		°F	82
FT	Window Framing Types (1:Wood, 2:Vinyl)	–	2
slab_th	Concrete slab thickness	m	0.25
		in	10
vwall_th	Concrete wall thickness (basement)	m	0.15
		in	6
zone_mix	Air circulation rate between thermal zones	L/s	133
		cfm	280
infil	Envelope air-tightness (natural infiltration rate)	ACH	0.025
$f(\mathbf{x})$	Net-Energy Consumption of Individual	kWh	-3150
$g(\mathbf{x})$	Net-Present Value of Individual	\$	32,000

Figure 9 shows the back-tracking search from the initial Écoterra design, to an optimal solution using the life-cycle cost objective function defined in equation 2.

Note that the variable order is changed slightly when considering life-cycle costs. Decreasing the thickness of concrete passive solar storage and eastern window to wall ratios takes precedence over improving the tightness of envelopes and adding more insulation. However, improving PV efficiency and increasing the

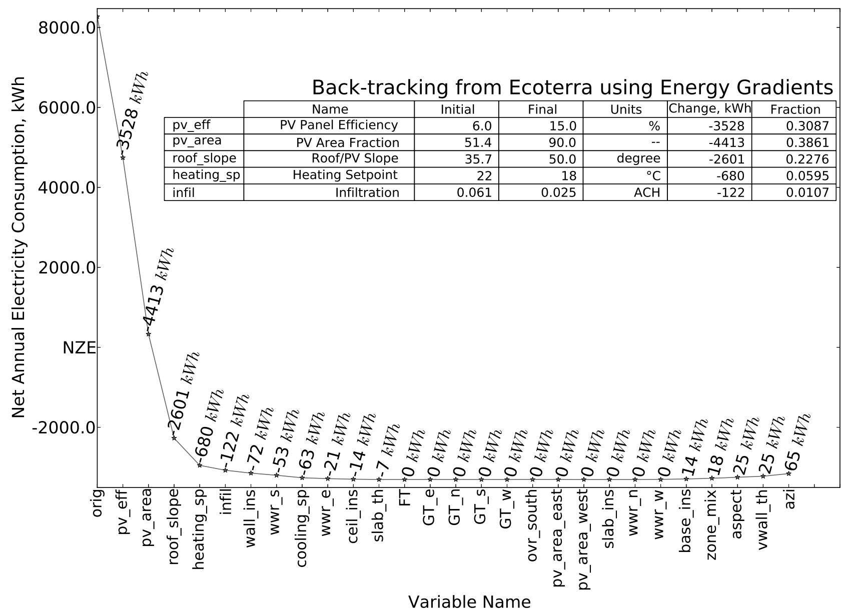

Figure 8: Back-tracking of ÉCOTERRA design to the optimal design: Net-energy consumption objective function.

