Design Methodology Embodying the Energy and Economic Performance of Solar Houses

Abstract

The process for efficiently designing solar houses (a.k.a. low energy houses, in some cases net-zero energy houses) has significantly advanced with the development of early-stage (conceptual) design tools. Ecos is a conceptual energy modelling tool for solar houses that deploys the EnergyPlus computational engine. The functionality of Ecos was defined as a result of a survey of the suitability of existing tools to perform conceptual design for low energy houses, wherein it was determined that two major weaknesses were: 1) they lacked the ability to accurately model many passive and active solar features; and 2) they targeted detailed design that required over-specification of house features. In Ecos, only the variables that have a significant impact on energy performance need to be considered by the user, allowing for some other variables users like to have control over even if their interactions are not very significant. This software enables a large number of inter-dependent performance variables to be combined and arranged to achieve a desired net energy use target. However, the design software is not yet capable of assisting the user to identify the most cost effective among a large number of alternative with similar levels of energy and comfort performance.

This paper presents a general methodology for considering energy and economic performance at the early design stage, and then goes on to demonstrate how it can be applied within a specific context. In this example, an archetype house representing the typical characteristics of new houses built in Ontario is selected as the reference house for comparative assessments. It embodies energy conservation measures that reflect the prescriptive requirements of the Ontario Building Code in terms of building envelope components and HVAC system equipment. A life cycle cost over a 25-year study period, corresponding to a normative amortization period, can be calculated for this reference house using the Modified Uniform Present Worth measure that accounts for the discount rate and the energy escalation rate. Only its life cycle energy costs are considered because as the Code minimum, it is assumed to have a capital cost of zero in relation to alternatives with upgraded energy conservation measures. Greenhouse gas emissions may also be assessed as these have economic implications, albeit unresolved at present in Ontario. By combining energy and economic analyses at the schematic design stage, it is possible to identify a combination of energy conservation/generation measures that deliver a cost effective solar house-as-a-system.

1 Introduction

Schematic design of buildings is usually performed by architects and involves a large number of variables that are difficult to reconcile because of the often overwhelming number of plausible/feasible possibilities. For relatively simple buildings like houses, the design problem is technically less complex, although the clients' intimate relationship to the house they are planning to inhabit can render the design process quite challenging.

From the perspective of the energy modeller (and energy modelling tool developer) it is important to appreciate where in the design process the early stage or schematic design will occur and how it is related to the overall house design problem. The primary purpose of energy modelling at the schematic design stage is to accurately predict the energy and economic performance of a combination of physical attributes that may be varied within a set of constraints determined between the buyer and designer/builder. This predictive modelling output data is input to the schematic design decision-making process to identify opportunities, avoid conflicting relationships (incompatibilities) and assess important factors, such as affordability. In view of these relationships, the focus of this paper is on establishing a methodology whereby an early stage energy modelling tool in conjunction with selected cost-benefit measures can inform the design of houses in order to take the fullest possible advantage of solar energy contributions.

The specific example demonstrated in this paper looks at the new house market in Toronto, Ontario, Canada after the enhanced requirements for energy efficiency measures in new houses come into effect as of January 1, 2012 under the Ontario Building Code.[1] The methodology and techniques, identified generally in this paper, are specifically applied to determining suitable energy conservation/generation measures for new housing in Toronto. The energy modelling and cost-benefit analysis are deployed to answer the following commonly asked questions:

- Is it cost-effective[2] to optimize/maximize the passive solar efficiency of a typical new home, or are the required efficiency levels now so high the benefit is marginal?
- Is it cost effective to invest in solar water heating (SWH) technology in an area that is supplied with relatively low cost natural gas?
- Is it cost effective to invest in a photovoltaic panel electrical energy generation (PV) system and take advantage of a feed-in-tariff program?
- For these two renewable energy technology measures, can their installation be deferred to improve housing affordability[3], and still be cost effective? (Assumes solar-ready house with deferred installation costs similar to those for a new home under construction.)

These questions represent a consumer perspective on investments in solar buildings technology, but could also be considered by energy utilities and government agencies seeking to develop appropriate incentives for reductions in energy demand and greenhouse gas emissions.

It is interesting to note that the issue of how policies can influence housing affordability has been studied in the past (Miron, 1984). Today, the issue of willingness to pay contradicts the various affordability measures, particularly as these apply to investments in energy efficiency upgrades. The building industry continues to lobby the government to lower or maintain current levels of energy efficiency required under building codes because enhanced measures adversely impact housing affordability. At the same time, upgrades to kitchens and bathrooms, which do not have any economic payback or return on investment because there are no corresponding energy savings, continue to be promoted to new homebuyers. The willingness to pay for aspects of a building which are not visible (e.g., thermal insulation) is often more of an obstacle to voluntary improvements in energy efficiency than affordability.

