Thermal Collection and Seasonal Storage Potential of a Mixed-Use Neighborhood

Abstract

This paper summarizes the energy performance of a mixed-use community, which combines residential and commercial/institutional buildings, in a northern cold climate. The energy performance criteria include, in addition to thermal and electrical consumption, the balance between energy consumption and solar energy generation. The community is designed according to various existing guidelines of sustainability. Energy efficiency measures are implemented in all building types, while PV panels are assumed to be integrated on all available near south-facing roof surfaces. A solar thermal collector system combined with a borehole thermal energy storage is designed to investigate the impact on the overall performance of the neighbourhood. The design of solar thermal collectors and the sizing of short-term thermal storage is based on the analysis of the thermal loads for heating and domestic hot water in each district of the community. The results indicate that implementing thermal collectors and seasonal storage, in this high energy performance neighbourhood, leads to a net positive energy status.

Keywords: Seasonal storage, thermal collectors, solar energy, mixed-use neighborhoods, energy efficiency.

1. Introduction

Space and water heating constitute a large portion of energy consumption of the residential sector, especially in cold climate regions. For instance, in Canada around 82% of energy consumed by the residential sector is allocated to space heating and domestic hot water (NRCan, 2013). While implementation of energy efficiency measures in buildings enables reduction of energy consumption by up to 35% (ECBCS News, 2012; ASHRAE 2008), it is not sufficient to address an expected increase in future energy demand of the building sector (Cellura et al, 2013). Coupling these measures with increased renewable energy production technologies, enables energy generation amounting to a large portion of a buildings' energy consumption, and in some cases exceeding it, thus reducing dependence on fossil fuel.

Utilizing solar energy in applications such as passive and active space heating, domestic hot water (DHW) and for electricity generation is a large step towards increasing efficiency and reducing GHG emissions by the built environment. This is especially applicable in a cold sunny climate such as the climate of Alberta (Canada), the pilot location of this study. In addition, due to the abundance of solar radiation during the cold period of the year, in this region, thermal storage becomes a promising method to reduce or eliminate the need for space and water heating.

A number of studies have been carried out to determine the potential of solar collection and thermal storage (long-term and short-term) in reducing energy consumption for space heating and domestic hot water. These includes studies on single buildings and on residential small-scale neighbourhoods. Results of some of these studies indicate that solar systems can cover all the heating and domestic hot water needs of a typical house located in cold climate (Montreal, Canada), without using electricity for the storage tank (Hugo et al, 2008). On a neighbourhood level, a demonstration project shows that it is possible to supply around 97 % of the total thermal demand (including DHW of 52 houses using solar thermal collectors and seasonal thermal storage (Drake landing, Calgary, Canada), (McDowell and Thornton, 2008; Sibbit et al., 2005).

Mixed-use communities that combine commercial and residential buildings offer several environmental and economic advantages, however they can also present significant challenges to achieve high-energy performance. Exploring the benefits of solar thermal collection and storage for such communities represents a significant strategy towards reaching energy self-sustained communities (Hachem et al, 2018).

The paper presents a summary of research of the energy performance of a mixed-use solar community combining various types of buildings. The energy performance includes the potential of solar thermal collection and storage, and solar electricity generation of this mixed-use neighbourhood.

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2. Methodology

A large-scale mixed-use neighbourhood of land area of 64 hectares is designed, based on various considerations of sustainable design (see section 2.1) (Hachem, 2016). The residential buildings include single-family detached houses, attached houses, and mid-rise apartment buildings (3 to 5 stories). The main commercial amenities include office buildings, retail area and grocery store, in addition to a primary school (See Figure 1 below).

The methodology employed in this study comprises a detailed simulation of the buildings energy performance and of the energy systems employed. For the thermal study, the neighbourhood is divided into sub-districts, each equipped with a set of thermal solar collectors, closed in a loop with a thermal storage tank system. A geothermal seasonal storage is assumed to interface with each of these tanks through a hot water system, allowing mutual charging between the two storage systems. The studied parameters include solar collectors' performance, hot water tanks sizes and thermal features, pipelines geometry and thermal properties, and thermal loads.

Thermal energy consumption for heating and domestic hot water are first computed using EnergyPlus software (EnergyPlus. 2016) in conjunction with Openstudio (Legacy OpenStudio Plug-in for SketchUp, 2014), which is used to generate the geometry of the various types of buildings .The thermal load is then employed to explore the potential of solar thermal collection and seasonal storage of the studied neighbourhood. TRNSYS (University of Wisconsin et al., 2014) is employed to determine the thermal collection and seasonal storage potential. The simulation settings include a one-year pre-heating for the geothermal storage and five overall years of simulation.

The major stages of the study are summarized below.