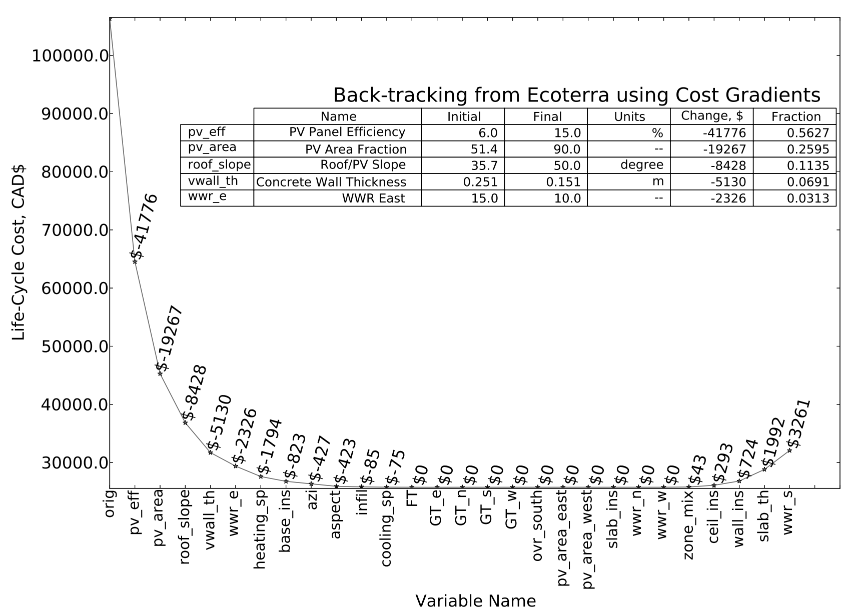

Figure 9: Back-tracking of ÉCOTERRA design to the optimal design: Life-cycle cost objective function.

PV area by increasing roof slope and adding more panels represents the steepest objective function gradients in both back-tracking cases.

CONCLUSION

Optimization approaches can identify pathways to significantly reduce the net-present cost and net-energy consumption of homes. This paper explored two redesign case-studies: (1) design changes that did not require major renovation to the archetype ÉCOTERRA home, and (2) a complete redesign to achieve NZE. Without adding higher efficiency PV panels, it was not possible for the design to achieve NZE. However, the ÉCOTERRA design was near to the energy-cost optimal trade-off curves indicating the success of the original design.

The second part of the case-study demonstrated how a time-of-use FIT incentive can influence NZE home design. The algorithm found that it was more cost-effective to orientate the primary solar collector ten degrees east of south rather than orientating directly south and using solar panels on the east or west facades. This design choice had two benefits: (1) more energy was generated during peak times which increases annual income, and (2) the slightly east-orientated passive solar glazing surface was able to reduce the heating-system dependency when transitioning from a nightly set-back schedule to the morning heating schedule. This reduced heating system peak-loads without significantly changing annual heating consumption. West-facing glazing surfaces were not selected since they typically resulted in overheating of living spaces.

There are several areas for future work. Initial cost still remains a major challenge in NZE home design. Further research is needed to identify incentives which reduce initial and life-cycle costs by generating revenue over the life-cycle period.

Further work should focus on collaborating with policy makers to develop incentives that ensure future buildings are both cost and energy optimal.

ACKNOWLEDGMENTS

This work was funded in part by NSERC and by the Faculty of Engineering and Computer Science at Concordia University.

REFERENCES

Anderson, R., Christensen, C., Horowitz, S., 2006. Analysis of residential system strategies targeting least-cost solutions leading to net zero energy homes. *ASHRAE Transactions* 112 (2), 330–341.

ASHRAE, 2008. ASHRAE Vision 2020: Providing tools by 2020 that enable the building community to produce market-viable NZEBs by 2030. Tech. rep., ASHRAE 2020 Ad Hoc Committee.

Bank of Canada, 2009. Rates and Statistics: Interest rates, Canadian interest rates. Accessed January, 2013.
URL `http://www.bankofcanada.ca/rates/interest-rates/`

Berggren, B., Hall, M., Wall, M., 2013. LCE analysis of buildings - Taking the step towards Net Zero Energy Buildings. *Energy and Buildings* 62 (0), 381–391.

Bucking, S., Zmeureanu, R., Athienitis, A., 2013. An information driven hybrid evolutionary algorithm for optimal design of a net zero energy house. *Solar Energy*, 1–36. In Press, Accepted Manuscript.

Candanedo, L., Athienitis, A., Candanedo, J., O'Brien, W., Chen, Y., 2010. Transient and Steady State Models for Open-Loop Air-Based BIPV/T Systems. *ASHRAE Transactions* 116 (1), 600–620.

Chen, Y., 2009. Modeling and design of a solar house with focus on a ventilated concrete slab with a building-integrated photovoltaic/thermal system. Master's thesis, Concordia University.

Chen, Y., Athienitis, A., Galal, K., 2010a. Modeling, design and thermal performance of a BIPV/T system thermally coupled with a ventilated concrete slab in a low energy solar house: Part 1, BIPV/T system and house energy concept. *Solar Energy* 84 (11), 1892–1907.