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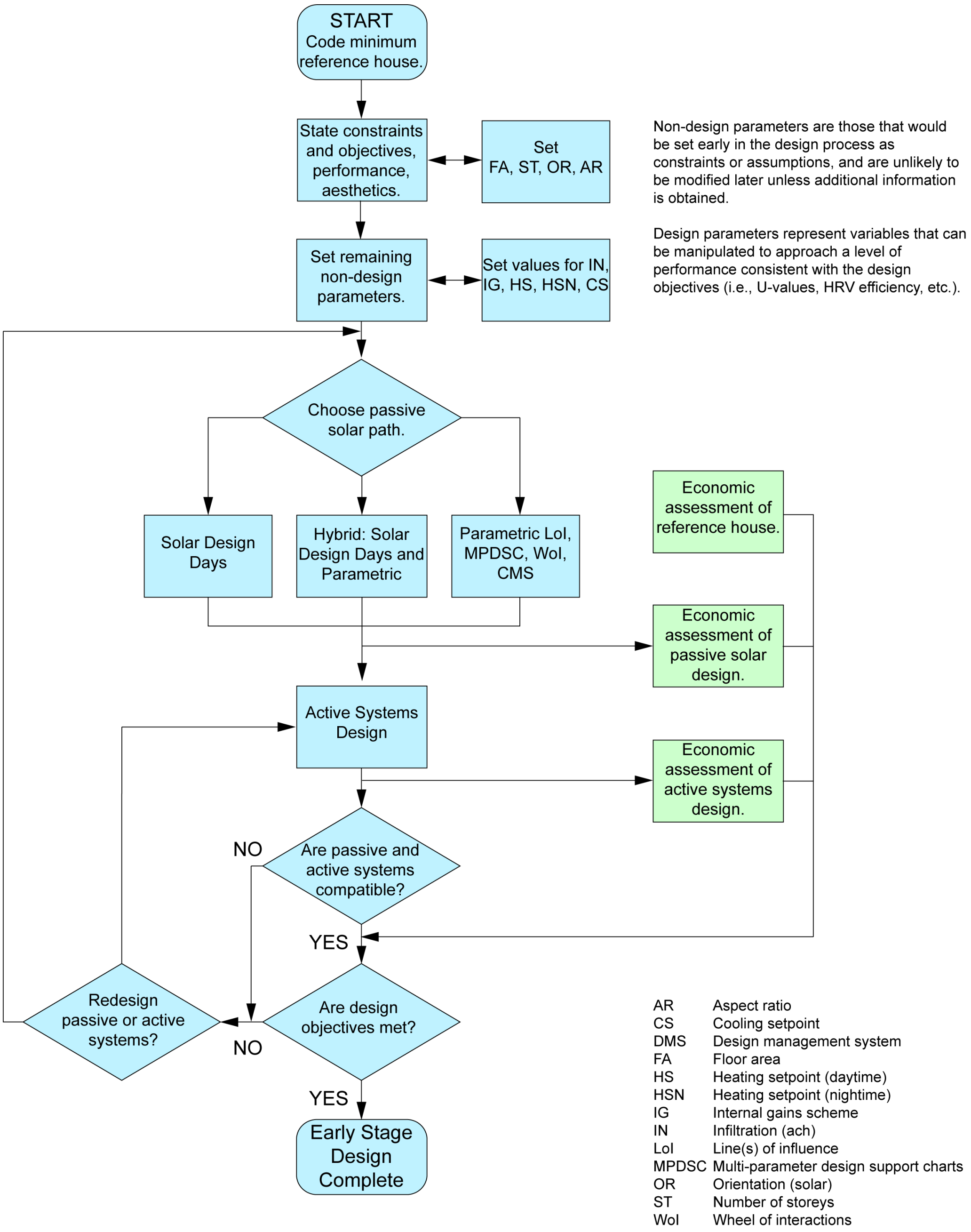
[1] Under the 2006 Ontario Building Code, effective January 1, 2012, homes are required to meet the performance level that is equal to a rating of 80 or more, when evaluated in accordance with Natural Resource Canada's EnergGuide for New Houses: Administrative and Technical Procedures. This level of energy efficiency roughly corresponds to the R-2000 house standard.

[2] Cost effective may be defined as: giving the most profit or advantage for the amount of money that is spent; and/or the extent to which an activity is thought to be as valuable as it is expensive.

[3] Traditionally, it was deemed the cost of adequate shelter should not exceed 30% of household income. Housing which cost less than this was considered affordable. However, consumers, housing providers, financial institutions and advocacy organizations tend to use numerous definitions of housing affordability. Refer to: Hulchanski, J. David, October 1995. *The concept of housing affordability: Six contemporary uses of the housing expenditure-to-income ratio*. Housing Studies; Oct 95, Vol. 10, Issue 4, p 471.

