2013 Solar Decathlon: Technologies, Modelling Tools and Canadian Applications

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Abstract

The 2013 U.S. Department of Energy, Solar Decathlon (SD) competition gave post-secondary students the opportunity to design and build novel net-zero energy (NZE) houses. Energy system information was collected to find ways of designing more cost-effective NZE houses for Canadian climates. Information on the design tools, performance and affordability of the houses was also collected. The teams used a wide variety of drawing and energy modelling tools. The most prevalent technologies for heating, cooling and domestic hot water (DHW) systems included air source heat pumps (ASHPs) and solar thermal systems of various types. The most likely candidate for a Canadian cost-effective design is a SD house that has highly insulated walls, an ASHP and an instantaneous DHW system. This house performed adequately, was designed for a cold climate and had the lowest cost. However, finding the most cost-effective full scale NZE house for Canadian climates will likely require optimization.

1 Introduction

Residential buildings are responsible for 17% of the secondary energy use in Canada (NRCan 2012a), with most of this due to single detached houses. Net-zero energy (NZE) houses are houses that generate as much energy from renewable sources as they use on an annual basis. Production of more NZE houses in Canada would reduce the energy and GHG impact of the residential sector. This paper describes the NZE houses that competed in the 2013 Solar Decathlon (SD). It looks at the house energy systems from an energy and cost stand-point, especially focussing on technologies would be suitable for Canada. Because Solar Decathlon houses typically use technologies that may be commonplace in the 5 to 10 year horizon, they were used to assess the state of modelling and simulation for NZE houses. The potential of modelling tools and house systems for cost-effective Canadian NZE house design is discussed.

The Solar Decathlon competition

The Solar Decathlon (SD) competition was started by the United States Department of Energy (DOE) in 2002 to help promote energy efficient houses and their respective industry. The competition invites teams of post-secondary institutions to build and compete their NZE houses against other teams through ten different challenges (Lockheed 2012). Currently the 10 challenges in the SD are: 1) Architecture, 2) Market Appeal, 3) Engineering, 4) Communications, 5) Affordability, 6) Comfort Zone, 7) Hot Water, 8) Appliances, 9) Home Entertainment, and 10) Energy Balance (DOE 2013b). The first five competitions are juried, and the last five use measured performance.

The competition houses are designed to be NZE not only at the competition site, but also at the site where they will be located permanently (usually near their cities of origin) (DOE 2013b). The 2013 competition houses and their intended permanent locations are listed in Table 1, along with the ASHRAE climate zone at that location. Climate zones range from very hot climates (1) to subarctic climates (8). The letter corresponds to the type of environment: humid (A), dry (B) or marine (C). The competition site was the Orange County Great Park in Irvine, California, a climate zone 3B, which is warm and dry. More details on the definitions of climate zones are listed in ANSI/ASHRAE/IESNA Standard 90.1 Appendix B (2004). The letter indicator was not available for locations outside of the US.

Table 1: SD 2014 competitors and their intended destinations after the competition, climate zone data from ASHRAE (2004)

Lot Number	*Team Name and Universities*	*Intended Destination*	*Climate Zone*
101	Southern California Institute of Architecture and California Institute of Technology	Los Angeles, California	3B
102	Stevens Institute of Technology	San Marcos, California	3B
103	Czech Republic: Czech Technical University	Prague, Czech Republic	5*
104	Stanford University	Palo Alto, California	3C
105	Norwich University	Northfield, Vermont	6A
106	Team Texas: The University of Texas at El Paso and El Paso Community College	El Paso, Texas	3B
107	Missouri University of Science and Technology	Rolla, Missouri	4A
108**	Tidewater Virginia: Hampton University and Old Dominion University	Hampton, Virginia	4A
109	Team Austria: Vienna University of Technology	Vienna, Austria	5*
110	Middlebury College	Middlebury, Vermont	6A
111	University of Southern California	Los Angeles, California	3B
112	The University of North Carolina at Charlotte	Charlotte, North Carolina	3A
113	Kentucky/Indiana: University of Louisville, Ball State University and University of Kentucky	Louisville, Kentucky	4A
114	University of Nevada Las Vegas	Las Vegas, California	3B
115	Team Capitol DC: The Catholic University of America, George Washington University, and American University	Washington, District of Columbia	4A
116	Team Alberta: University of Calgary	Fort McMurray, Alberta	7
117	Arizona State University and The University of New Mexico	Phoenix, Arizona	2B
118	Santa Clara University	Santa Clara, California	3C
119	West Virginia University.	Morgantown, West Virginia	5A
120	Team Ontario: Queen's University, Carleton University and Algonquin College	Ottawa, Ontario	6

* The climate zones for Prague and Vienna are similar to the climate in Germany, which is an ASHRAE climate zone 5 (ASHRAE 2004; Kottek et al. 2006). ** Team Tidewater Virginia was not able to attend the competition, so there is less information available for this house.

