THE ESSENCE OF LOW-ENERGY AFFORDABLE HOUSING DESIGN STRATEGIES
Learnt from Scottish and Canadian Homebuilders' Attempt and Experience

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ABSTRACT

Nearly one-third of the Scottish population is struggling to heat their home properly today. There is an urgent need for the delivery of low-energy affordable homes. However, the homebuilding industry has no systematic way to deliver such unconventional homes, although the UK government has set out a bold "green" target that all newly-built homes be carbon neutral by 2016. Accordingly, this paper explores the status quo of today's affordable homes being built in Scotland; and secondly, it extends the scope to the review of successfully commercialized low- to zero-energy affordable housing developments in Canada. This study emphasizes the significant impact of design choices on the delivery of low- to zero-energy affordable housing, including housing orientations and configurations; construction materials and systems, including renewable energy technologies; and internal planning, with due consideration to the time-related sun positions and the internal space day-lighting and heat gain potentials. In addition, the paper argues that the absence of clear definitions as to housing quality and affordability, and the lack of industry capacity for technical knowledge learning activities, are potential obstacles that limit the spread of sustainable zero-carbon homes in Scotland today. Moreover, the effect of the design charrette *approach being practiced in Canada on the homebuilding decision making process was reviewed, with the aim of providing a base for further discussion on the applicability of Canadian low-energy affordable housing design techniques to sustainable zero carbon homes of the future in Scotland.*

KEYWORDS

sustainable residential development, affordable homes, low-energy housing design techniques and technologies, zero carbon emission building

INTRODUCTION

The Scottish Government (2010) warns that 'as many as 46,000 more households (i.e. 2% of households in Scotland) will be pushed into fuel poverty every time energy prices rise by 5%.' In fact, it also reports that 32.7% of Scottish households in 2009 fell into families experiencing fuel poverty and it is a drastic increase from 18.2% in 2004. The 2002 Scottish Fuel

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Poverty Statement determines that 'a household is in fuel poverty if, in order to maintain a satisfactory heating regime, it would be required to spend more than 10% of its income (including Housing Benefit or Income Support for Mortgage Interest) on all household fuel use.' The majority of households in low income groups are suffering from fuel poverty as they have to spend a high proportion of their income on fuel and sacrifice other parts of their family budgets. Indeed, there is an urgent need for the delivery of low- to zero-energy and carbon affordable homes. In fact, the government published a report entitled 'A low-carbon building standards strategy for Scotland' (known as the 'Sullivan Report') which recommends that carbon dioxide (CO_2) emissions derived from energy use for space and water heating, lighting, and ventilation in all newly-built homes achieve nil by 2016/17 (Scottish Building Standards Agency, 2007).

In the Scottish Planning Policy 3 document, affordable housing is defined broadly as 'housing of a reasonable quality that is affordable to people on modest incomes' (Scottish Government, 2008). It also refers to a proportion of the housing market targeted at or reserved for people who are unable to acquire housing through open market purchase (Aberdeen City Council, 2005). Housing affordability refers to the ability of homeowners and renters to allocate their income on shelter, encompassing initial costs that are spent on building the house, as well as operating costs on maintaining it to be adequate and comfortable. In Canada, a house is considered as affordable when the homebuyer spends no more than 32% of the household's gross monthly income on the mortgage principal, interest, taxes, and heating expenses, or P.I.T.H. The second rule is that the entire monthly housing household debt load should not exceed more than 40% of the borrower's gross monthly income. These rules have widely been recognised as the benchmark of housing affordability in Canada (Friedman, 2005). However, it is unclear if the Canadian measurement of housing affordability can be directly applied to the UK market. This aspect requires further discussion and will be left for future in-depth studies.

In Scotland, today's drastic increase of energy prices necessitates the industry to consider the production of energy-efficient homes in order to mitigate housing affordability issues. The mass delivery of such homes also contributes to tackling global warming issues. Today, 27% of CO_2 emissions in the UK are derived from the housing sector and the government has set out the green target of cutting CO_2 emissions by as much as one-third in all housing stock by 2050. In order to achieve this ambitious goal, three gradual steps to regulate the extent of domestic CO_2 emissions have been established based on the Code for Sustainable Homes, which is now compulsory for new homes in England (Communities and Local Government, 2006). The government's initial step aims for the 25% reduction of operational CO_2 emissions in newly-built homes by 2010 (CSH Level 3), followed by a 44% reduction by 2013 (CSH Level 4). Eventually, all newly-built homes need to be carbon neutral by 2016—i.e., the CSH Level 6 accompanied by the *Lifetime Home*[1] design standards, with a mandatory heat loss parameter of 0.8 W/m^2K or less (Communities and Local Government, 2007). However, the code disregards means of reducing construction costs, focusing mainly on the improvement of housing quality; therefore, the challenge today centres around how to deliver affordable zero-carbon homes, where Lifetime Homes design features are also brought into effect. Accordingly, it is important to re-examine existing affordable housing delivery processes for the further upgrades.