2.1 Overall design considerations

The mixed-use neighbourhood is designed employing guidelines of traditional neighbourhood developments (TND) (Traditional Neighbourhood Development (TND)), the Canada Mortgage and Housing Corporation (CMHC) fused grid (CMHC, 2011), and other existing design guidelines. A TND, known as a village-style development, includes a variety of residential building types, a mixed land use, an active centre, a walkable design, and often a transit option within a compact neighbourhood area. TND defines as well approximate land areas for each of the functions.

The CMHC fused grid is designed to allow mixed-use, densification and efficient public transportation, and thus can be a comprehensive basis for the design of a new energy efficient sustainable neighbourhood. As such, the neighbourhood is composed of 16 quadrants (as shown in Figure 1), with some of these quadrants consisting of low-density detached houses, while other quadrants contain both commercial and residential buildings.

A low density is assumed on average in this study to correspond to the prevailing density in the area (outskirt of Calgary), around 15 units per hectare (u/h) (6 units per acre (u/a)). The central business district, which includes all commercial buildings, is located at the edge of the neighbourhood, while the school is located at the center of the development (See Fig. 1). These design decisions are based on common acceptable practices in the region.

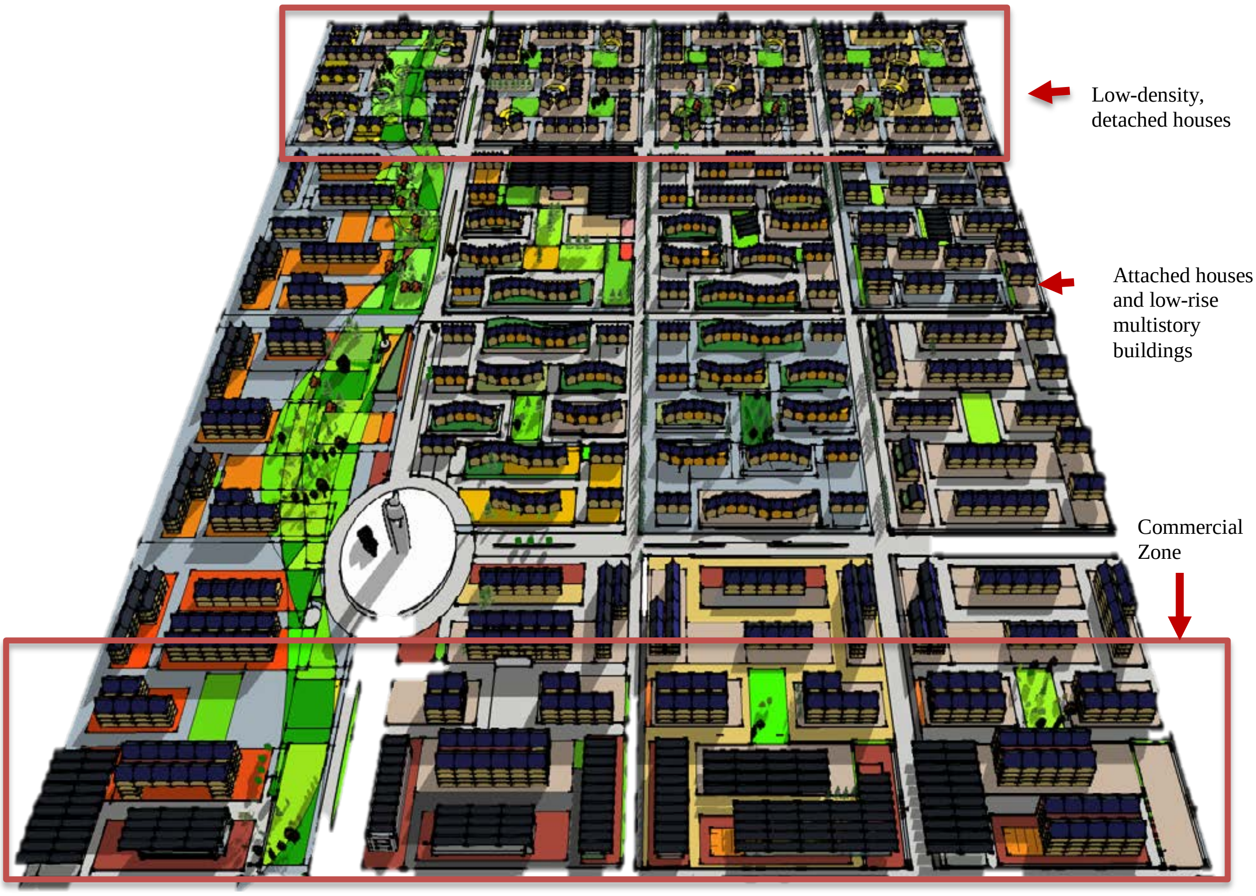

Fig 1: Different views of the overall neighbourhood design

Buildings design assumptions

Residential Buildings

Residential buildings consist of single-family houses and apartment buildings. Two types of houses are designed, a detached house of total floor area of 180m^2 and attached houses (townhouses) of floor area of 120m^2 each. The area is based on average areas of houses in the studied location (CHBA Pulse Survey, 2014). Two-storey house design is employed for both attached and detached houses. Low–rise multi-storey buildings (3, 4 and 5- floors) are considered in this base case study. Apartments have a floor area of 110m^2 (average apartment size in Canada (Armestrong et al, 2009)). Design of houses and south facing apartments take into account passive solar design principles, to maximize solar capture and utilization.