Net-zero energy houses in Canada

The Canada Mortgage and Housing Corporation (CMHC) has engaged home builders to build NZE or near-NZE (NNZE) houses through an initiative called the EQuilibrium™ Sustainable Housing Initiative in 2008. The 12 NZE or NNZE houses from the EQuilibrium™ initiative (CMHC 2008) were significantly more expensive than typical houses. However some of the builders have continued their own research leading to more cost effective houses. For example Habitat Studio out of Edmonton, Alberta collaborated with Howell Mayhew Engineering to substantially reduce the incremental cost on subsequent NZE houses, while also reducing complexity by moving away from custom solar thermal systems (Howell 2010). Other builders have followed suit; however there is a lack of convergence in terms of heating energy management. Effect Home Builders recently built three NZE houses in Edmonton and each house has a different heating system: ground source heat pump (GSHP), air source heat pump (ASHP), and electric baseboards. Also, two of the houses have engineered wall systems, while the third has a blown-in cellulose wall construction (Effect Home Builders 2013). This lack of convergence is reflected in the 2013 SD houses.

More recently the CanmetENERGY through Natural Resources Canada (NRCan) initiated funding for NZE house research through the EcoEnergy Innovation Initiative (ecoEII) demonstration project: "Integrating Renewables and Conservation Measures in a Net-Zero Energy Low-Rise Residential Subdivision". This project involves five Canadian builders constructing NZE house communities. The initiative's focus is to increase accessibility of NZE houses for consumers (NRCan 2013a).

Current state of building modelling and optimization for NZE house

Building modelling tools are usually used in the design of NZE houses. However, some of the problems with building modelling tools are that they are very complex, yet at the same time, most tools are unable to model all building aspects (Hensen 2004). The most comprehensive tools (ESP-r, EnergyPlus, TRNSYS and DOE2) are the most complex and difficult to use, so they are usually used sparingly in industry, to check certain major design options or to certify buildings.

When designing the houses, different design options are modelled sequentially and compared. Usually a cost analysis is involved and the best of the modelled options is chosen. However, there are many interactions between the components of a house neglected by sequential modelling. For example, changing the amount of floor thermal mass affects the optimal south-facing window area. A multi-parameter optimization technique is capable of capitalizing on these interactions.

The two major tools that are used in building optimization are MATLAB and GenOpt (Attia et al. 2013). However another notable tool is BEopt, which was designed to find optimal pathways to NZE house designs. These tools can interface with the major modelling tools listed above. Unfortunately optimization tools are even more difficult to use, usually being much more complex. Optimization sometimes requires cost information as well for the component options. Getting cost information at the early stage of design can be difficult. Thus very little optimization work is done in industry at the moment.

Net-zero energy house energy and cost optimization

Our research group is working to improve the cost-effectiveness of NZE house designs so that they might one day be production built. This research involves building a database of NZE house energy systems and their prices. This database is used in conjunction with energy modelling software for running multi-parameter energy and cost optimizations. As part of this research it was decided that the SD may be a valuable resource for finding cost-effective energy systems to populate the database used in design optimizations. The SD may also help identify effective energy modelling and optimization tools.

Collecting Solar Decathlon house information

As part of the competition the teams are obligated to generate a number of documents and communication material about the house. These include the house manual, construction drawings, and the house website. At the competition, house tours are offered to spectators. In addition to these tours, interviews were conducted with competitors from each team. All these sources were used to build the descriptions of the houses.

2 The 2013 Solar Decathlon house designs

The SD houses had many different design aspects, more than can be presented concisely in this paper. This paper seeks to look at the systems related to the greatest energy use in Canada: heating (64%), appliances and lighting (19%), and DHW (17%) (NRCan 2012a). These figures shift for an example Canadian NZE home, the EQuilibrium™ EcoTerra™, but the order remains the same for these categories: heating (47.3%), appliances and lighting (38.5%), and DHW (14.2%) (Doiron et al. 2011). Attention is focussed on the major energy consumers and the areas where technologies are less established. This section describes what modelling tools were used to design the houses, what technologies were used in the houses, and how the houses performed in the energy and cost related portions of the SD competition.

Modelling tools used at the Solar Decathlon (Building modelling programs)

Many different drawing, energy modelling, and building information modelling (BIM) programs were used for the design of the SD houses. It is likely that all houses used at least one drawing program and energy modelling program; however more information was available from some teams than others.

The most popular programs (those that were mentioned by two or more teams) are listed in Table 2. It is interesting to note that the most frequently used programs provide whole house modelling, but only one program, BEopt, provides optimization. MATLAB and Excel are also listed, but were used for calculation and data visualization, not optimization or dynamic modelling.

Table 2: Building energy modelling programs and drawing software used by at least two SD teams

Modelling Tool	*101*	*102*	*103*	*104*	*105*	*106*	*107*	*108*	*109*	*110*	*111*	*112*	*113*	*114*	*115*	*116*	*117*	*118*	*119*	*120*	*Count*
Revit			✔	✔	✔						✔		✔	✔	✔	✔			✔	✔	10
EnergyPlus				✔						✔		✔	✔	✔	✔		✔		✔	✔	9
Excel				✔							✔		✔				✔			✔	5
TRNSYS									✔							✔	✔			✔	4
SketchUp				✔	✔										✔					✔	4
Vasari				✔							✔			✔	✔						4
DOE-2													✔		✔	✔	✔				4
MATLAB													✔				✔			✔	3
BEopt												✔	✔	✔							3
eQuest													✔			✔	✔				3
PVWatts													✔				✔			✔	3
THERM															✔	✔				✔	3
Climate Consultant				✔							✔	✔									3
System Advisor Model	✔			✔																	2
TRACE 700	✔														✔						2
Rhinoceros		✔													✔						2
Diva		✔													✔						2
Energy calculations			✔			✔															2
OpenStudio				✔											✔						2
Ecotect											✔				✔						2
ElumTools													✔			✔					2