2 General Methodology

This general methodology is premised on the notion that an energy modeller is capable of predicting energy and economic performance measures within a reasonable degree of accuracy, assuming suitable tools. Analysis would include estimating the greenhouse gas emissions associated with a particular house design. Information obtained from this process forms part of a larger decision-making process for housing design that includes factors such as style, size, layout, location, etc. The methodology presented in this paper is not intended to optimize the house design, in and of itself, although the information generated could be used with other data for this purpose. Instead, the methodology depicted in Figure 1 is geared toward the integrated design process where the energy modeller has the potential to make a significant contribution to the efficiency of the design at the early design stage.



Non-design parameters are those that would be set early in the design process as constraints or assumptions, and are unlikely to be modified later unless additional information is obtained.

Design parameters represent variables that can be manipulated to approach a level of performance consistent with the design objectives (i.e., U-values, HRV efficiency, etc.).

AR	Aspect ratio
CS	Cooling setpoint
DMS	Design management system
FA	Floor area
HS	Heating setpoint (daytime)
HSN	Heating setpoint (nightime)
IG	Internal gains scheme
IN	Infiltration (ach)
LoI	Line(s) of influence
MPDSC	Multi-parameter design support charts
OR	Orientation (solar)
ST	Number of storeys
WoI	Wheel of interactions

Figure 1. General methodology for the assessment of energy and economic performance.

The first step in the application of the general methodology is to establish constraints and objectives. In this paper, a typical new house for the Ontario market sets the physical constraints. It is based on an archetype house developed for a study of housing energy efficiency in Ontario (Lio, 2010). Physical characteristics of the archetype house are depicted in Figure 2, and the thermal and efficiency attributes are summarized in Table 1. The objective is to cost effectively maximize/optimize the passive solar efficiency of the house, allowing solar orientation, building aspect ratios, envelope components and HVAC equipment to be manipulated along with the deployment of shading devices, thermal mass and air circulation to control overheating. The gross floor area remains constant throughout this process, and the passive solar design must deliver *comparable* comfort to the reference house (i.e., *zone temperatures cannot exceed the maximum values in the reference house*). For the example in this paper, the *solar design days* method in Ecos[4] was used to maximize the passive solar gains (O'Brien et al., 2008, 2009b).

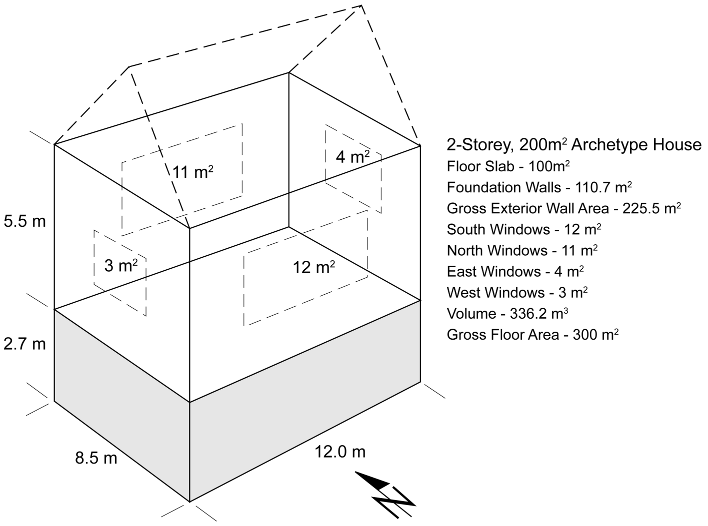


Figure 2. Physical characteristics of archetype new Ontario (reference) house.

Table 1. Thermal and efficiency attributes of building envelope components and HVAC equipment used to model reference house.

Component	**RSI**	**R-Value**
Ceiling with Attic Space	8.81	50
Ceiling Without Attic Space	5.46	31
Exposed Floor	5.46	31
Walls Above Grade	3.87	22
Basement Walls	2.11	12
Below Grade Slab	-	-
Heated Slab	1.76	10
	USI	**U-value**
Windows and Sliding Glass Doors	1.8	0.32
Skylights	2.8	0.49
Space Heating Equipment (min. AFUE)	94%	
HRV (min. Efficiency)	60%	
Domestic How Water (min. EF)	0.67	
Excerpted from: Compliance Package J, Table 2.1.1.2.A, Supplementary Standard SB-12, 2006 Ontario Building Code.		

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[4] Ecos is an early stage (conceptual) energy modelling tool for solar houses that deploys the EnergyPlus computational engine. The program enables a rapid modelling of energy performance that accounts for passive solar gains, internal gains, active photovoltaic system electrical energy generation and solar water heating systems. It dynamically models internal zone temperatures to represent thermal comfort conditions and enables variable air circulation rates and shading devices to control solar gains.