The following section aims to initially document the status quo of selected affordable housing developments delivered by Tenants First Housing Co-operative in Aberdeen as the case studies that link to the next section concerning design techniques being applied for the successful development of net low- to zero-energy affordable homes in Canada. In the end, based on the case studies, this paper will clarify some key obstacles that potentially hinder the delivery of affordable zero-carbon homes today in Scotland.

AFFORDABLE HOUSING DELIVERY IN SCOTLAND

With due consideration of today's economic recession that accelerates fuel poverty issues, the Scottish government is facing acute pressure to provide affordable homes. The pressure derives from not only potential homebuyers, but also from those who live in rented accommodations owned by either the public or private sectors. In fact, Shelter Scotland (2009) emphasizes a growing demand for affordable housing, taking into account the number of household applicants who are presently on waiting lists. Local authorities today may need to compel housing developers to provide affordable homes as per the Scottish Planning Policy 3, published in 2003, supplemented by the Planning Advice Note 74 in 2005. Each development should contain a variety of affordable homes. The rented units are allocated in accordance with demographical housing needs and the sold units are intended to be allocated for people of a limited financial capacity who are at or below the threshold of market purchase.

The Aberdeen City Council expects an affordable housing contribution of no less than 10% from new developments of 20 dwelling units or more (Aberdeen City Council, 2008a). Recently, the Strategic Development Planning Authority (2009) proposed the latest percentage allocation for the delivery of affordable housing in the range from 20% to 30% of new housing development in Aberdeen City. In delivering the target for affordable housing provision as set out in the Local Development Plan, Aberdeen City Council and Aberdeenshire Council are working closely in partnership with Registered Social Landlords (RSLs), such as Tenants First Housing Co-operative (TFHC). TFHC is the largest fully mutual Housing Co-operative in the UK with over 1,300 homes in affordable settlements throughout Aberdeen City and Aberdeenshire. It was formed from an amalgamation of small housing co-operatives in Aberdeenshire. TFHC is involved in a number of successful affordable housing developments, providing homes for tenants with varying needs, including single persons and families, young and elderly residents, and people with support needs. In developing new homes, TFHC recognises the need for modernised procurement processes which encompass a consortium-led and integrated approach (Communities Scotland, 2006). In 2006, TFHC became a founding member of Devanha Limited, a consortium formed by five local RSLs based in Aberdeen. The consortium is aimed at delivering an improved programme and quality efficiencies in housing procurement for affordable home developments throughout the North East of Scotland (Collaborative Working Centre, 2007). It is achieved through the use of long-term framework agreements with construction partners and open-book cost management, which provides the consortium members with the ability to select appointed contractors to work on a framework for all of their new housing developments. Selected contractors and consultants are required to fulfill their duties under the agreed design and construction standards to achieve the highest quality in the development. This procurement model was seen to be desirable in the North East of Scotland. The organised coordination allowed local councils to clearly identify the particular needs and allocate specific RSLs to address the issues. It is widely known that the success of the Scottish RSL movement is based on a flexible and locally responsive system.

Devanha Limited is currently engaged in a programme for the Scottish government on behalf of Scottish Ministers to deliver 1,563 affordable homes for social renting and low-cost home ownership from 2007 to 2010. The programme comprises 1,188 houses for rent and 375 houses based on shared equity. For potential low-income first-time buyers, dwellings, mainly in the form of flats or semi-detached houses, will be built. The government grant funding also targets the reinforcement of housing schemes accompanied by environmental improvement (Communities Scotland, 2007). Having recognised the significance of environmental responsibility and cost in use for their membership, TFHC aims to improve the energy efficiency of its future homes. This benefits not only the environment but also TFHC member tenants by minimising maintenance and running costs. Taking into consideration the benefits of Modern Methods of Construction, TFHC expects to establish high quality standards that can be applied to the delivery of energy-efficient homes (Barr, 2009a).

Case Studies: Tenants First Housing Co-operative's Housing Projects Today

In order to deliver high-quality affordable housing, Tenants First Housing Co-operative (TFHC) contributed to publication of the Housing Quality and Design Brief, which outlined the commitment to delivering housing solutions aligned with the combined measurement tools of cost, quality, performance, and sustainability (Barr, 2007). The contents of the Housing Quality and Design Brief can be summarised as follows:

- Promoting higher-quality building within the agreed target cost;
- Achieving the very good standard rate according to the *Ecohomes*[2] scheme;
- Introducing and incorporating renewable materials and energy sources;
- Exploring the potential for innovative, modern methods of construction;
- Promoting the principle of mixed communities to ensure the development of successful sustainable communities;
- Ensuring all development schemes meet the minimum Scottish Government standards and achieve a Standard Assessment Procedure (SAP) rating of no less than of 80 or equivalent (against SAP 2005); and
- Developing a Housing and Quality Standards assessment and measurement tool for ongoing and regular monitoring, evaluation, and review process.