Heating, Ventilation and Air Conditioning (HVAC) and Domestic Hot Water (DHW) systems

Heating ventilation and air conditioning (HVAC) systems and domestic hot water (DHW) systems can sometimes be intertwined, usually with the heating system providing both space heat and DHW. The combined heating/cooling/DHW choices are expressed as a letter code in Table 3 and 4. Table 4 shows how the systems are paired and how often the system combinations were observed. It can be seen in Table 4 that the heating/cooling/DHW systems are usually of two types: ASHP and/or solar thermal systems, however the way they are put together differs greatly from house to house. The combined systems that are built to provide heating and DHW are referred to as "combi-systems", either as ASHP combi-systems or more typically as solar thermal combi-systems. The combined ASHP and solar thermal combi-system are referred to as a solar thermal assisted heat pump (STAHP). Of the STAHP systems, two were custom systems from both the Canadian teams, houses 116 and 120; the rest of the STAHP systems came as packaged units from manufacturers. These systems all included a heat pump, an outdoor air heat exchanger, solar thermal panels, and provided heating, cooling and DHW.

Table 3: Designs of the 2013 SD houses

House	*Climate zone*	*Floor area m^2 (ft^2)*	*PV size kW*	*Heating, cooling and DHW type**	*Heat recovery*	*Insulation type***	*Wall R-value Km^2/W ($hrft^2°F/BTU$)*	*Window type*	*Appliances ****	*Lighting*	*Control and monitoring *****
101	3	55.7 (600)	6.0	D	ERV	1	4.1 (23)	2-L-Ai	2	LED	3
102	3	85.3 (918)	5.8	A	ERV	4	4.2 (24)	2-L-Ar	1	LED, CFL	3
103	5	40.0 (431)	6.1	H	HRV	3	5.3 (30)	2-L-Ar	1	LED, INC	3
104	3	92.9 (1000)	6.4	A	HRV	2	2.6 (15)	2-L-Ar	2	LED	3
105	6	72.5 (780)	5.8	C	HRV	3	9.0 (51)	3-L-Ar	2	LED	2
106	3	74.3 (800)	7.6	E	-	2	8.1 (46)	2-L-Ar-Vi	2	LED	1
107	4	91.0 (980)	10.5	F	ERV	2	5.6 (32)	3-L-Ar	2	LED, CFL	3
108	4	78.3 (843)	10.0	G	ERV	2	N/A	3-L-Ar-Vi	1	LED	2
109	5	58.5 (630)	8.6	B	ERV, DWHR	3	6.7 (38)	3-L-Ar	3	LED	3
110	6	88.8 (956)	6.2	C	ERV	3	9.3 (53)	3-L-Ar	2	LED	3
111	3	83.2 (896)	8.8	H	-	1	3.3 (19)	2-L-Ar-Al	2	LED, CFL	3
112	3	76.4 (822)	8.7	A	ERV	5	5.3 (30)	3-L-Ar	3	CFL	3
113	4	88.1 (948)	7.8	A	ERV	2	7.0 (40)	2-L-Ar-Fi	2	LED	1
114	3	69.7 (750)	6.8	G	ERV	4	5.3 (30)	2-L-Ar	2	LED	3
115	4	70.6 (760)	7.8	D	-	2	3.5 (20)	2-L-Ar	2	LED	2
116	7	83.6 (900)	10.0	H	HRV	4	7.0 (40)	3-L-Ar-Vi	1	LED	2
117	2	78.0 (840)	9.5	A	ERV	4	7.0 (40)	2-L-Ar-Al	2	LED	3
118	3	89.6 (964)	7.1	H	HRV	4	4.6 (26)	2-L-Ar	3	LED	3
119	5	87.3 (940)	9.9	D	-	2	6.2 (35)	3-L-Ar-Wo	2	LED, CFL, HAL	3
120	6	87.3 (940)	7.8	H	E/HRV	6	9.3 (53)	3-L-Ar-Al	3	LED	3

* Mechanical system identifiers A-H are listed in Table 4. ** Insulation type identifiers correspond to 1) batt, 2) SIP, 3) blown cellulose, 4) spray foam, 5) concrete sandwich panel, and 6) vacuum insulation panels. *** Appliance type identifiers correspond to 1) high efficiency, 2) energy star rated and 3) best in class. **** Control and monitoring identifiers correspond to 1) thermostatic control, 2) energy use monitoring, 3) application based lighting and appliance control.

Table 4: The heating, cooling and DHW options used on the SD houses. The letter code corresponds to that in Table 3, also shown is the number of times the system combination was observed. Note that combi-systems provide both heating and DWH.

Heating, cooling and DHW type	*Occurrences*	*Primary heating and cooling*	*Primary DHW*
A	5	ASHP	Interior air source HPWH
B	1	ASHP	Exterior air source HPWH
C	2	ASHP	Instantaneous electric
D	3	ASHP	Solar thermal
E	1	ASHP combi-system	
F	1	Solar thermal combi-system with backup AC	
G	2	Solar thermal combi-system with backup ASHP	
H	5	Solar thermal assisted heat pump combi-system	

In addition to heating and cooling systems, most houses have a ventilation heat recovery device, either an energy recovery ventilator (ERV) or a heat recovery ventilator (HRV). ERVs and HRVs perform a similar function but ERVs can work better or worse than HRVs depending on the climate because they transfer latent heat (NRCan 2012b).