An occupancy of 2.5 persons per residential unit is adopted throughout the study, to match the average Canadian occupancy.

Commercial and public buildings

The commercial/public buildings considered in this mixed-use neighbourhood consist of office buildings, a school and a supermarket/retail building. Below is a summary of the commercial buildings included in the study. These buildings are illustrated in Figure 2.

- Three mid-size 3-storied office buildings of 3200m^2 each are assumed.
- A single storied school building is designed to specifications for a primary school serving a residential population, based on an estimated number of pupils, based on the population of the neighbourhood (Barton et al, 2010).
- Other commercial buildings include a supermarket and a retail building of 1200m^2 each. Since only 20% of the total land use is dedicated to commercial buildings, this retail area is adopted to fit the concept of TND development, and the available space.

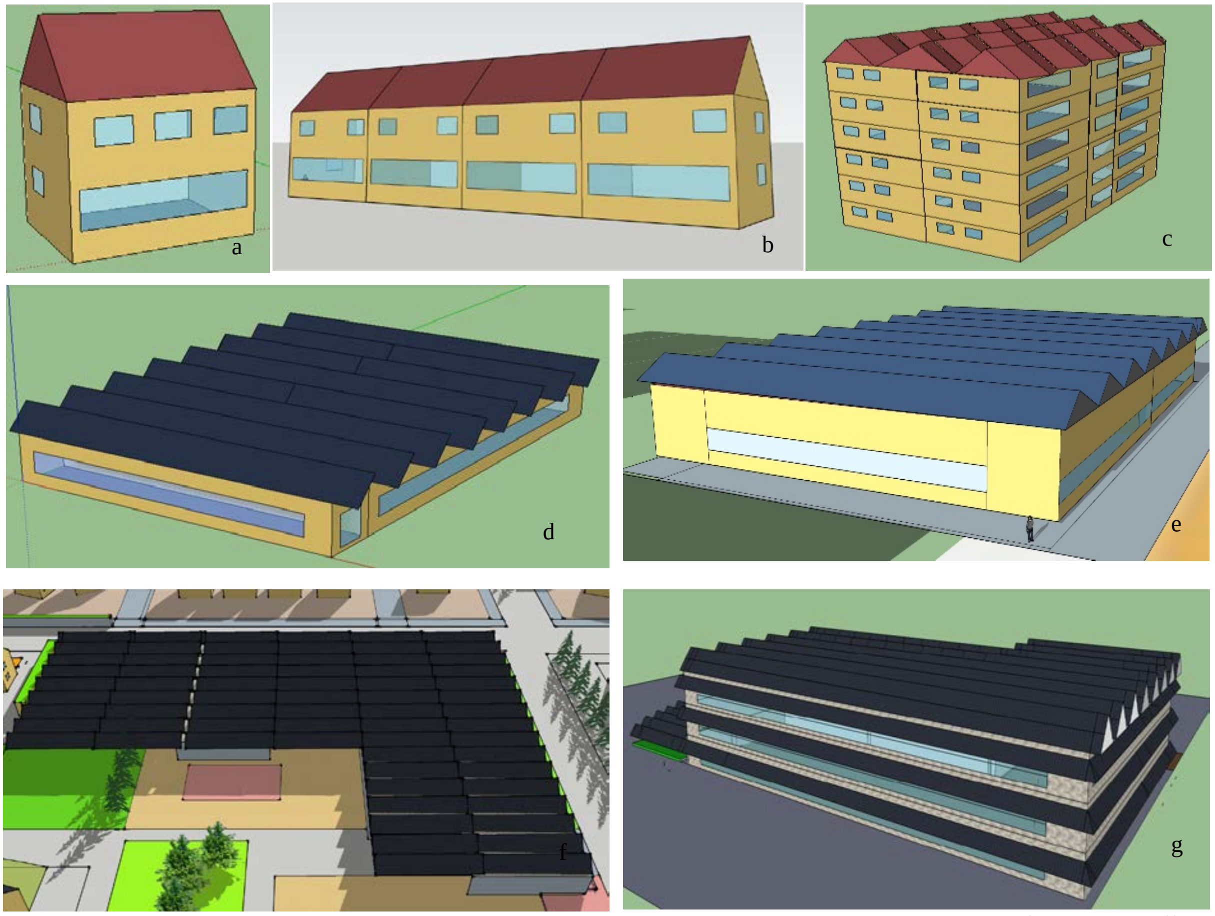

Figure 2. (a) detached house model, (b) attached houses, (c) Apartment building, (d) Supermarket, (e) Retail , (f) School, (g) Office building

An all-electrical neighbourhood is assumed throughout this study. This assumption is adopted to enable comparison of total energy consumption per building (as electricity) to the potential of energy generation from PV systems, and therefore to assess the potential of these neighbourhoods to achieve an on-site net-zero energy status.