By applying this brief, all new developments are expected to exceed these minimum standards that also reflect the contexts of the Scottish Housing Handbook, Housing for Varying Needs, Scottish Federation of Housing Associations' Special Needs Code of Practice, Standard Assessment Procedure and Grampian Police Secured by Design. Moreover, TFHC homes are built in accordance with current legislation governing building standards and the Construction (Design and Management) Regulations.

In order to deliver sustainable low- to zero-energy homes, TFHC today is planning to apply the Code for Sustainable Homes (CSH) guidance as a minimum quality standard for their new homes of the future. TFHC also strives to influence the Scottish construction industry in the application of offsite construction approaches through the benefits of housing product quality, delivery time and safety, and guaranteed construction costs. To this end, TFHC has employed a number of sustainable building materials and systems, which are supplied outside the UK, in order to demonstrate their good practice to the Scottish construction partners and encourage them to learn from such innovations (Barr, 2009b). The housing project in Ballater, for instance, was developed using prefabricated concrete panels supplied by Opstalan, based in the Netherlands. TFHC also carried out a housing development in Aboyne where a timber frame open panel system was brought into effect for the delivery of quality affordable homes. Furthermore, the ongoing School Lodges development in Kingsford and Kirkhill, Aberdeen, has been applying the Canadian *Super* E^3 housing programme that helps to lower the homes' operational energy consumption. John Hockman (2009), certified Super E evaluator, estimates that the energy performance of the house built based on the Super E housing standards may achieve the reduced CO_2 emissions equivalent to the CSH level 3. The key features of these above mentioned construction developments will be summarised in the following sections.

Invercauld Park Housing Development in Ballater, Aberdeenshire

The Invercauld Park housing development is located in Ballater, Aberdeenshire. The construction was started in February 2004. It was completed and occupied in September 2004. As part of the conditions of the local council's planning consent to Scotia Homes, the builder of the neighbouring development, TFHC was given the land to supply affordable homes. The site accommodated a total of five two-storey three-bedroom houses built for rent (Fig.1).

In order to enhance the product quality and the efficiency of operational energy use, TFHC applied prefabricated insulated concrete wall panels imported from Holland. The building envelope was multi-layered, comprised of an external veneer brick and polyurethane insulation and 100mm concrete layers, with which all windows and doors had already been fitted. The prefabricated structural insulated roofs were also applied to this project (Forbes, 2005). To achieve the desired quality, the wall panels were shipped to Aberdeen and delivered to the construction site using low-loader lorries. The panels were then installed on in-situ concrete ring beam foundations and substructure services.

The positive feature of this concrete panel system is the integrated thermal insulation, which reduces the fabric heat loss of the houses. The heavyweight concrete material has high heat capacity, which to some extent captures heat from internal and external ambiances—i.e., thermal mass. This not only reduces the annual running cost of fuel, but also gives additional benefits in noise insulation and fire resistance (Communities Scotland, 2007). However, heat loss may not be avoidable around the unsealed joints between the panel and

FIGURE 1. Affordable housing development in Ballater, Aberdeenshire.

substructure. In theory, effective project management and an integrated approach to the design and build phases, as well as rigorous training of contractors before product arrival and installation, will benefit the whole process (Forbes, 2005). In reality, the local contractor encountered problems during the installation of these panels due to their unfamiliarity with this innovative building system. This resulted in slowing the installation; thus, the progress of the development was delayed and led to an increase of the project costs. In fact, the build cost for the Ballater project was estimated at £103,000 per unit. In other words, it became a 38% increase when the prefabricated house was compared with an ordinary timber frame house that could be estimated at £75,000 per unit when the project was carried out.

As there was no mains gas connection, an oil heating system was used to provide the central heating and hot water. Several tests for the energy-efficiency and environmental performance, such as infrared thermographic survey, Ecohomes assessment, SAP rating, and National Home Energy Rating (NHER) assessment, were carried out between July 2005 and July 2006. According to a report developed by Hexagon Research and Consulting and Alembic Research (2007), the temperature monitoring results showed a generally comfortable range achieved across the rooms in all of the dwellings. The report indicated that the average weekly oil cost for the prefabricated dwellings was 13.6 percent less than the average cost of the non-prefabricated dwellings. Among five prefabricated dwellings surveyed, the occupants of the detached dwelling spent the highest amount on fuel.

The use of this prefabricated concrete panelised system imported from Holland contributed to reducing the houses' utility cost and CO_2 emissions and resulted in making these houses more energy-efficient and affordable when they came into operation. However, the industry's unfamiliarity with the concrete panelised system led to a 38% increase in the build cost. This meant that the implementation of the concrete panelised system could not sufficiently underpin the notion of housing affordability where the reduction of initial costs is still of importance. As well, this imported concrete system might have increased the amount of embodied energy use in the production and delivery when compared with its timber frame counterparts, which can be procured locally.