Envelope and windows

The primary insulation types that the houses use are listed in Table 3. The houses that used batt insulation achieved minimal insulation levels; both cases (houses 101 and 111) had their intended location in southern California. Structural insulated panels (SIPs) were utilized in some houses and cellulose insulation was blown into thick wall sections in others houses. The cellulose used was mostly recycled newspaper but both the European teams (houses 103 and 109) used wood fibre. Some houses used spray foam as their primary insulation type. Additionally, two unique wall sections were observed. House 112 used a geopolymer cement sandwich panel, with two 10 cm (4") slabs of cement separated by a 10 cm (4") layer of rigid foam. House 120 used a complex system consisting of vacuum insulation panels, rigid foam and spray foam. The different types of insulation used in these houses came in various insulation levels.

The code given to each window design in Table 3 is made up of four codes separated by dashes. The number of panes of glass (2 or 3), if the glass is low-e or uncoated (L or U), if the gas fill is argon or air (Ar or Ai), and finally, the window frame type: aluminum, vinyl, fibreglass or wood (Al, Vi, Fi or Wo). Usually aluminum frames were thermally broken to reduce conductivity. Information on spacers or SHGC was not included because of limited information. Along with triple paned windows house 119 also had windows that were quadruple paned, but were of unknown construction.

Appliances, lighting and control

The type of appliances that were used in the houses fell into three categories: high efficiency, Energy Star rated and best in class (see Table 3). These represent a sliding scale of efficiency, but also cost. Many of the houses with Energy Star or Best in Class appliances had induction cooktops to reduce cooking load.

The SD houses mostly used light emitting diode (LED) lighting (shown in Table 3), while some used a combination of LED and compact fluorescent lighting (CFL), incandescent (INC) or halogen (HAL).

Many teams incorporated an advanced control and monitoring system in their houses, usually in a tablet based application. Other teams preferred to have energy monitoring systems, to show the energy generated and where energy was being consumed in the house. Some teams used typical thermostat controls since it would be easy for occupants to use and understand. The types of control strategies used are also listed in Table 3.

Competition results

Some results of the competition are shown in Figure 1 and Figure 2. All contests were out of 100 points; however the Affordability and Energy Balance contests were based on a single number so the number is shown on the figures as opposed to the score. In this way the data is more relevant. For instance, the houses were net-metered over the eight competition days. Since all houses generated more energy than they consumed during the competition, they all received an Energy Balance score of 100. Therefore more information can be gathered from knowing the net-metered energy of the house. Similarly, the costs for the Affordability contest (determined by a professional cost estimator) are shown instead of the Affordability score.

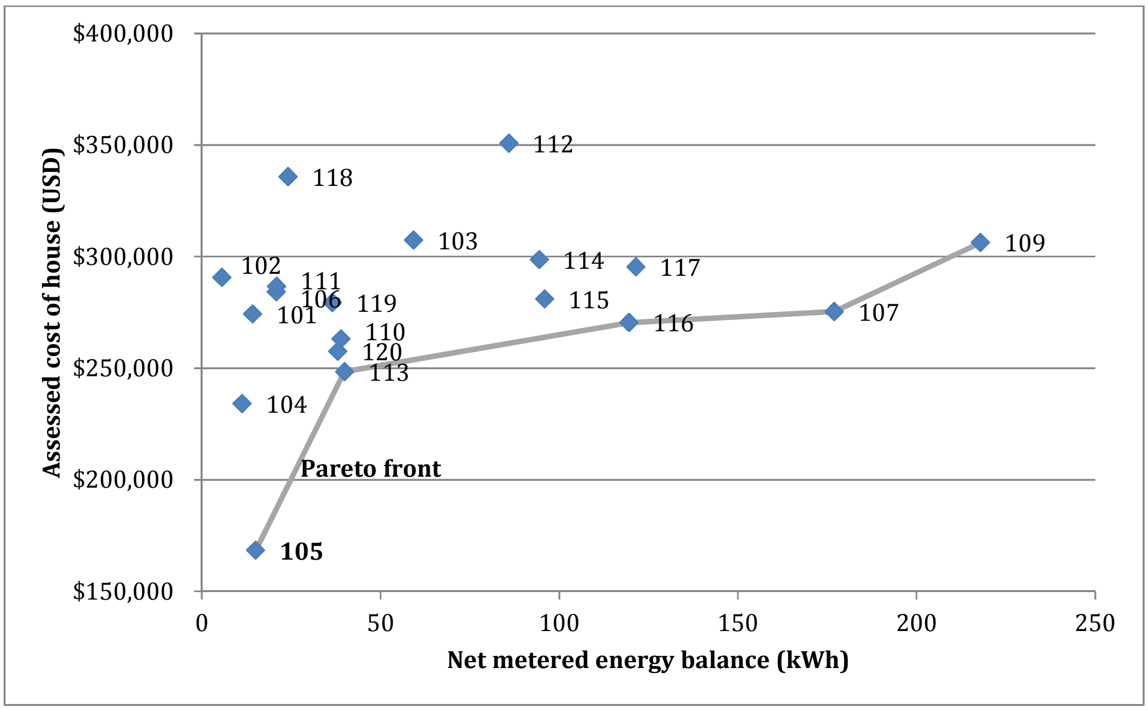

Figure 1: Plot of the assessed cost of the house (from the Affordability contest) versus the net-metered energy balance of the house. The houses that are on the Pareto front have the best performance for their cost.