Buildings are designed with the objective of achieving net zero energy status. High performance building envelope is assumed in all types of buildings: wall and roof insulation of $7m^2k/W$ and $10\ m^2k/W$, respectively; triple glaze, low-e argon fill windows, and airtight construction. High performance building envelope can significantly improve the energy efficiency of buildings. In addition, the design of residential units assumes optimal passive solar principles such as longer south façade (with respect to the perpendicular facades) and larger south facing windows (about 35% of south façade) (Hachem et al, 2013). Commercial buildings assume the same building envelope characteristics as residential, while energy consumption is determined based on lighting and electrical specifications of the National Energy Code of Canada for Buildings.

Building integrated PV (BIPV) system is assumed to cover the complete south facing roof surface of all buildings. For buildings with large plan area, including multi-storey and commercial buildings, the roof is designed as “saw tooth”, where PV is integrated on south facing surfaces (See Fig. 2). In the saw-tooth design, the south facing BIPV surface has a 45^o tilt angle and the saw-tooth has a total width 2.5 times the height, to reduce shading.

2.2. Thermal collectors and seasonal storage

This study assumes a design of thermal collectors and thermal storage that can cover the total requirement of heating and domestic hot water of the whole community. The neighbourhood spatial arrangement consisting of sixteen equally sized neighbourhoods termed districts (or quadrants) facilitate the spatial design of the thermal network, summarized in the following

The solar thermal systems are first sized to cover the thermal needs of each quadrant. The total solar collectors' area per single district range from 2500 m^2 in district 1 to around 750 m^2 in districts 13-16. The solar thermal collectors (STCs) are assumed to be installed on dedicated structures within the area of the each quadrant, which serve as public areas (e.g. parking lots, gathering areas, etc.). A south orientation and tilt angle of 50° are employed in the simulations of the STC system.

Thermal storage is based on two different levels: district solar tanks and seasonal borehole thermal energy storage (BTES). The short-term tanks representing a first level of energy storage are directly connected to the solar thermal collectors and to the building loads. All thermal storage tanks are connected, via an insulated pipework system, the borehole thermal energy storage, which uses the thermal capacity of the ground as seasonal storage, to be used during the cold period. The cylindrical storage tanks volume for each district is directly related to the respective thermal collectors' area and ranges from around 250 m^3 in quadrant 1 to around 75 m^3 in quadrants13 to 16, with an average loss coefficient equal to 5 kJ/(hr m^2) K. This is due to the different thermal load requirement in each quadrant. A distribution system connects the buildings through a district heating network providing both heating and domestic hot water.

Figure 3 presents an overview of the thermal network. Each quadrant uses a short-term thermal storage (pink tank in Fig 3), connected to the solar collector systems. Every short term thermal storage system is then connected through pipelines (the red lines) to the borehole energy storage (BTES), placed in quadrant 10.

