Exploring Hydrogen-Based Energy Storage Systems for Canadian Residential Buildings: An Energy Evaluation Methodology

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Abstract. In recent years, integrating solar energy systems and hydrogen-based energy storage systems into residential buildings has shown promise in reducing urban greenhouse gas emissions and achieving clean energy supply. However, there is a lack of evaluation on the application potential of hydrogen-based energy storage systems in urban residential buildings. Therefore, a comprehensive energy evaluation method that considers urban building energy differences was implemented in 20 Canadian cities to evaluate the net-zero energy building status. The simulations were based on a typical residential building in North America. The results indicate that, for selected cities, the hydrogen-based energy storage system effectively addresses the seasonal energy mismatch and improves the energy self-sufficiency rate of urban residential buildings. These cities are classified as net-zero energy cities, nearly zero-energy cities, and non-net-zero energy cities based on their energy self-sufficiency rate. It is recommended to adopt hydrogen-only energy storage systems, hydrogen-electricity energy storage systems, and diverse renewable energy resources as integrated solutions to achieve net-zero emission buildings. The proposed energy analysis method can provide technical references for Canadian planners to plan a reasonable hydrogen roadmap for urban residential buildings.

1 Introduction

Over 15 million residential buildings in Canada contribute to approximately 18% of greenhouse gas (GHG) emissions due to space heating and cooling, cooking, domestic hot water, and electrical appliances [1]. This consistent energy demand has resulted in a rapid increase in GHG emissions. Developing high-efficiency and low-cost urban residential buildings that integrate solar energy conversion technology is essential for alleviating the adverse environmental impact of carbonaceous energy sources and reducing GHG emissions. However, the seasonal production of solar energy poses a considerable obstacle to the continuous fulfillment of building energy demand, making it necessary to implement an energy storage system to relieve the seasonal mismatch between energy production and demand. In Canada, a significant challenge pertaining to energy storage systems is developing long-term and high-energy density storage carriers to manage significant seasonal mismatches caused by extreme seasonal climate variations in high-latitude areas [2]. Compared to batteries, which have low energy densities and high leakage rates, and hydro pumps, which have high energy dissipation rates, hydrogen is a green energy carrier with non-carbonaceous characteristics, high energy density, low leakage rate, and various storage forms. Therefore, integrating hydrogen-based energy storage systems with solar energy systems in urban residential buildings is a promising approach to achieving net-zero emission buildings (NZEBs) in Canada.

Solar energy systems with hydrogen-based energy storage systems (SESH$_2$ES) are comprised of hydrogen-only energy systems and hybrid hydrogen electricity systems. Due to the low conversion efficiency of hydrogen-only storage systems, hybrid hydrogen electricity SESH2ES has been extensively investigated for designing distributed energy systems in various urban residential buildings, where hydrogen is applied as the primary energy carrier for long-term and large-scale energy storage. However, classical energy operation strategies are inadequate to address complex energy conversion processes and various storage carrier combinations [3].

Recently, many new energy management approaches based on different optimization goals have been proposed to improve the system configuration and performance of SESH$_2$ES for optimal decision-making strategies. For example, Endo et al. [4] proposed an optimal energy storage operation method to achieve minimal GHG emissions and validated the feasibility of implementing SESH$_2$ES in Japanese low-rise buildings. Zhao et al. [5] proposed an energy allocation strategy based on the minimum operational cost of SESH$_2$ES, which decreased the annual power cost of storage priority systems by 9.8% and 25.1%. Fan et al. [6] developed a comprehensive energy management schedule for SESH$_2$ES to achieve the best balance among carbon emissions, cost, and grid interaction by employing a multi-objective optimization model. The results showed that the maximum reductions achieved in terms of annual carbon emissions, annual costs, and total grid interactions were 8.2%, 2.3%, and 13.8%, respectively. These studies demonstrate the potential of using advanced energy management approaches to improve the performance of SESH$_2$ES and promote the adoption of sustainable energy systems in urban residential buildings.

While most studies mentioned above have focused on analyzing the application of SESH$_2$ES for urban residential buildings in specific cities, analyzing specific buildings alone cannot provide comprehensive results for developing hydrogen standards for urban residential buildings. It is essential to consider urban energy differences in the application evaluation of SESH$_2$ES. As Canada begins the large-scale implementation of SESH$_2$ES for urban buildings to reduce GHG emissions, it is crucial to evaluate the urban application potential of SESH$_2$ES to formulate more effective urban energy policies for different cities.