The other contests had more complex scoring algorithms or were based on multiple factors. Contest 6, Comfort Zone, is based on keeping the air temperature between 22°C-24°C (71°F-76°F), and the relative humidity below 60%. Contest 7, Hot Water, is in based on delivering 57 litres (15 gallons) of water in 10 minutes 16 times during the competition. Contest 8, Appliances, is based on the performance of the major appliances. Contest 9, Home Entertainment is based on lighting, cooking, minor appliances, and some juried parties. The scores from contests 6 to 9 are summed to give an overall idea of the HVAC, DHW and appliance performance (see Figure 2). The other contests: 1) Architecture, 2) Market Appeal, 3) Engineering and 4) Communications do not involve energy or cost performance and are not used.

Figure 1 shows that the lowest cost NZE house is House 105. This house achieved NZE over the competition and also received reasonable scores in contests 6 to 9 (see Figure 2). It was also designed for a climate zone 6, which is a prominent climate zone in Canada. This makes this house design a good example of a possible cost-effective Canadian NZE house. The other designs on the Pareto fronts in Figure 1 and Figure 2 also performed well for their price. However the Solar Decathlon is a very different testing environment than experienced in practice.

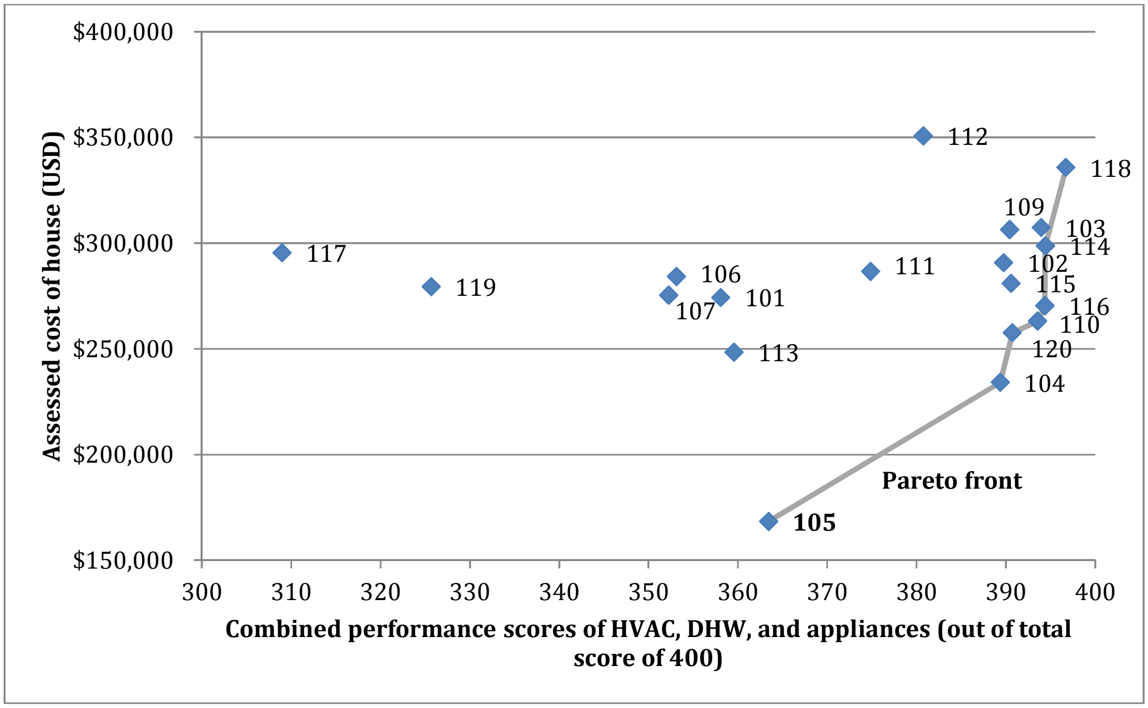

Figure 2: Plot of the assessed cost of the house (from Affordability contest) versus the combined score from contests 6, 7, 8 and 9, which reflects the performance of the HVAC, DHW, and appliances. The houses that are on the Pareto front have the best performance for their cost.

3 Discussion

The Solar Decathlon (SD) has many strengths and weaknesses. The following section describes how the designs encouraged by the SD may be less relevant for industry and what might possibly be improved. The section also describes which mechanical systems displayed at the SD are likely to be suitable for Canadian climates, and their relative cost and efficiency. Possible improvements in modelling and optimization tools and design strategies are discussed. Lastly, promising novel systems that were observed at the competition are listed.

Drawbacks of the Solar Decathlon competition

The SD successfully promotes NZE house research (Lockheed 2012); however, the conditions in which the houses compete are artificial, thus extrapolating the competition results requires care. The houses compete for eight days in one location, while to find which energy systems (mechanical and envelope) are the most efficient would require testing in the desired climate for at least a year. Inferring affordability of the energy system design is also difficult because of the many other systems and architectural features that go into the houses. Thus to correctly evaluate cost-effectiveness, the houses would have to be identical, except for the energy systems, to see the cost differences due to these systems. The competition also restricts the type of systems that can be used. No combustive systems are allowed, meaning any gas furnaces or water heaters are ineligible. The teams are not allowed to drill the ground at the competition site, so ground source heat pumps (GSHPs) are also ineligible (DOE 2013b). The houses are also significantly smaller than a typical new house in Canada. Typically SD houses are between 56 and 93 m^2 (600 and 1000 ft^2), whereas a typical new house in Canada is about 177 m^2 (1900 ft^2) (CHBA 2012). Finally, because the houses tend to be leading edge, the systems tend to be riskier and more expensive, which means they are less likely to be used by industry. The team of House 105 partnered with a modular home builder that is now producing their design. This partnership possibly gave the team the realism needed to make a cost-effective design. However, it is possible that other design strategies may also lead to cost-effective NZE houses.