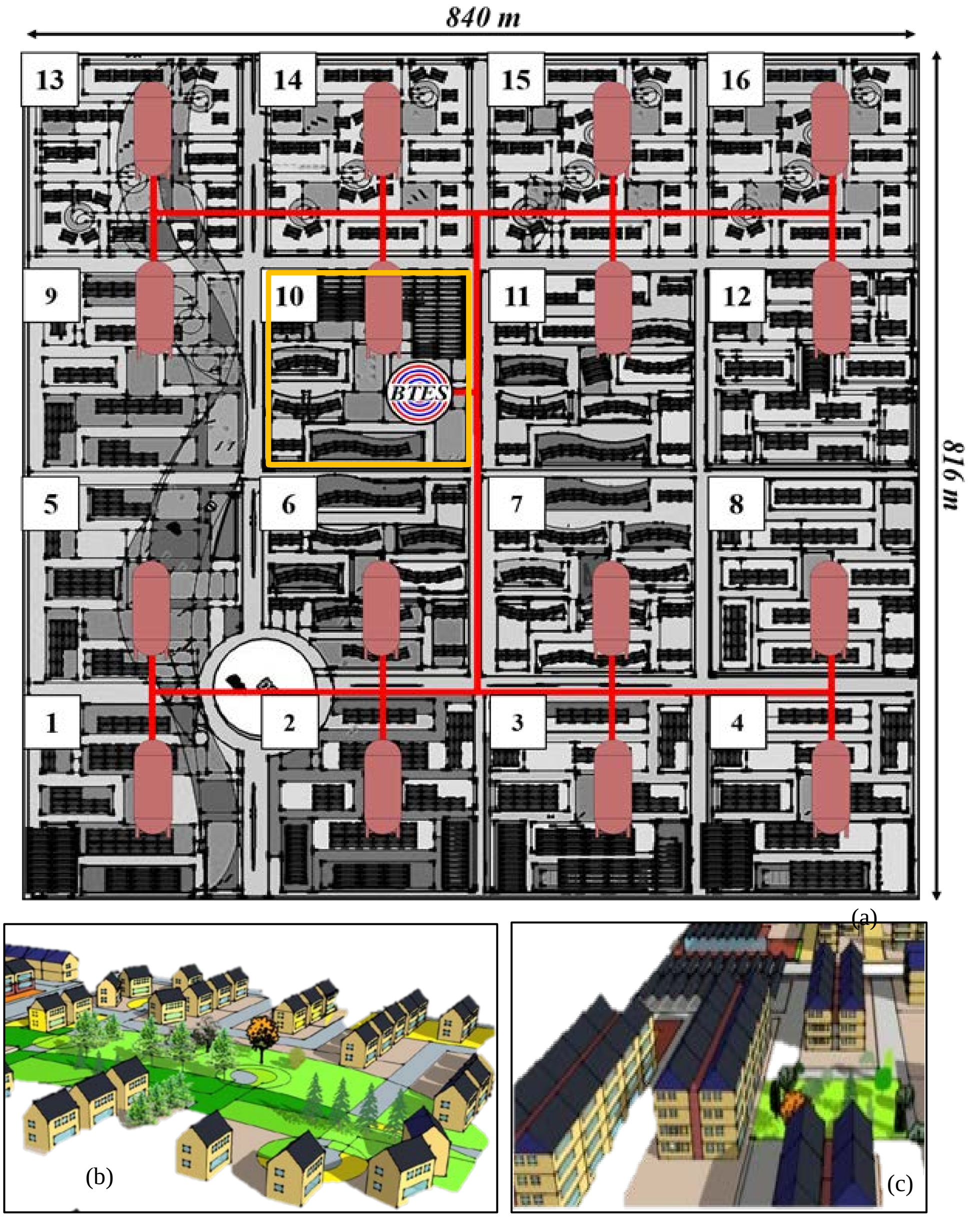

Fig. 3. (a) Concept of the energy management of the system investigated, (b) example of residential low density district (D13), (c) example of a commercial buildings district (D4).

2.3. Simulations

The simulations of annual heating and cooling thermal loads, as well as PV electricity generation, are carried out using EnergyPlus. The weather files of EnergyPlus based on the Canadian Weather for Energy Calculations (CWEC) are used for the simulations (EnergyPlus: Weather files). PV array is selected from the EnergyPlus database to provide approximately 15% electricity generation efficiency.

TRNSYS is used to perform detailed simulation of the heat pump and chiller, assumed in all scenarios, to supplement the heating and cooling for all buildings. For this purpose, the hourly heating and cooling loads of each building in the neighbourhood, estimated in EnergyPlus, are used as input for the analysis performed in TRNSYS.

Simulation of the solar thermal system employs TRNSYS environment. The simulation settings include a one year pre-heating for the geothermal storage and five overall years of simulation. For each district, a single thermal storage tank is modelled. Thermal stratification is considered through eight isothermal nodes modelled in the storage tanks. The fluid flow temperature is set at 55°C to allow heating through fan coils and domestic hot water. Auxiliary space heating is provided through an auxiliary heater in order to meet the set-point.

The geothermal BTES is modelled employing TRNSYS Type 557, a model based on (Mazzarella 1993) and (Pahud et al., 1996). The heat flow from the pipe to the ground is determined by the temperature of the fluid, the heat transfer properties and the temperature in the ground surrounding the pipe. These parameters are considered variable along the pipes. The ground heat exchangers are assumed to be uniformly placed in the storage region.

The most relevant thermal and geometrical features are summarized in Table 1

Table 1: Thermal and geometrical features of the BTES

Ground	Value	Units
Thermal conductivity	2.11	W/(m K)
Thermal Capacity	2500	kJ/(m^3 K)
Top insulation		
Thickness	20	cm
Thermal conductivity	0.043	W/(m K)
Boreholes		
Height	40	m
Diameter	15	cm
Header depth	1	m
Thermal resistance	0.223	(m K)/W
Number of boreholes	2500	
Borehole spacing	1.6	m

3. Results

The results presented in this section summarize the performance of each building type included in the studied neighbourhood, as well as the overall performance of the neighbourhood. The results are presented first for the high-performance neighbourhood, without the implementation of the STC/BTES system.

3.1 Energy consumption and PV generation

Yearly energy consumption of each type of building – total and per unit area – is presented in Figure 4. Due to high-energy efficiency measures, houses as well as apartment units have low energy intensity (around 60kWh/m^2 and 70kWh/m^2, respectively). Retail and school are energy intensive, while supermarket building is the highest energy intensity building type, consuming about 264kWh/m^2, after implementation of various energy efficiency measures.