Aboyne Village Housing Development

The Aboyne Village housing development is located in the centre of Aboyne village. The site was vacant and formerly part of the old auction cattle mart. Since the site had been derelict for a considerable period of time, the enhancement of the site for residential use was needed. The site's proximity to the River Dee meant that the building platform was raised by one metre in order to mitigate water damage from flooding. The development involves the delivery of sixteen two- and three-storey affordable houses, which correspond with locally identified housing need. To increase the production efficiency, an offsite open panel timber frame system was applied to the mass housing development. The panels were supplied by Deeside Timberframe. These factory-assembled open panels consist of timber studs incorporating batt insulation. The wall will then be covered externally with oriented strand board (OSB) wall sheathing and moisture barrier membrane before cladding, as well as internally with vapour barriers and plaster boards. The materials are installed in a conventional manner.

The open panel timber frame system dominates the industry and is considered one of the most cost-effective construction systems applied by Scottish homebuilders. However, this system is still heavily reliant on on-site assemblies; thus, the product quality and energy-efficiency cannot be considered to be as consistent as the properties of a closed panel system.

School Lodges Development in Kingsford and Kirkhill, Aberdeen

The School Lodges development was carried out with the financial support of the Aberdeen City Council and included four wheelchair-accessible residential properties, which are located in close proximity to primary schools in Kingsford and Kirkhill, Aberdeen (Aberdeen City Council, 2008b). To meet the development guidance provided by Aberdeen City Council, TFHC considered several off-site construction methods such as a concrete panelised system, timber frame panelised system, and a concrete or wood frame modular system. However, in view of the available budget, the Canadian Super E® holistic housing programme was selected. The houses in Kingsford were built using the pre-engineered Super E timber frame closed-panel system supplied initially by JPJ Environmental, the housing supplier in Canada. The panels were erected using a hoist and placed on the in-situ concrete foundation built by a local contractor.

The energy performance of the Super E homes was analysed carefully by making use of the Canadian HOT 2000 software tool. Thus, the results help TFHC to identify whether or not the annual energy use of the homes in question meets the Super E housing standard established by the Canadian government. Homes are granted the Super E certification when built according to the quality standard. The Super E housing programme aims to improve air-tightness, thermal performance, and ventilation of housing with the support of a mechanical heat recovery system, which recuperates pre-heated indoor air for supplementing the house's space heating.

Today, Super E advisors often recommend the use of foam insulation products (e.g. Icynene®) that drastically enhance the air-tightness of building envelopes (Hockman, 2009). Where foam insulation is utilised, the global warming potential may also need to be taken into account in order to reduce the pollution risk from blowing agent emissions that arise from the manufacture, installation, and disposal of foamed thermal (and acoustic) insulants. This pollution issue affects the environmental assessment of the Code for Sustainable Homes. For instance, Icynene is open cell foam insulation and allows for the use of a 100% water-blown agent that minimises air leakage for increased energy efficiency, creates a healthy indoor environment, reduces airborne sounds, and offers design freedom (Icynene, 2009). On the other hand, such open cell foam insulation is usually considered to be permeable to vapour. Moreover, it does not have high thermal properties or offer structural strength when compared to the closed cell counterpart, which has the great potential for the elimination of a number of building materials such as wall sheathing (e.g., OSB or Plywood) and vapour barriers (e.g., polyethylene sheets) as exemplified by the construction of the EcoTerra net zero-energy sustainable house in Canada (Noguchi, 2008). In other words, the use of closed cell foam insulation can be considered more effective in reducing the amount of building materials and operational energy costs than the installation of an open cell one.

The aforementioned case studies of residential developments delivered by Tenants First Housing Co-operative somewhat demonstrate the capacity of the Scottish homebuilding industry today. It still seems to be struggling to find a systematic way to deliver zero carbon affordable homes which can accommodate the needs and aspirations of individuals as well as society. Although TFHC has taken the initiative for implementing some innovative offsite construction technologies, the outcomes turned out to be more expensive than the traditional alternative due to local industry's unfamiliarity with the technologies. In Canada, design and production strategies (including the Super E home programme) that aim to commercialise energy-efficient affordable homes had been studied intensively. Today, the homebuilding industry succeeds in delivering low- or zero-energy marketable homes.

To investigate Canadian affordable housing design techniques, which are accompanied by energy-efficient construction solutions, the authors organised site visits to Canada's successful residential developments—this knowledge transfer event was later called *Net Zero-energy Affordable Home Mission to Canada 2009*. The following section will summarise the mission contents and the findings of design and production strategies being applied by Canadian homebuilders and housing manufacturers for the commercialisation of net low- to zero-energy affordable homes.

NET ZERO-ENERGY AFFORDABLE HOME MISSION TO CANADA

The Net Zero-energy Affordable Home Mission to Canada was held from June 6th to 11th, 2009, with the support of the UK government through the Knowledge Transfer Partnerships programme, as well as of the CanmetENERGY-Varennes, Natural Resources Canada, and the CMHC International, Canada Mortgage and Housing Corporation. The visits included the following residential housing projects situated in and around the city of Montreal, Quebec: Cité-jardin Fonteneau, Parc Angus, Bois Franc, 2005 & 2007 Canadian Solar Decathlon Houses, Saint-Basile PV Solar House, ÉcoTerra Net Zero-energy Healthy House, Green Energy Benny Farm, and Coteau Vert Projects. The first three projects (i.e., Cité-jardin Fonteneau, Parc Aungus, and Bois Franc) visited were originally affordable housing developments that successfully adopted the *Grow Home®* design concept that was established in the early 1990s with the lead of Prof. Dr. Avi Friedman, Director of the Affordable Homes Programme at the School of Architecture, McGill University. The Cite-jardin Fonteneau project was developed with the aim to achieve a moderately high density of affordable homes accompanied by detached, semi-detached, and attached dwelling units—i.e., the income mix of neighbourhood (Friedman, 2005) (Fig.2).