A few options are available to make the SD more relevant to industry and to help designers make more informed choices. One would be to have a more aggressive cost function. The teams were able to get full affordability points for a house that was less than $250,000 however this does not reward teams like Team 105, who make significant steps to reduce costs. Another option would be to monitor the houses for a year after they are in their intended location to show the long term viability of designs. Thirdly the occupants of these houses could be asked to fill out surveys on the comfort and ease of use of the home to provide feedback on the mechanical system and user interface performance.

Opportunities for improved modelling and optimization for NZE house design

Traditionally, a straightforward but expensive approach to produce a NZE house was to have a large PV solar panel array to offset the energy use of a typical house. However, with the price of PV decreasing, this may not be as expensive as it seems (DOE 2012), although there still may be issues with adequate roof area. A second way is to have a very complex mechanical system that provides heating and hot water at minimal electrical demand, which reduces the size of the solar panel array. The third way is through the envelope; maximizing the insulation and minimizing floor area can make a house that only needs a small amount of heat, which can be met by electric resistance. This approach also has favourable comfort implications since well insulated walls and windows reduce radiative losses from occupants and draftiness in the winter. In this case the PV array is also kept to a reasonable size. Between these three dimensions (PV, mechanicals and envelope) there is a cost optimal design that depends on house location and system costs. The many options and no clear optimal design lead to a lack of convergence that can be seen in the SD and also in the NZE house industry. Currently, finding designs that are close to cost-optimal will require some type of optimization technique.

The current findings are similar to those reported elsewhere (Attia et al. 2012). It is common to use multiple tools to design a NZE house. Meanwhile the majority of these tools (listed in Table 2) are primarily targeted at detailed design and not at early stages of design when the greatest opportunity to influence design exists. The only early stage energy modelling tools in the list above are PVWatts and Climate Consultant. Tools such as EnergyPlus and TRNSYS typically take days to months to build a single model. Given the timeframe of Solar Decathlon and "real" design procedures, it is unlikely that the design team could use these tools to thoroughly evaluate multiple design alternatives.

The prevalent systems of the SD houses listed above include air-source heat pumps, some of which are solar assisted. Such systems (particularly if they include custom controls and short-term storage) are difficult or impossible to model in all but TRNSYS and possibly EnergyPlus. However it would be advantageous if early stage tools (e.g., HOT2000) includes such systems so that they can be properly evaluated. One possible solution would be to model the HVAC system separately and then apply the seasonal COP factors to an ideal air model of the home.

A good user interface on a modelling program also helps makes modelling quicker and easier. Revit, Vasari, eQuest and BEopt all provide an easier to use user interface. Problem specific programs like SketchUp, PVWatts, THERM, and Climate Consultant cannot do whole house energy modelling but can be used for component level decision making.

It can be seen from the list of popular software tools in Table 2 that the use of optimization tools is rare. BEopt is the only optimization tool mentioned and it was only used on three of the houses. BEopt employs a modified sequential search technique, which may have some disadvantages against the evolutionary algorithms found in MATLAB and GenOpt (Tuhus-Dubrow 2007). Also, the library of mechanical systems is large, but is still limited to more conventional systems. However, BEopt is an integrated tool that provides approximate cost data and is straightforward to use for early stage design. It is far simpler to run than MATLAB or GenOpt based optimization. Therefore it has the highest potential for being used by industry for early stage design, modelling and optimization.

Types of SD house mechanical systems that could be useful for Canadian application

Aside from optimization some known parameters about the systems can influence design decision making. HPWHs are an inexpensive way to decrease the DHW load (NRCan 2013b); however, in cold climates they are only beneficial when the heating system has a high coefficient of performance (COP), as with a cold climate ASHP. A combined ASHP that provides both heating and hot water may save some money over buying a separate ASHP and HPWH; however the efficiency might not increase very much. Solar thermal hot water systems also perform worse in colder climates because the discrepancy between the summer and winter performance increases, meaning the system will only provide a small fraction of the heat in the winter while providing near 100% in the summer. However they do have a higher COP equivalent than HPWHs (Aldrich & Vijayakumar 2006). Solar thermal systems that provide heat and hot water (without the help of an ASHP) have a reduced COP over solar thermal systems that just provide hot water, because the load is even higher in the winter time, when the system is at its worst performance. Yet the summertime load remains unchanged so the size of the system cannot be increased without adding a summertime heat rejection system. This option is not recommended for a cold climate. Solar thermal assisted heat pump (STAHP) systems are the next step up because they can provide greater efficiencies than heat pump systems by making use of heat from the sun, although the benefit depends on how the system is designed. STAHP systems are also the most expensive and complex, especially if they are custom designs. To summarize, the mechanical heating, cooling and DHW systems organized by increasing cost and efficiency for a cold climate NZE house would go in the order shown in Table 5.