Subsequently, an economic assessment of this passive solar house design may be performed. The general methodology does not specify the economic measures to be deployed as these are at the discretion of the modeller. In this example, the net present value using the Modified Uniform Present Worth measure over a-25 year period is determined for two discount and energy price escalation rate scenarios (ASTM, 2007). Annual greenhouse gas emissions have also been estimated based on recent published emission factors (Kikuchi et. al., 2009).

With the passive elements of the house resolved, design of the active systems may proceed. Active systems include HVAC equipment as well as renewable energy systems. In this example, two active solar energy technologies are considered: 1) solar water heating (SWH); and 2) photovoltaic electricity generation (PV). Other active systems such as ground source heat pumps, bio-fuel space and domestic water heating system, and wind power generation could also be modeled and assessed. These were not considered in this paper because it focuses on maintaining a highly conventional HVAC system for all variations of house designs in order to examine the feasibility of passive and active solar technologies within the context of conventional market housing.

A standard, off-the-shelf SWH system is modeled using Ecos and afterwards the performance of a 2-kW peak, grid-tied PV system is simulated using the methodology described in O'Brien et al. (2009b). The cost and performance data are input to the economic assessment process taking into account prevailing Feed-In Tariff (FIT) rates for the PV system. A special economic model is also developed to assess a deferral of solar energy technology installation. For both reasons of initial affordability, as well as the natural efficiency improvements coupled with price deflation for active solar energy technologies, the impact of deferring installation until later is also economically assessed. The economic assessments are performed separately for SWH and PV systems, and later combined for both the initial installation and the deferred installation scenarios. Finally, passive and active solar system combinations are assessed. The attributes of the energy conservation/generation measures are presented in Table 3.

Modified Uniform Present Worth

$$P = A_o \cdot \left(\frac{1+e}{i-e}\right) \cdot \left[1 - \left(\frac{1+e}{1+i}\right)^N\right]$$

Uniform Present Worth

$$P = A \cdot \left(\frac{(1+i)^N - 1}{i\,(1+i)^N}\right)$$

where:

P = present sum of money.

A = end-of-period payment (or receipt) in a uniform series of payments (or receipts) over N periods at i interest or discount rate.

A_o = initial value of a periodic payment (receipt) evaluated at the beginning of the study period.

N = number of interest or discount periods.

i = interest or discount rate.

e = price escalation rate per period.

Figure 2. The Modified Uniform Present Worth measure is able to account for differences between the discount (interest) rate and the energy price escalation rate. All other cost-benefit assessments employed standard time value of money equations.

Table 2. Assumptions/data/factors for energy and economic assessments.

Study Period (years)	**25**			
Economic Scenario	*Current*	*High*		
Discount Rate	**3%**	**4%**	#,%,$	Data/assumptions input by user.
Energy Escalation Rate	**5%**	**8%**	#,%,$	Data from energy analysis.
R.E. Technology Deflation Rate	**5%**	**8%**	#,%,$	Indicates derived values.
R.E. Technology Efficiency Gain Rate	**2%**	**3%**	Floor Area (m^2)	300
R.E. - renewable energy				
Unit Cost of Carbon Fuel ($/ekWh)	$0.039	Cost of SWH System		$4,500
Unit Cost of Electricity ($/kWh)	$0.105	Cost of PV System (2 kW peak)		$10,000
Electricity Feed-In Tariff ($/kWh)*	$0.802	FIT Length of Contract - Years		20
Greenhouse Gas Emission Intensity Factors (kg CO_2e/kWh)				
Natural Gas	0.179			
Electricity (Ontario)	0.310			
Present Value of R.E. Technology with Deflating Price per $ of Current Cost				
Net Deflation Rate	**-2%**	**-4%**		
Deferred Purchase Period (years)	**7**	**7**		
FV Factor	**0.87**	**0.75**		
PV Factor	**0.71**	**0.61**		
Increase in Efficiency of R.E. Technology During Deferral Period				
Efficiency Factor	**1.149**	**1.230**		
Present Value of Energy Savings per Current $ of Annual Savings				
MUPV Factor	**32.41**	**42.36**		
MUPV Factor (Deferral Period)	**7.57**	**8.16**		
MUPV Factor (Post-Deferral Period)**	**28.54**	**42.06**		
** (Includes efficiency gain and energy price escalation rates.)				
Present Value of FIT per Current $ of Annual Generation				
PV Factor (Term of FIT Contract)	**14.88**	**13.59**		
PV Factor (Deferred)	**8.65**	**7.59**		
*Ontario Power Authority, 2010. Feed-In Tariff Program. http://fit.powerauthority.on.ca/Storage/11160_FIT_Program_Overview_August_new_price_version_1.3.1_final_for_posting-oct_27.pdf				

Table 3. Energy conservation/generation measures considered for assessment.