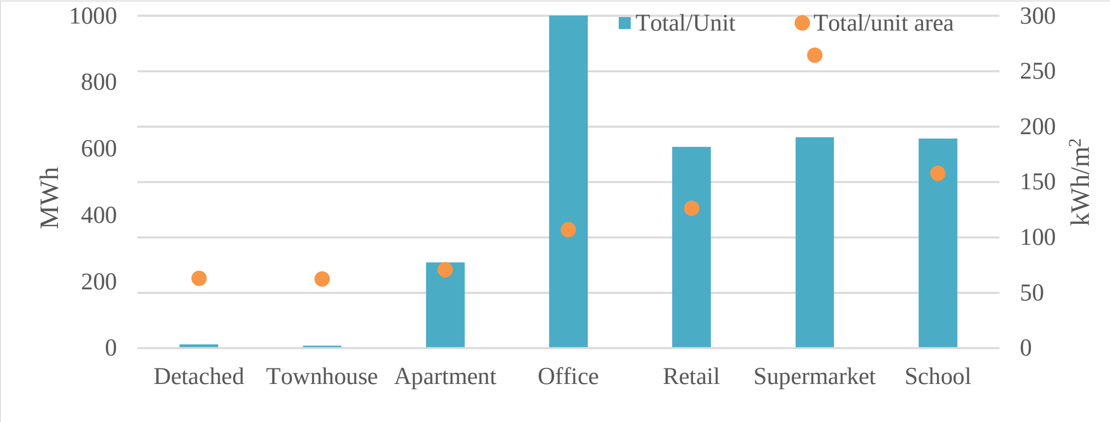

Fig. 4: Yearly energy consumption of each type of building, total and per unit area

Comparing energy consumption to potential energy generation, single-family houses, both detached and attached, can achieve an energy positive status, under the given climatic conditions. All buildings (other than houses) generate a portion of consumption, as detailed.Apartment buildings generate about 67% of their total energy consumption. The commercial buildings generate a portion of their energy consumption ranging between 45% for the office buildings and about 54% for the retail and supermarket. The school, due to its large roof area relative to its surface, generate about 90% of its energy consumption. Figure 5 presents the total energy consumption of all buildings and their potential electricity generation from BIPV.

On the level of neighbourhood, integrating PV in all available roof areas allows generation of up to 70% of the total energy consumption of this neighbourhood.

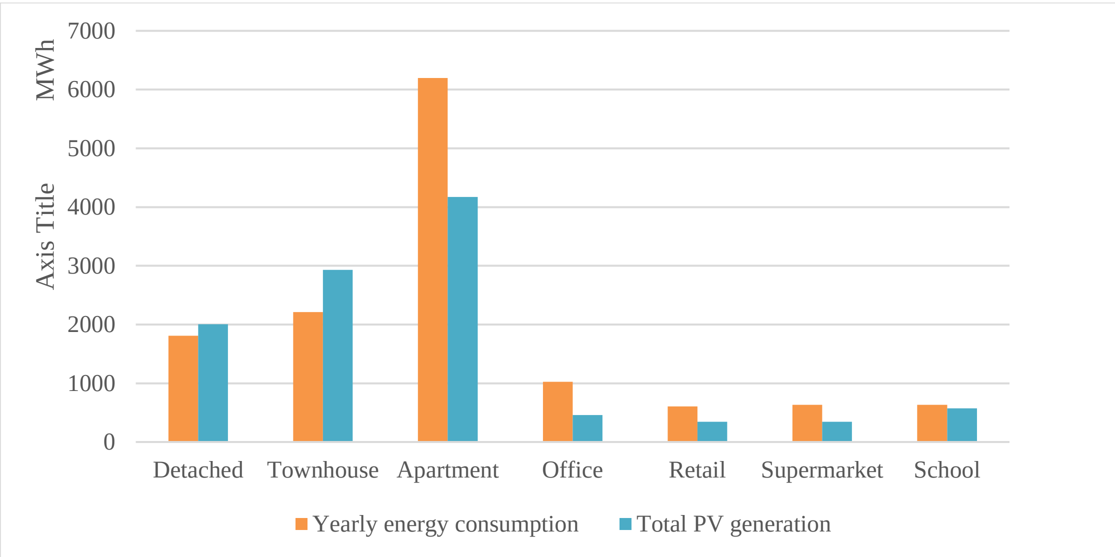

Fig. 5: Yearly energy consumption and potential electricity generation of all buildings, by building type

3.2 Solar thermal potential

Table 2 presents the combined energy needs for heating and domestic hot water for each district and their respective peak demand. The table presents as well the area used for thermal collectors, the peak thermal energy generation, and the volume of the thermal energy storage tanks. Some of the quadrants are characterized by similar profiles of energy requirements, depending on the number and types of buildings included in these districts. For instance, D13-D16 (Fig 3) are low-density residential districts with the same amount of housing units, and therefore have identical heating and DHW profiles.