Chen, Y., Galal, K., Athienitis, A., 2010b. Modeling, design and thermal performance of a BIPV/T system thermally coupled with a ventilated concrete slab in a low energy solar house: Part 2, ventilated concrete slab. *Solar Energy* 84 (11), 1908 – 1919.

Christensen, C., Barker, G., Horowitz, S., 2004. A sequential search technique for identifying optimal building designs on the path to zero net energy. In: Proceedings of the Solar 2004. American Solar Energy Society.

CMHC, 2008. Canada Mortgage and Housing Corporation EQuilbrium Homepage. Retrieved July, 2013.
URL `http://www.cmhc-schl.gc.ca/en/co/maho/yohoyohe/heho/eqho/index.cfm`

Deb, K., 2001. *Multi-objective optimization using evolutionary algorithms*, 1st Edition. Wiley, New York, USA.

Deb, K., Pratap, A., Agarwal, S., Meyarivan, T., 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation* 6, 182–197.

Doiron, M., 2010. Whole-building energy analysis and lessons-learned for a near net-zero energy, passive solar house. Master's thesis, Concordia University.

Doiron, M., O'Brien, W., Athienitis, A., 2011. Energy performance, comfort, and lessons learned from a near net zero energy solar house. *ASHRAE Transactions* 117 (2), 1–12.

Doty, S., Turner, W. C., 2012. *Energy management handbook*. The Fairmont Press, Inc., 8th Edition.

EnergyPlus, 2011. DOE Building Technologies Homepage. Retrieved April, 2011.
URL `http://apps1.eere.energy.gov/buildings/energyplus/`

EU Parliament, 2010. Directive of the European Parliament and of the council on the energy performance of buildings (recast). Accessed Nov 2012.
URL `http://www.eceee.org/buildings/EPBD_Recast`

Hydro-Québec, 2010. Hydro-Québec: Annual Report 2010. Accessed January, 2013.
URL `http://www.hydroquebec.com/publications/en/annual_report`

IEA/ECBCS, 2013. IEA Task 40/ECBCS Annex 52 Homepage. Accessed March 2013.
URL `http://task40.iea-shc.org/`

IEEE, 2012. Power Systems of the Future: The Case for Energy Storage, Distributed Generation, and Microgrids.
URL http://smartgrid.ieee.org/images/features/smart_grid_survey.pdf

NRCan-OEE, 2009. Energy use data handbook. Accessed Nov 2012.
URL http://oee.nrcan.gc.ca/publications/statistics/handbook09/pdf/handbook09.pdf

O'Brien, W., 2011. Development of a solar house design methodology and its implementation into a design tool. Ph.D. dissertation, Concordia University.

OPA, 2013. Ontario power authority feed-in tariff program. Accessed January, 2013.
URL http://fit.powerauthority.on.ca/fit-program

Pike Research, 2012. Zero Energy Buildings: Global Market, Regulatory, and Technology Analysis for Energy Efficiency and Renewable Energy in Commercial and Residential Buildings.
URL www.pikeresearch.com/research/zero-energy-buildings

RSMeans, 2012. *RSMeans Electrical cost data*. RSMeans Company, Kingston, MA.
URL http://www.rsmeans.com

RSMeans, 2013. RSMeans building construction cost data. Retrieved April 2013.
URL http://www.rsmeans.com

Sadineni, S. B., Atallah, F., Boehm, R. F., 2012. Impact of roof integrated pv orientation on the residential electricity peak demand. *Applied Energy* 92 (0), 204–210.

SNEBRN, 2013. NSERC Smart Net-zero Energy Buildings strategic Research Network Homepage. Retrieved March, 2013.
URL http://www.solarbuildings.ca

Toronto Hydro, 2011. 2011 Annual Report.
URL http://www.torontohydro.com/sites/corporate/InvestorRelations/FinancialReports/Documents/FinancialReports/2011Interactive/pdf/2011AR.pdf