Passive Solar	- thermal mass: 0.15 m concrete, south half of floor and partition wall - south window-to-wall ratio = 0.40 - aspect ratio (L/W) = 1.412
Passive Solar Plus	- ceiling RSI 10.58, R-60 - walls RSI 7.05, R-40 - basement walls RSI 3.52, R-20 - slab RSI 1.78, R-10 - windows, triple, low-e, argon USI = 1.25, R-4.54, SHGC = 0.45
Solar Water Heating System	2 - $2.8m^2$ flat plate panel collectors with 400 L tank
PV System	2 kWp amorphous silicone, grid tied inverter, meter

Table 4. Summary of energy and economic analyses.

	OBC	Passive Solar	Passive Solar +	SWH	PV	SWH Deferred	PV Deferred	SWH + PV	SWH+PV Deferred	SWH+PV + Passive Solar	SWH+PV + Passive Solar +
Performance Parameter	1	2	3	4	5	6	7	8	9	10	11
Annual Space Heating (ekWh)	20,234	18,012	14,468	20,234	20,234	20,234	20,234	20,234	20,234	18,012	14,468
Annual Space Heating Cost	$793	$706	$567	$793	$793	$793	$793	$793	$793	$706	$567
Annual DWH (ekWh)	5,301	5,301	5,301	5,301	5,301	5,301	5,301	5,301	5,301	5,301	5,301
Annual DWH Cost	$208	$208	$208	$208	$208	$208	$208	$208	$208	$208	$208
Annual Electricity (kWh)	9,300	9,300	9,300	9,300	9,300	9,300	9,300	9,300	9,300	9,300	9,300
Annual Electricity Cost	$974	$974	$974	$974	$974	$974	$974	$974	$974	$974	$974
Annual Solar Thermal (ekWh)	0	0	0	1767	0	1767	0	1767	1767	1767	1767
Annual Solar Thermal Savings	$0	$0	$0	$69	$0	$69	$0	$69	$69	$69	$69
Annual PV Generation (kWh)	0	0	0	0	2461	0	2461	2461	2461	2461	2461
Annual PV Revenues	$0	$0	$0	$0	$1,974	$0	$1,974	$1,974	$1,974	$1,974	$1,974
Net Present Value (Current)	$63,976	$61,155	$56,656	$66,232	$44,612	$65,177	$53,967	$46,868	$55,168	$44,048	$39,548
Life Cycle Savings (Current)	$0	$2,821	$7,320	-$2,257	$19,364	-$1,201	$10,008	$17,107	$8,807	$19,928	$24,427
Net Present Value (High)	$83,620	$79,933	$74,052	$85,188	$66,797	$83,458	$74,753	$68,364	$74,591	$64,677	$58,797
Life Cycle Savings (High)	$0	$3,687	$9,568	-$1,568	$16,824	$162	$8,867	$15,256	$9,029	$18,943	$24,823
Annual Solar Heat Gains (kWh)	5,404	7,586	7,939	-	-	-	-	-	-	7,586	7,939
Solar Fraction (by end use)	21.1%	29.6%	35.4%	33.3%	26.5%	-	-	29.0%	-	29.4%	32.9%
Site EUI (ekWh/m^2.year)	116.1	108.7	96.9	110.2	107.9	110.2	107.9	102.0	102.0	94.6	82.8
Annual GHG Emissions (kg)	7,464	7,065	6,430	7,147	6,701	7,147	6,701	6,384	6,384	5,985	5,350

LEGEND

1. Reference - OBC typical new house (MMAH archetype)	7. Reference house with PV system installation deferred.
2. Optimized/maximized passive solar house.	8.Reference house with SWH and PV system.
3. Passive solar house with enhanced building envelope.	9. Reference house with SWH and PV system installations deferred.
4. Reference house with solar water heating.	10. Passive solar house with SWH and PV systems installed.
5. Reference house with 2-kW peak PV.	11. Enhanced passive solar house with SWH and PV systems installed.
6. Reference house with SWH system installation deferred.	#,%,$ Data from energy analysis. #,%,$ Indicates derived values. (Also see Table 2.)

3 Analysis of Results

Results of the analysis are presented in Table 4. For each house variation, the annual space heating, domestic water heating, and electrical energy consumption and corresponding costs are shown. These are followed by the renewable energy generation (solar thermal and PV) indicating the value of savings in the case of solar water heating, and the FIT revenues in the case of the grid-tied PV system. Then, the life cycle cost and savings relative to the reference OBC house are shown for the current and high energy price escalation rate scenarios. Solar fraction, is defined as the fraction of energy needs for a particular end use that are met by solar energy. Site energy use intensity is calculated by summing the annual purchased energy less the renewable energy contribution and dividing by the total conditioned floor area. Annual greenhouse gas emissions were calculated by applying the emission factors to the type and quantity of annual energy consumption - renewable energy generation was credited against the purchased energy where applicable.