The community's visual quality was enhanced by vehicular circulations that were well organised in consideration of road hierarchy and safety, parking spaces, car-free pedestrian paths, and green public and private open spaces including allotments (Fig.3).

In this project, a semi-basement that accommodates a private indoor garage is introduced and connected to a rear communal car (and wheelchair) circulation that leads to the front

FIGURE 2. Cité-jardin Fonteneau project—view from Rue Joseph-A.-Rodier.

street through the side sloped access, yet the rooftop of the communal vehicular circulation serves as a private rear garden of each dwelling unit—i.e., the multi-functionality of space. The attractiveness of both the Parc Angus and Bois Franc projects visited during the mission can be characterised by the uniqueness of housing façade and internal design arrangements, made in such a way that each dwelling unit has its own style and functions, yet the design components themselves were well standardised in order to maintain the production efficiency, which affected construction costs. Particularly, the Bois Franc project's Village Renaissance (terraced house development) employed classical design elements for the façade decorations that might never fall out-of-date—rather, the beauty might have been captured through the 'sieve of history' (Clément, 1995) (Fig.4).

FIGURE 3. Private rear gardens and allotments.

The Bois Franc development is located in St. Laurent in the Greater Montreal area and dates back to 1993. Originally ten builders were involved in the project; however, only three builders remain today (Groupe Montclair, Groupe Maltais, and Groupe Sotramont). These builders continue to pursue the original vision of the development, which consists of a total of 2,800 dwelling units, excluding the number of homes that accommodate senior citizens. The Village Renaissance was representative of a typical Montclair's townhouse development in the Bois Franc project. In the autumn of 1999, the builder reported that they had already sold more than 100 terraced housing units. The dimensions of the first and second floors of the Village Renaissance terraced house model, sold in 1999, were 5.5m × 10m (55m^2 each floor). Similar to the Cite-jardin Fonteneau project, a semi basement was employed, composed of a multipurpose room (including a laundry space) and an indoor integral garage that leads to a communal car (and wheel chair) circulation. In 1999, the house was sold at CAN$139,900

FIGURE 4. Bois Franc Project—Village Renaissance.

(£78,344, where a currency exchange rate was estimated at CAN$1.00 = £0.56). In Canada, the average total annual income of an economic family (defined as a group of individuals sharing a common dwelling unit who are related by blood, marriage, including common-law relationships, or adoption) was estimated CAN$63,818 (£35,738) in 1999. This attests to the fact that the Village Renaissance terraced house sold for almost double the average household's annual income (Noguchi, 2004).

Cost-reduction Housing Design Strategies

Broadly speaking, the Cité-jardin Fonteneau, Parc Aungus, and Bois Franc projects are all featured by their affordable selling prices that might derive from moderately low construction costs. Canadian homebuilders appear to be succeeding in practicing cost-reduction design (and production) strategies. In consideration of our observations through the mission visits and literature reviews, particularly on the Grow Home concept developed by Friedman (2001), the Canadian homebuilders' cost-reduction strategies can be summarised as follows:

- *Reducing the size of a housing unit:* the amount of building materials could be reduced by minimising the internal space. Also, the smaller volume will consequently reduce the ventilation and fabric heat losses;
- *Grouping housing units:* attaching dwelling units (i.e., semi-detached or terraced houses) accompanied by the placement of party walls will not only reduces the amount of building materials but also the fabric heat loss due to the smaller external surface exposure;
- *Simplifying a housing configuration:* the simple building shape with less corners and projections (e.g., bay windows) can lead to a reduction in thermal bridging areas as well as construction complexity that increases build costs;
- *Introducing an open floor plan layout:* this arrangement maximises the spread of natural daylight and maintains cross ventilation. These aspects lead to the reduction of lighting and heating costs. Also, the open floor plan layout provides a high level of design flexibility in internal space, which facilitates the rooms' future renovation, as well as reduces initial construction costs by eliminating unnecessary partitions;
- *Introducing a back-to-back arrangement to kitchen, toilet and bathroom planning:* attaching these service rooms helps reduce the length of service and drainage pipes, which in turn lower material costs. Also, the concentrated drainage pipes through which warm grey (drain) water passes can somewhat heat incoming water to be used at a shower, sink and bath, if arranged intelligently;
- *Modularising a housing configuration:* designing the dimensions of a housing unit in consideration of commercially available sizes of building materials and components (e.g. OSB, plywood, and plasterboards) helps reduce the amount of construction waste; thus, reducing or eliminating unnecessary investment;
- *Standardising homebuilding products and processes:* the standardisation plays a role as a medium of prefabrication and mass production (and *mass customisation*) that helps reduce construction costs and maintain consistent product quality in view of the learning curve (Noguchi, 2004); and
- *Introducing unfinished upgradeable spaces:* an unfinished space that can be completed by housing users themselves (i.e., Do-It-Yourself) after occupancy result in the initial material cost savings and the rooms can grow according to the occupants' individual

needs, desires, and expectations—i.e., personalisation. An unfinished basement at the time of sale can be considered as a typical approach being implemented in Canadian affordable homes.