Table 2: Thermal loads, generation from solar thermal and solar storage tanks

Districts		D1,2,4	D3	D5-8	D9,11,12	D10	D13-16
Total energy req. (H+DHW)	MWh	888.46	767.10	481.90	500.64	563.49	265.35
Peak thermal power demand	MW	1.22	1.00	0.65	0.66	0.91	0.35
Area solar thermal	m2	2500	2159	1356	1409	1586	747
Peak generated thermal power from ST	MW	1.50	1.30	0.81	0.85	1.15	0.45
Volume thermal energy storage tank	m3	250	206	134	136	187	73

Table 3 presents the total solar thermal energy generation potential of the neighbourhood, together with the auxiliary heating, and the solar fraction for each of the 5-year simulations period. Solar fraction is defined as the ratio of energy provided by the solar thermal collectors to the total thermal energy required by the neighbourhood. The results show that the solar thermal energy can supply up to 90% of the total thermal energy use in the last year (i.e. year 5 of the simulation period).

Table 3: Summary of solar fractions for the whole community

	Energy from solar collectors [MWh]	Auxiliary heating [MWh]	Solar Fraction [-]
Year 1	13,565.81	2,012.80	76.28%
Year 2	12,521.39	1,381.45	83.72%
Year 3	12,088.67	1,131.81	86.66%
Year 4	11,951.01	1,060.33	87.51%
Year 5	11,882.50	1,017.68	88.01%

3.3 Impact of thermal collection

The implementation of solar thermal collections to supply heating and domestic hot water for the neighbourhood is presented in this section. Both the original neighbourhood, where heat pump is employed to supply heating and cooling, and the updated solar neighbourhood implementing STC and BTES are presented in Figure 6.

The results show that employing STC combined with BTES has a significant potential to reduce the overall energy consumption of the residential sector (by up to 50%) (See Fig. 6a). Although the impact of this technology is somewhat lower on the commercial sector, energy reduction can reach up to 30% for some building types (e.g. Retail) (Fig6b).

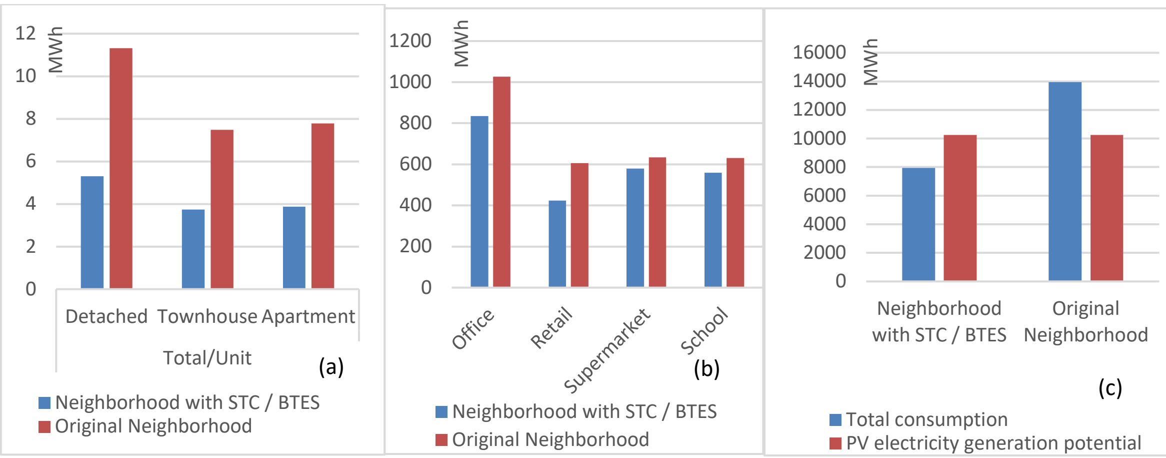

Fig. 6: performance of each type of building and of the neighbourhood, with and without the implementation of the STC/BTES; (a) Energy consumption of residential buildings, (b) Energy consumption of commercial buildings, (c) energy generation and energy consumption of all the neighbourhood

The reduction in energy consumption of the whole neighbourhood as compared to the original neighbourhood (high performance but without STC+BTES) is about 40% (see Fig 6c). This is mostly due to the reduction in energy consumption of residential sector especially the apartment buildings, which contribute to a large part of the energy consumption of the neighbourhood. The neighbourhood as a whole is 20% energy positive with implementation of STC, BTES (See Fig. 6c).

4. Conclusion

This paper presents a mixed-use neighbourhood (residential and commercial) designed in Calgary, AB, Canada, based on available guidelines and on existing standards of community designs. This neighbourhood is developed through a series of studies to achieve a high-energy performance. In addition, a solar thermal collection and storage system is implemented.