Life cycle savings (positive numbers) indicate that under the current energy price escalation scenario, the passive solar maximized house is as cost effective as the OBC reference house if the passive solar features can be obtained for $2,821 or less ($3,687 or less under the high energy price escalation scenario). As this would simply involve solar-orienting the house, re-arranging the location of the existing windows to the southern exposure, and adding thermal mass to the direct gain zones, it appears for little to no cost a 10% decrease in space heating energy consumption is achievable. The actual cost premium could be determined by modifying the reference house design and costing the labour and materials. At the schematic design stage, the purpose of energy/economic modelling is to identify feasible energy conservation measures, not to engage in detailed analyses.

Upgrading to an enhanced passive solar with higher levels of thermal insulation and triple glazed windows results in between $7,320 and $9,568 in life cycle savings, depending on the energy price escalation rate scenario. In this case, the additional cost of insulation and high performance windows would have to be priced to see if an upgrade can cost effectively fall within this range. If it does not, then the prospective buyer would have to assess whether or not the superior passive survivability of the house was worth the additional investment.

Since the performance of the active solar technologies and the building are not interrelated, solar water heating and photovoltaic electrical energy generation can be considered separately. In the case of solar water heating, the cost savings are negative, meaning that the investment in this measure is not recovered within the 25-year study period. The relatively high cost of the SWH system and the low cost of natural gas contribute to this relationship. By manipulating the escalation rate for energy, it is estimated a full 7% difference between the discount rate and the energy price escalation rate over the entire 25-year study period would be necessary to breakeven on this investment.

A grid-tied, photovoltaic panel electrical generation system that takes advantage of the current feed-in-tariff program in Ontario delivers impressive life cycle savings ($19,364 for the current energy price escalation rate scenario, $16,824 for the high scenario). The present value of a series of annual payments decreases as discount rates increase.

Common to both active solar system investments is their impact on affordability. While the life cycle savings over 25-year are difficult to predict accurately, it is a fair certainty that the capital cost of these energy conservation measures will reduce the amount of house the typical prospective homebuyer can afford. Is an additional $4,500 or $10,000 premium affordable? If the investment results in savings that cover the additional amount paid on the mortgage, then there is no impact on affordability, as is the case with the PV system. But for the SWH system, the savings do not carry the additional $4,500 of principal owing on the mortgage. Would this disqualify a new homebuyer? The monthly premium for an additional $4,500 is $18 a month on a 25-year mortgage at 4% - this requires a $55 higher per month income. It is doubtful that given today's new home prices in the Greater Toronto Area, a $4,500 energy conservation premium would adversely impact affordability. In general, the volatility of mortgage interest rates is of far greater concern.[5]

Assuming that affordability is a concern of the new homebuyer, is it feasible to defer the installation of active solar technologies? This depends on several factors. Two are related and involve the deflation rate in the cost of a technology, often coupled to an increase in its operating efficiency. Typically, prices for novel technologies slowly fall and their efficiency gradually improves. In the example presented in this paper, two annual technology price deflation rates are set, along with two efficiency gain rates. Given the economic parameters set out in this example, the cost of the active solar technology is predicted to fall between 29% and 39% over a 7-year deferral period. During this time, the efficiency will improve between 14.9% to 23.0%. Assuming the current scenario, a contemporary PV panel with 14% efficiency is estimated to deliver 16.1% efficiency 7 years from now at 71% of today's price. When technological innovation is factored into the cost-benefit analysis, it is cost effective to defer the SWH system under the high energy price escalation rate scenario. In the case of the PV system, it realizes life cycle savings between $10,008 and $8,867 even though installation has been deferred by 7 years and only 18 years of revenues are considered within the 25-year

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[5] The sensitivity of affordability to household income and mortgage interest rates can be explored at http://www.canadamortgage.com/calculators/affordability.cgi.

study period. If nothing else, this suggests it makes sense to build houses solar-ready (Ashuri et al., 2011) to enable the easy installation of active solar technologies in the future. In this way, new homebuyers can afford passively maximized/optimized housing today without sacrificing cost effective future investments in active solar technologies. The option of deferring envelope upgrades was not considered because of the relatively high cost implications of doing so after construction is completed, and the fact that technological innovation of envelopes is significantly slower than that for active solar systems.

When both active solar systems are installed, or deferred, the economic relationships remain fairly consistent with the individual cases. It may be concluded that the PV system with its revenue generating power subsidizes the solar water heating system such that together, the suite of active systems yield lifecycle savings. This is attributable to Ontario's feed-in-tariff program and without it the PV system would not recover its cost over the useful life of the technology.

Finally, the active solar technologies are combined with the passive solar house variations to assess their energy and economic performance. The passive solar house with solar water heating and PV system indicates life cycle savings with a present value ranging from $18,943 and $19,928. This combination is clearly more cost effective than the reference Ontario Building Code house, but the additional $14,500 outlay must be reconciled with affordability criteria - financial institutions must develop mortgage instruments that encourage investments in revenue generating renewable energy technologies. It is important to bear in mind that the life cycle cost assessed in this example includes the $14,500 investment. The savings indicate how much more money could be invested in the passive solar house to breakeven with the reference house.