Table 5: Order of system choices organized from lowest efficiency and lowest cost to highest efficiency and highest cost (type letter corresponds to those listed in Table 4)

Heating, cooling and DHW type	*Description*
C	ASHP heating with electric DHW
A/B/E	ASHP heating and ASHP DHW
D	ASHP heating and solar thermal DHW
H	STAHP systems

↓ Increasing efficiency and cost

This discussion is limited because it is based on the SD assumptions that GSHPs or combustive heating options are not available, and that PV is the only viable electricity generation method. Of these systems the one that would be most cost-effective for a project depends on the price to upgrade the envelope, and the price of PV.

Promising systems

It is stated above that the SD is leading edge and that makes the houses a bit less relevant for industry. However, the opposite side of that coin is that the SD can be a testing ground for novel systems. Here are some systems that may help future designers make more cost-effective or more-efficient NZE house designs.

- STAHP systems have the greatest efficiency. If these systems could be optimized and sold as packaged systems this could possibly drive their price down.
- Energy monitoring systems, which display energy usage to the occupant, have been shown to reduce electricity usage by about 9-12% on the systems that were monitored (Ehrhardt-Martinez et al. 2010).
- A possibly less expensive alternative to micro-inverters is called module energy management systems. These systems monitor the outputs of PV panels and shuts down poor performing panels so the rest can output more.
- DWHR systems can drastically reduce DHW loads. The shower pan heat exchanger system used in House 109 presents a good option for DWHR in places where conventional DWHR systems cannot go, such as on single floor houses, or in basements.
- Automated blinds in houses 120 and 115 allow for active control of the heat gain from the sun. If designed correctly these systems will move to the most thermally advantageous position when the house is unoccupied, but will move to the occupants' desired location when the occupants return.
- Geopolymer cement used in House 112 is stated to have a 90% lower carbon footprint than typical cements and could be used as an alternative for typical cements.
- House 113 had a novel way of dealing with the fact that HPWHs need lots of room to draw air from in order to be efficient. This house ducted the HPWH into the furnace meaning that the air of the whole house was used as a sink for the cold air put off by the HPWH. By doing this the HPWH needs less room and will work more efficiently.
- A clothes dryer heat recovery system was installed in House 118, similar to an HRV, allowing the heat from hot dryer exhaust to be recycled.

4 Conclusions

Out of all the SD competition houses, house 105 provides the most likely system options for creating a cost-effective NZE house in Canada. The house used thick cellulose insulation walls of R51, a simple mechanical system consisting of an ASHP and an instantaneous DHW heater, and a small 5.8 kW PV array. The house received a substantially lower cost rating than the other houses at the competition, likely because the team partnered with a modular home manufacturer.

These system options could be cost-effective if implemented in a typically sized Canadian house. However more cost-effective designs might exist since the SD design constraints, such as those on the HVAC system, would not be a factor for industry. Also, industry constraints, such as lot size, might affect the cost-effectiveness of designs in other ways. Therefore, some type of optimization method used in the design process would be helpful for finding cost-effective designs.

The more modelling and optimization can be done throughout the design process, but especially at the conceptual phase, the more the house will be energy efficient and cost effective. There are a number of issues that prevent early stage modelling and optimization of NZE houses; the most prominent issue being that most tools are too complex and time consuming to use. However, BEopt, the only optimization tool used at the competition, is likely straightforward enough to be used by industry for early stage cost optimization of NZE houses.

The competition also demonstrated some novel technologies that may make future NZE houses more efficient or cost-effective. These include: solar thermal assisted heat pumps, energy monitoring systems, PV module energy management systems, shower pan heat exchangers, automated blinds, geopolymer cement, HPWH connections to HVAC ducting, and clothes dryer heat recovery.

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6 References

101 SCI-Arc/Caltech Solar Decathlon Team, 2013. *Communications package and interview*, Southern California Institute of Architecture and California Institute of Technology, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_sci_arc_caltech.html>.

102 Stevens Solar Decathlon Team, 2013. *Communications package and interview*, Stevens Institute of Technology, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_stevens.html>.

103 Czech Republic Solar Decathlon Team, 2013. *Communications package and interview*, Czech Republic: Czech Technical University, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_czech_republic.html>.

104 Stanford Solar Decathlon Team, 2013. *Communications package and interview*, Stanford University, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_stanford.html>.

105 Norwich Solar Decathlon Team, 2013. *Communications package and interview*, Norwich University, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_norwich.html>.

106 Team Texas Solar Decathlon, 2013. *Communications package and interview*, The University of Texas at El Paso and El Paso Community College, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_texas.html>.

107 Missouri S&T Solar Decathlon Team, 2013. *Communications package and interview*, Missouri University of Science and Technology, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_missouri.html>.

108 Tidewater Virginia Solar Decathlon Team, 2013. *Communications package*, Tidewater Virginia: Hampton University and Old Dominion University, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_tidewater_virginia.html>.

109 Team Austria Solar Decathlon, 2013. *Communications package and interview*, Vienna University of Technology, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_austria.html>.

110 Middlebury College Solar Decathlon Team, 2013. *Communications package and interview*, Middlebury College, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_middlebury.html>.

111 U of So Cal Solar Decathlon Team, 2013. *Communications package and interview*, University of Southern California, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_southern_california.html>.