The aforementioned affordable housing design (and production) strategies are effective in reducing both the initial build cost of housing and the operational energy cost. Today, the Canadian government encourages the public and private sectors together to build more sustainable homes than ever. The following section unveils some design features of net low- to zero-energy healthy housing in view of the authors' visits to Canadian energy-efficient housing construction sites.

Net Zero-energy Housing Design Features

In May 2006, Canada Mortgage and Housing Corporation (CMHC) launched the *EQuilibrium*[4] sustainable housing demonstration initiative. This housing competition, previously called *Net Zero Energy Healthy Housing Initiative*, was aimed at bringing private and public sectors together to develop homes that encompass: climate- and site-specific design; energy- and resource-efficient construction; passive solar heating and cooling; natural day-lighting; integrated renewable energy systems; energy-efficient appliances and lighting; water conservation and re-use; land and natural habitat conservation; and sustainable community design and green infrastructure practices (CMHC, 2007). Thus, the overall goals of Canada's EQuilibrium sustainable housing were: to develop a clear vision and approach to homebuilding; to build the capacity of the national housing and renewable energy industry sectors to create high product quality across the country over the long term; to achieve market acceptance of low-impact healthy houses and sustainable communities; and to enhance the domestic and global leadership in sustainable residential community design and development.

As a result, a total of 72 homebuilding teams submitted applications as of July, 2006. On February 13th, 2007, the Honourable Monte Solberg, Minister of Human Resources and Social Development, and Minister responsible for CMHC, and Jacques Gourde, Parliamentary Secretary to the Honourable Gary Lunn, Minister of Natural Resources, made the public announcement at CMHC's National Office and selected the twelve teams from the original entries as winners of the EQuilibrium sustainable housing competition—later, the demonstration number had been increased to 15 projects.

The *ÉcoTerra*[5] zero-energy sustainable house is one of the original winning projects (Fig.5). The EQuilibrium house was constructed in Eastman, Quebec, in order to demonstrate how far the low-energy healthy housing techniques and technologies can be implemented within marketable prices (Solar Buildings Research Network, 2007).

On November 9th, 2007, the grand opening of the house was held at the construction site where the Honourable Christian Paradis, Secretary of State, made the inaugural address and congratulated Alouette Homes, the project lead and modular housing manufacturer, on the successful construction of Canada's first EQuilibrium net zero-energy healthy house. The project was completed through a *design charrette* (or brainstorming workshop) process, which is increasingly used as a planning tool to bring together relevant stakeholders for the design decisions (CMHC, 2001). In fact, this project was carried out by a number of housing experts with multidisciplinary background. The architectural design of this housing was developed by Dr. Masa Noguchi, one of the authors of this paper, in collaboration with Alouette Homes. The house was further engineered by Dr. Andreas Athienitis, Concordia University, Dr. Yves

Poissant, Natural Resources Canada, and Claude Agouri, Airtechni Inc. The ÉcoTerra house was an attempt to use a simple formula of adding readily-available renewable energy technologies to proven energy-efficient construction techniques in order to achieve Canada's energy efficient guide, or *EnerGuide*, for house rating in excess of 98 points. To achieve the project objectives, the team introduced a number of low-energy healthy housing techniques and technologies (Noguchi, 2008).

The ÉcoTerra house is a single-family detached home built in a 1.077 hectare rural area within a new residential development consisting of total 48 dwelling units in Eastman, Canada. The floor area of this house is 141m^2. Semiprivate spaces, such as the kitchen, dining room, lounge, and passive solar heating and day-lighting sunspace/family room, are located on the ground floor and two private bedrooms and a small convertible study/bedroom are on the first floor. An unpartitioned open staircase that allows for the distribution of daylight and preheated indoor air from the sunspace links the semiprivate interior to the private rooms on the upper floor. An unfinished semi-basement is provided to encompass both the family's spatial flexibility after occupancy and the affordability at the time of sale. The semi-basement accommodates a machine room and a multipurpose space, and the south-facing warm area can be converted into a children's bedroom, playroom, guestroom, and/or a home theatre, as per the family's spatial demands and requirements that may change over time. The semi-basement's external walls are covered half with the earth to reduce fabric heat losses, while the wall's partial exposure helps maintain adequate levels of natural light and ventilation that enter the habitable space. The interior is composed of a concrete thermal wall and floor mass that stores internal heat, linked to the similar one placed in the sunspace on the ground floor.