Looking at the enhanced passive solar house, its life cycle savings range between $24,427 and $24,823. The convergence of the life cycle savings indicates that under all economic assumptions, this level of performance begins to approach the limits of cost effectiveness. Since the building envelope system enhancements were not assigned a cost premium, in the case of the enhanced passive solar house, these life cycle savings represent the upgrade allowance available for comparable cost effectiveness with the reference house. It is important to note that no incentives or rebates have been considered in this analysis.

The analyses also reveal important insights in regards to the solar energy utilization, the site energy use intensity, and annual greenhouse gas emissions. For the three building envelope options, passive solar heat gains range from 5,404 kWh to 7,939 kWh annually, as indicated in Table 4. The row below indicates the solar fraction by end-use (passive solar heating, SWH and PV systems). Unlike previous measures of solar fraction employed in software such as HOT2000, the approach taken here was to derive the solar fraction by taking the useful annual solar heat gains and dividing them the sum of the annual space heating energy and useful solar heat gains (i.e., 5,404/(20,234 + 5,404) = 21.1%). The previous convention was to express the solar fraction for space heating as the useful solar gains divided by the purchased energy to provide a convenient means of estimating the annual cost savings. It is being proposed in this paper that a standardized means of calculating the passive solar heating fraction is needed for meaningful comparison of solar house performance. The enhanced passive solar house captured the most useful solar heat gains, 7,939 kWh and this resulted in the highest solar fraction for space heating at 35.4%. While passive solar heating delivers more efficient utilization of solar energy than photovoltaic panels, there is still a significant margin of improvement available to research and development efforts.

Solar water heating, as it is configured in this example, yields an end use solar fraction of 33.3%, while the PV system collects 26.5% of the estimated household electrical energy consumption. When these two active technologies are combined with passive solar heating measures, a combined solar fraction of 32.9% is attained by the enhanced passive solar house. It is important to note that strictly speaking, this is not the overall solar fraction for the house since the PV system energy generation does not necessarily coincide with the household demand for electrical energy. This raises important issues related to how the energy flow boundaries for houses are defined, and how this definition may be influenced by whether or not all of the renewable energy generation is useful to the grid.

Site energy use intensity ranges from 116.1 ekWh/m^2.year for the reference OBC house, down to 82.8 ekWh/m^2.year for the enhanced passive solar house with SWH and PV systems. Again, it should be noted the PV electrical energy generation was deducted from the annual household consumption to arrive at this EUI rating, fully acknowledging the time of use and the time of generation are unlikely to fully coincide.

The calculation of greenhouse gas emissions followed the procedure for site energy use intensity, admitting the same shortcoming for the assessment of electrical energy. In fact, it may be argued that the emission factors for greenhouse gases for new houses should consider marginal emission rates since it is the new buildings, and not the existing ones, that drive peak electrical power generation (Farhat and Ugursal, 2010). Based on the convention used in this paper, the enhanced passive solar house with SWH and PV systems emits about 2 tonnes/year less greenhouse gases than the reference OBC house. If the size of the PV array was expanded to the point of achieving net zero energy consumption, this house would still be emitting over 6 tonnes of greenhouse gases every year due to its natural gas utilization. There appears to be a need to better correlate site energy use intensity, net-zero energy performance and carbon footprint so that the effective impact of the energy conservation measures can be better discerned.

4 Discussion

A number of interesting questions arise about the FIT program and its potential to underwrite energy efficiency improvements in new housing. It also speaks to the synergies in solar houses that arise not from physical but economic policy relationships. Before appreciating the importance of policies supporting solar buildings, this discussion turns to more fundamental issues.

Is the solar house more affordable? Is it more energy resource efficient? Does it have a smaller carbon footprint? The enhanced passive solar house with SWH and PV systems is the most resource efficient in terms of its operating energy and has an annual carbon footprint that is just over 2 tonnes smaller than the reference OBC house (2,114 kg fewer GHG emissions, a 28.3% reduction). The solar utilization for passive space heating is 29.6%. Returning to the first question, it is likely most, if not all or slightly more, of the approximately $24,000 in life cycle savings would have to be invested at the time of construction, along with $14,500 for the SWH and PV system, a $38,500 premium. Assuming a 25-year amortization period at 4% interest, this would add about $202 to the monthly payment, versus the $189 per month in combined savings and FIT revenues. Under these assumptions, a solar house costs about $150 more per year than the reference OBC house, well within affordability tolerances. A similar relationship has been demonstrated for near net-zero energy production houses in New England (Uehno and Bergey, 2011).