112 North Carolina Solar Decathlon Team, 2013. *Communications package and interview*, The University of North Carolina at Charlotte, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_north_carolina.html>.

113 Kentucky/Indiana Solar Decathlon Team, 2013. *Communications package and interview*, University of Louisville, Ball State University and University of Kentucky, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_kentucky_indiana.html>.

114 Las Vegas Solar Decathlon Team, 2013. *Communications package and interview*, University of Nevada Las Vegas, Irvine, California: US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_lasvegas.html>.

115 Team Capitol DC Solar Decathlon, 2013. *Communications package and interview*, The Catholic University of America, George Washington University, and American University, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_capitol_dc.html>.

116 Team Alberta Solar Decathlon, 2013. *Communications package and interview*, University of Calgary, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_alberta.html>.

117 AZ State/New Mexico Solar Decathlon Team, 2013. *Communications package and interview*, Arizona State University and The University of New Mexico, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_asu_unm.html>.

118 Santa Clara Solar Decathlon Team, 2013. *Communications package and interview*, Santa Clara University, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_santa_clara.html>.

119 West Virginia Solar Decathlon Team, 2013. *Communications package and interview*, West Virginia University, US DOE Solar Decathlon Competition, <http://www.solardecathlon.gov/team_west_virginia.html>.

120 Team Ontario Solar Decathlon, 2013. *Communications package and interview*, Queen's University, Carleton University, and Algonquin College, US DOE Solar Decathlon Competition. <http://www.solardecathlon.gov/team_ontario.html>.

Aldrich, R., & Vijayakumar , G., 2006. *Cost, Design, and Performance of Solar Hot Water in Cold-Climate Homes*, Denver, Colorado: Proceedings of the American Solar Energy Society Annual Conference.

ASHRAE, 2004. ANSI/ASHRAE/IESNA 90.1-2004, *Energy Standard for Buildings Except Low-Rise Residential Building*, Atlanta, Georgia: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Attia, S., Hamdy, M., O'Brien, W., & Carlucci, S., 2013. *Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design.* Energy and Buildings, 60, 110-124.

------, Gratia, E., De Herde, A., & Hensen, J. L., 2012. *Simulation-based decision support tool for early stages of zero-energy building design.* Energy and buildings, *49*, 2-15.

Canada Home Builders' Association (CHBA), 2012. *The 45th Pulse Survey*, Ottawa, Ontario.

Canada Mortgage and Housing Corporation (CMHC), 2008. *The EQuilibrium™ Sustainable Housing Demonstration Initiative*, Ottawa, Ontario, viewed Jan, 2014, <http://www.cmhc-schl.gc.ca/en/inpr/su/eqho/eqho_008.cfm>.Doiron, M., O'Brien, W., & Athienitis, A., 2011. *Energy Performance, Comfort, and Lessons Learned from a Near Net Zero Energy Solar House*, ASHRAE Transactions, 1–13.

Effect Home Builders, 2012. *Net zero energy home*, Edmonton, Alberta, viewed Jan, 2014, <http://www.effecthomes.ca/?section_name=net_zero_homes>.

Ehrhardt-Martinez, K., Donnelly, K.A., & Laitner, S., 2010. *Advanced metering initiatives and residential feedback programs: a meta-review for household electricity-saving opportunities*, Washington, DC: American Council for an Energy-Efficient Economy.

Hensen, J. L., 2004. *Towards more effective use of building performance simulation in design*. In Proc. 7th International Conference on Design & Decision Support Systems in Architecture and Urban Planning.

Howell, G., 2010. *Edmonton's netzero cold climate houses… what we've learned*, presentation, Northern Housing Forum 2010, Inuvik, North West Territories.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F., 2006. *World map of the Koppen-Geiger climate classification updated*, Meteorologische Zeitschrift,15(3), 259-264.

Lockheed Martin Energy Services (Lockheed), 2012. *Impact evaluation of the U.S. Department of Energy's Solar Decathlon program*, Washington, D.C.: U.S. Department of Energy.

Natural Resources Canada (NRCan), 2013a. *ecoENERGY INNOVATION INITIATIVE Demonstration Projects*, Office of Energy Efficiency, Ottawa, Ontario, viewed Jan, 2014, <http://www.nrcan.gc.ca/energy/funding/current-funding-programs/eii/4989>.

------2013b. *Net Zero Energy House Cost Data*, Database, CanmetEnergy, Ottawa, Ontario

------2012a. *Energy Efficiency Trends in Canada: 1990 to 2009*, Natural Resources Canada, Office of Energy Efficiency.

------2012b. *Heat recovery ventilators*, Energy Publications, Office of Energy Efficiency, Ottawa, Ontario.

Office of Energy Efficiency and Renewable Energy (EERE), 2013. *U.S. Department of Energy Solar Decathlon 2015 Funding Opportunity Announcement*, Washington, D.C.

Tuhus-Dubrow, D., 2007. *Assessing the suitability of genetic algorithms for application in building envelope optimization*, University of Colorado at Boulder.

U.S. Department of Energy (DOE), 2013a. *Scoring spreadsheet*, Database, Washington, D.C., viewed Jan, 2014, <http://www.solardecathlon.gov/past/2013/download/sd2013_scores_final.xlsm>.

------2013b. *Solar Decathlon rules*, Washington, D.C.

------2012. *Photovoltaic (PV) pricing trends: historical, recent and near term*, Office of Energy Efficiency, Washington, D.C.