The paper summarizes the performance of various types of buildings, the overall energy performance of the neighbourhood, as well as the impact of implementing solar thermal collectors coupled with thermal storage on the performance of this neighbourhood.

The study shows that under the given climatic conditions, and the assumption that PV panels are integrated on all available south facing roof areas, apartment buildings and offices are capable of generating only a portion of their energy consumption while detached and attached houses can achieve an energy positive status.

Combining solar collection (STC) with geothermal storage (BTES) technologies can significantly reduce the overall electrical energy consumption of both residential and commercial/institutional sectors (by up to 50% and 30% respectively, for the model neighbourhood). This is particularly relevant to high-density apartment buildings, having energy consumption higher than their potential to generate renewable energy from building integrated PV systems, due to reduced available building surfaces for PV integration. Employing STC and BTES leads to over 40% overall electrical energy reduction of the whole neighbourhood, as compared to the scenario of high performance but without STC/BTES. Implementing STC coupled with BTES, allows this high-performance neighbourhood to achieve an energy positive status, generating up to 20% energy in excess of consumption. This represents a significant improvement to the original neighbourhood, which supplies about 70% of its total energy consumption. The storage system, needs however about 3 to 5 years to reach stable performance, with solar fraction of about 90%.

5. References

Armstrong, M., Swintona, M.C., Ribberink, H., Beausoleil-Morrison, I., Millette, J., 2009. Synthetically Derived Profiles for Representing Occupant-Driven Electric Loads in Canadian Housing, Journal of Building Performance Simulation.

Barton, H., Grant, M., Guise, R., 2010. Shaping Neighbourhoods: For Local Health and Global Sustainability, Routledge; 2nd edition.

Cellura, M., Di Gangi, A., Longo, S., Orioli, A. 2013. An Italian input-output model for the assessment of energy and environmental benefits arising from retrofit actions of buildings. Energy and Buildings, 62, 97-106. doi:10.1016/j.enbuild.2013.02.056

Cellura, M., Guarino, F., Longo, S., Mistretta, M., & Orioli, A. 2013. The role of the building sector for reducing energy consumption and greenhouse gases: An Italian case study. Renewable Energy, 60, 586-597. doi:10.1016/j.renene.2013.06.019

CHBA Pulse Survey, 2014. http://chba.ca/uploads/pulse%20survey%20results/Pulse%20-%20Alberta%20-%20Winter%202014-5.pdf

CMHC, 2011. The Fused Grid. http://www.cmhc.ca/en/inpr/su/sucopl/fugr/index.cfm, visited on Jan. 12, 2014.

De Winter F. Solar collectors, energy storage, and materials. Massachusetts: The MIT press; 1991.

EnergyPlus. 2016 Version 7.2, Lawrence Berkeley National Laboratory, Berkeley, CA

Hachem , C., Guarino, F., and Cellura, M., 2018, Towards Achieving Net-Zero Energy Communities: Investigation of Design Strategies and Seasonal Solar Collection and Storage net-zero, Journal of Solar Energy, in press.

Hachem C., Fazio, P., and Athienitis, A., 2013. Solar optimized residential neighbourhoods: Evaluation and design methodology, Journal of Solar Energy, 95, 42–64.

Hachem, C., 2016. Impact of neighbourhood design on energy performance and GHG emissions, Applied Energy, 177, 422–434.

Hugo, A., Zmeureanu, R., and Rivard H., Modelling of a Seasonal Thermal Storage System in a Residential Building, 3rd Canadian Solar Buildings Conference Fredericton, N.B., Aug. 20-22, 2008.

Legacy OpenStudio Plug-in for SketchUp, 2014. https://bigladdersoftware.com/projects/euclid/

McDowell, T.& Thornton, J. 2008. Simulation and model calibration of a large-scale seasonal storage system. Proceedings of the 3rd National Conference of the International Buildings Performance Simulation Association, USA, Berkeley.

NRCan (2013). Office of Energy Efficiency. Energy Efficiency Trends in Canada 1990 to 2013. https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/pdf/trends2013.pdf

Pahud D., Hellstrom G., MazzarellaL, 1996. Duct Ground Heat Storage Model, Manual for Computer Code, Department of Mathematical Physics, University of Lund, Sweden.

Sibbit, B., McClenahan, D., Djebbar, R., Paget, K. 2015 Groundbreaking Solar, High Performance Buildings Magazine p 1-12, www.hpbmagazine.org.

Thermal Storage Model. Lund-DST. TRNSYS 13.1 Version 1993. ITW, Universität Stuttgart, Germany, Dipartimento di Energetica, Politechnico di Milano, Italy.

Traditional Neighbourhood Development (TND). http://www.sustainablecitiesinstitute.org/topics/land-use-and-planning/traditional-neighbourhood-development-%28tnd%29), last accessed on 19/12/2017.

University of Wisconsin et al., 2014, TRNSYS 17 http://sel.me.wisc.edu/trnsys/index.html, last accessed on 19/12/2017.