Key to this affordability are the FIT revenues. While the performance of the PV system is entirely uncoupled from the building envelope and SWH system behaviour, it is critically coupled to the whole house system economically, and provides the necessary revenues to carry the difference in monthly mortgage payments needed to construct a properly integrated solar house. Ontario's FIT tariffs (OPA, 2011) were approximately correlated to the cost of developing conventional electrical generating plants and have not considered how the revenues could be directed towards achieving super efficient homes which also have the potential to reduce peak demand. In the example house design, doubling the PV system size would result in the house being more affordable than the OBC reference house since the additional revenue more than pays for the cost of the additional capacity.

Connected power and lighting distribution for equipment, appliances and lighting was not considered in the examples examined in this paper. Increasing electrical efficiency can further reduce the annual energy consumption. It results in a higher net contribution to the electricity grid while reducing peak electrical power demand. This aspect of low energy building design was not considered in this paper because it represents off-the-shelf technology that can be installed for the same cost as less efficient choices. For example, a higher recovery efficiency HRV or ERV could be selected over the 60% efficient unit assumed in the comparative examples, and a model with more efficient fan motors could be specified. This would reduce both electrical and space heating energy consumption.

The enhanced passive solar house also exhibits better passive sustainability. Climate change is expected to generate more frequent and extreme adverse weather events, possibly leading to increased electrical energy grid outages and disruptions. The thermally efficient envelope and internal thermal mass can sustain acceptable indoor temperatures for much longer than the reference OBC house, and it possible to divert PV-generated electricity from the grid to the house for periodic use of essential services.

Given this example, it is apparent that energy and economic analyses must be carried out in concert at the schematic or conceptual design stage so issues like the ones generated by the examples in this paper can be reasonably resolved to enable the properly integrated design of solar houses.

Several other issues are important to consider related to the time efficiency and accuracy of energy and economic assessments for early stage design. The total amount of time that can be afforded to this entire process cannot exceed several hours. This includes modelling the reference house, the various upgraded building envelope options and the renewable energy technologies, and then inputting the data into an economic assessment spreadsheet application. The Ecos software and a straightforward spreadsheet enabled the simulations and assessments presented in this paper to be carried out in less than half a working day - something that is feasible within a designer/builder office. It is important to appreciate the interpretation of the results and the performance of a thorough sensitivity analysis considering the critical variables influencing cost effectiveness would likely take as long, if not longer.

It is expected the accuracy of the results falls within +/- 10% of what would be obtained from a detailed energy model. This is all the accuracy that is required since it is a range that is seldom exceeded by the actual constructed building, due to imperfect materials and workmanship. A hypothesis that has not been tested is that the variable values, such as south-facing window-to-wall ratio, envelope thermal resistance levels, etc., would hold true over a variety of home designs similar to the reference OBC house. If this is true, than a finer grained early stage energy design tool may not necessarily yield more useful and reliable results. Extending this notion further, the methodology described in this paper may be able to develop schematic design recipes for typical solar house styles that deliver energy and economic performance that is near optimal for a given market and location. This would not eliminate the need for energy modelling, but would initiate the design process at a point that is closer to the optimum that a code minimum configuration. In this sense, the methodology advanced in this paper is generally applicable to a range of design decisions, ranging from the individual house to feed-in tariffs and energy efficiency policy for all new houses.

5 Conclusions

1. The methodology described in this paper, which is aimed at designing high performance solar buildings, is relatively straightforward, time efficient and effective.
2. Early design stage energy modelling tools combined with a simple spreadsheet can reveal critical energy and economic relationships that inform the conceptual design of solar buildings.
3. The same techniques are extensible to establishing cost effective energy conservation/generation measures in codes and standards governing new housing, as well as informing feed-in tariff rate schedules.
4. Current minimum requirements for energy efficiency in housing required by the Ontario Building Code are sub-optimal with respect to solar energy utilization. It is feasible, with presently available incentives and feed-in tariffs, to cost effectively deliver houses with significantly higher solar energy utilization and lower carbon footprints.
5. Solar ready measures are important to permit the deferral of active solar energy technologies in the event they exert a negative impact on affordability. The cost of installing conduit to interconnect zones of the building and facilitate the easy installation of tubing and wiring at a later date is minimal, but saves significant costs and disruption when the homeowner elects to install active solar technologies. It allows homebuyers to participate in the distributed energy generation industry when they can afford to do so without incurring easily avoidable economic penalties.
6. Passive sustainability is expected to become an increasingly important attribute of housing and it happens to be a fortunate by product of an enhanced solar house that is affordable, exerts a smaller carbon footprint and contributes to electrical energy generation (security).
7. Standardized conventions for measuring solar energy utilization in buildings are needed to meaningfully exchange performance metrics among the research community, and eventually, consumers.
8. There is a need to continue advancing early-stage design tools that quickly and accurately predict energy and economic performance. The deployment of more detailed design tools is better promoted by engaging the building design process at the beginning and demonstrating the power of performance simulation.

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