In this example, *solar thermal mass* was introduced. It is connected through embedded ducts to the building-integrated heat-releasing solar photovoltaic power generating panels (i.e., BIPV/Thermal system) installed on the south-facing upper rooftop and tilted at a nearly optimal angle that maintains the sufficient exposure to solar radiation. This BIPV/Thermal system has the capacity for the potential generation of electricity at 3,420kWh/yr and heat at 3,800kWh/yr. The solar-heated air leaves the roof approximately 35°C warmer than the outdoor ambient temperature and is used for heating indoor space through the solar thermal mass, pre-heating domestic hot water through an air-to-water heat exchanger, and supplying warm air to the clothes dryer. A south-facing lower roof is also provided for additional solar panels that can be installed after occupancy as the price of renewable energy technologies decreases over time. In addition, a geothermal heat pump was also installed in this house, functioning as the primary source for space-heating, particularly when the BIPV/Thermal system is not in operation. To retain the warm indoor air (heated by the sun and equipment installed in the house) as much as possible, the house was sealed tightly using airtight construction techniques. Its indoor air quality is well-controlled using a balanced heat recovery ventilator that recycles pre-heated indoor air up to 76% and ensures that the air pollutants are continuously exhausted with the fresh air intake. Prior to the installation of these advanced active renewable energy technologies, the ÉcoTerra house was designed on the first principles of passive energy and environmental design techniques. These relate to the building orientation and configuration, construction method and materials, and the placement of internal functional spaces with due consideration of the local sun position relating to time. All of these improve the thermal and lighting properties of the house.

FIGURE 5. South façade of the ÉcoTerra zero-energy sustainable house.

Architectural design essence and engineering expertise were collated and harmonised through the design charrette organised at the early stage of this project (Noguchi, 2008). For instance, an outdoor garage was attached to the house's northern façade aligned with the backyard, with the aim of drastically reducing the fabric heat loss from the notable north wall, which is always shaded. This arrangement was also effective in preventing a visually unpleasant front façade dominated by the presence of automobiles rather than trees and flowers, which tend to lower the level of ambient CO_2, serve as wind barriers, and maintain comfortable humidity that helps cool the ambient temperature in the hot summer months. A machine room that releases heat from equipment is located on the north side of the semi-basement floor in order to spread the heat into the habitable spaces on upper floors using the stack effect, while reducing fabric heat losses from the north walls. The machine room in the semi-basement, kitchen on the ground floor, and bathroom on the first floor, are aligned vertically so as to concentrate service water and drainage pipes, alleviating material cost and labour effort. A sunspace/family room is allocated to the south side of the ground floor consisting of thermal mass, like the one in the semi-basement, which stores internal heat of 3,491kWh/yr. Here, the indoor sunspace is featured particularly by the designer's original waist-high thermal wall mass that is made of concrete but covered with dark-coloured ceramic tiles, with the aim to sufficiently capture the solar and internal heat gains. Due to the limited height of about

1m from the floor level, the thermal wall still maintains adequate daylight penetration and cross ventilation, unlike traditional Trombe walls. In fact, the natural light distribution on the ground floor was analysed in foot-candles ranging from 60 lux to 821 lux at noon on December 21st—i.e., the winter solstice. In the ÉcoTerra house, the availability of sunlight entering the rooms was considered important in terms of the occupant's health and comfort, as well as the potential to supply heat in the amount of 9,592kWh/yr. To minimise ventilation heat losses, the building envelope was well-sealed to maintain the air-tightness at 0.8 air-changes per hour at 50 Pa and insulated to achieve U-values of $0.15W/m^2K$ in walls and $0.1W/m^2K$ in ceilings. All the windows installed feature triple glazing fitted with low-emmisivity (low-e) coating and argon gas, improving their thermal properties.

As regards the production innovation, approximately 80% of the homebuilding components applied to the ÉcoTerra house was prefabricated inside the Alouette Homes production facility. A factory-completed modular housing system helped eliminate or reduce on-site construction nuisances that lead to considerable material waste, such as bad weather, theft, and vandalism. Moreover, the housing manufacturer's waste management reinforced the reducing, recycling, and reusing of resources and ensured the procurement of responsibly-sourced local building materials.

In principle, the ÉcoTerra net zero-energy sustainable house was designed to optimise energy gains while minimising heat losses; thus, passive solar design techniques were well implemented in harmony with advanced active renewable energy technologies in order to achieve the net zero-energy cost when the home is used properly. The key innovative aspects of the house can be summarised as follows:

- South-facing building orientation with large lights that optimise the sun exposure for solar heat gains and day-lighting;
- Triple glazing windows filled with argon gas and low emissivity coating for reduction of fabric heat loss through windows;
- Minimised openings on the north, east, and west facades for reduction of fabric heat loss through the openings;
- Multifunctional outdoor garage that is equipped with a green roof terrace connected to the 1st floor main bedroom and serves as an air buffer space attached to the north façade for reduction of fabric heat loss from the critical north wall;
- High thermal performance foam insulation that achieves U-values of $0.15W/m^2K$ in walls and $0.1W/m^2K$ in ceilings and ensures air-tightness at approx. 0.8 air-changes per hour, reducing ventilation heat loss;
- Waist-high thermal mass wall that improves the house's capacity for heat-storing, day-lighting and natural ventilation, and distinguishes the project from others with this new environmental architectonic feature;
- Unpartitioned open staircase that allows for the human circulation and heat and daylight distribution, as well as giving a sense of visual extension to the moderately-sized interior, aimed at reducing the energy load for space-heating;
- Unfinished multipurpose semi-basement for spatial flexibility and affordability;
- Resource-efficient modern method of construction that helps ensure the high levels of product quality and waste management;
- Green landscaping (including the garage's roof terrace) that is aimed at reducing ambient CO_2 levels and rainwater runoff and conserving natural habitat, in response to sustainable community development;

- Building integrated photovoltaic thermal (BIPV/Thermal) system that generates not only electricity using free clean sunlight, but also solar-heated air applied for heating space through solar thermal mass, pre-heating domestic hot water through an air-to-water heat exchanger, and supplying warm air to the clothes dryer;
- PV and/or solar thermal capacity grow space that allows for the growth of rooftop solar panels after occupancy;
- Integral indoor sunspace on the semi-basement and ground floors that are composed of generous solar thermal mass connected to the BIPV/Thermal system;
- Balanced heat recovery system that recycles preheated indoor air up to 76%;
- Ground-source heat pump that is used as the primary system for heating and cooling the house;
- Heat exchanger designed to apply the heat from warm drain (waste) water for heating incoming cool water from the mains;
- Energy-efficient appliances and lighting; and
- Rainwater butt that harvests the natural free water for gardening and car-washing.

The ÉcoTerra sustainable house was designed to provide its occupants with a comfortable and healthy indoor living environment and produces as much energy as it consumes on an annual basis. The simulation of the energy use indicates that the house experiences nearly net zero-energy consumption when it comes into operation (Noguchi, 2008). However, the domestic energy use still depends on occupants' energy saving behaviour. Accordingly, a user manual that helps educate occupants about behaviour-related energy saving techniques may need to be developed and the effect can be calibrated through energy meters that can display both energy use and cost.

CONCLUSIONS

In principle, to build sustainable zero-carbon homes, the housing cost and quality first need to be clarified in consideration of societal demands and requirements, as well as local building regulations. In Scotland, the Code for Sustainable Homes that has already been implemented in England is still out, with the homebuilding industry's general practice and the vagueness of the notions of sustainable homes and zero-carbon housing leading housing suppliers, e.g., homebuilders and housing manufacturers, to the confusion of quality standards. Moreover, unlike Canadian contexts, there is no explicit means to measure housing affordability in Scotland today, where the hike of energy prices is leading nearly a quarter of the nation's households to fuel poverty. For the production of sustainable zero-carbon homes in Scotland, the housing suppliers are required to gain the technical knowledge of cost-effective energy-efficient building materials and systems, including passive energy and environmental design techniques and active renewable energy technologies. In reality, their business operations often develop into routine; thus, the application of unfamiliar housing materials and systems necessitates builders to spend extra time and money, and this in turn yields some technical and financial barriers that make them perceive risks in the delivery of such advanced homes.

In Canada, as exemplified in the EcoTerra house development, a *design charrette* approach has been introduced to the development of sustainable homes and communities, with the aim of engaging internal and external experts in the design decision making processes. This collaborative approach helps lighten the burden of builders' technical knowledge requirements by turning individuals' dispersed knowledge into the team expertise required to achieve the common goal set. It also helps the team make the proper design choices concerning housing orientations and configurations, construction materials and systems, including renewable energy technologies and internal planning, taking into account the relationship between the time-related sun positions and the internal space day-lighting and heat gain potentials. In Scotland, such a charrette approach is rarely applied by housing suppliers today, and thus it may be worthy of attention for the delivery of the sustainable zero-carbon homes of the future,

NOTES

1. *Lifetime Home* design standards incorporate 16 design features to create a flexible, accessible and adaptable space in dwellings for all kind of end users: old and young, single and family, abled and disabled people.
2. *Ecohomes* is an environmental assessment method developed by the Building Research Establishment (BRE) to measure the environmental performance of homes.
3. *Super E®* is a strategic initiative that was made possible by the on-going efforts of the Government of Canada agencies, Natural Resources Canada, Canada Mortgage and Housing Corporation and National Research Council Canada, and is a programme to disseminate Canadian energy-efficient healthy housing technologies.
4. *EQuilibrium™* is a national housing initiative led by Canada Mortgage and Housing Corporation (CMHC). It encourages private and public homebuilding sectors to build homes designed to address occupant health and comfort, energy efficiency, renewable energy production, resource conservation, reduced environmental impact, and affordability.
5. *ÉcoTerra® house* is Alouette Homes' brand and the term has been protected under the trademark acquired by the company.

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