Therefore, this study aims to develop an application potential evaluation method that considers urban energy differences. The study compares and quantifies the application potential of SESH$_2$ES for achieving NZEBs in major Canadian urban residential buildings based on a novel energy evaluation method. Canadian planners can use the simulation results to develop reasonable hydrogen policies for urban residential buildings. The energy analysis framework is jointly operated on the EnergyPlus and MATLAB R2021b platforms, providing an efficient tool for evaluating the application potential of SESH2ES in urban residential buildings.

2 Methodology

Figure 1 shows a typical grid-connected urban residential building equipped with SESH$_2$ES, which includes an individual building, an exterior power supply unit, and a hydrogen-based storage unit. The on-site rooftop photovoltaic system (PV) generates energy that is consumed by occupants, lighting, electric equipment, and heating, ventilation, and air conditioning (HVAC) in buildings. Any surplus energy is stored in the battery and hydrogen storage units of the hydrogen-based storage system. When the energy production of SESH$_2$ES is insufficient to satisfy the energy demand, the power grid matches the energy gap. This way, SESH$_2$ES can maintain the energy balance of the building, reduce energy costs, and promote clean energy consumption in urban residential buildings.

Single-detached houses were chosen to evaluate the typical energy production and demand of urban residential buildings in Canada. This choice is because single-detached houses account for 53.6% of all dwelling types in Canada [7]. The selected single-detached houses comprise two floors, one basement, and one garage, as shown in Figure 2. The building geometric parameters are summarized in Table 1. By selecting this type of building, the study can simulate the energy consumption and production of a typical urban residential building in Canada and evaluate the application potential of SESH$_2$ES for achieving NZEBs in urban residential buildings.

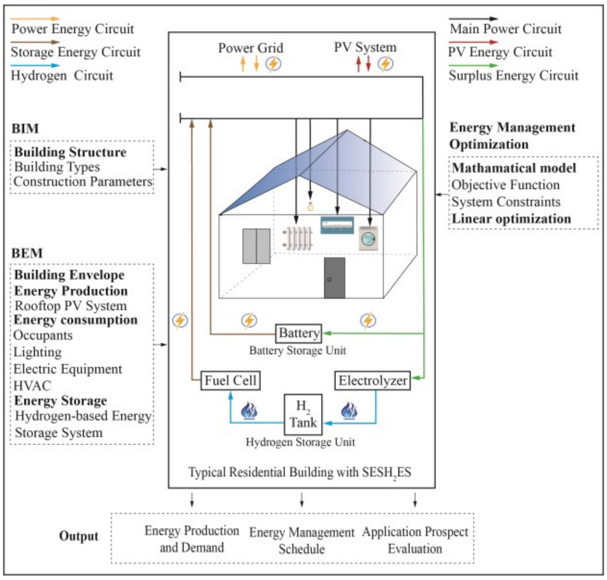

Fig. 1. Application potential evaluation method of SESH$_2$ES for residential buildings.

Fig. 2. Building model of single-detached houses.

Table 1. Information of building geometric characteristics.

Quantity	Value
Net floor area (m^2)	321
Net space volume (m^3)	1029
Total wall surface (m^2)	355
Wall surface (m^2)	174
Window-to-wall ratio (%)	23, 20*

*The maximum window-to-wall ratio is 0.27~0.40 in Climate Zones 4~7, and is 0.2 in Climate Zone 8, according to National Energy Code of Canada for Building [8].

The Canadian climate is divided into five zones, from Climate Zone 4 to Climate Zone 8, according to ANSI/ASHRAE Standard 169-2021 [9]. To improve the applicability and representativeness of the single-detached house in different regions of Canada, the building envelope, lighting, electrical equipment, and HVAC were adjusted according to the requirements of each climate zone in ASHRAE 90.2-2018 [10]. For building energy analysis, a simplified single-zone model was selected as the zoning configuration. The rooftop PV systems were parallelly installed on the roof of the main and second floors. The panel area was 137m^2, and the PV module efficiency and performance ratio were 0.22 and 0.8, respectively. By adjusting the building's features according to the climatic characteristics of different regions in Canada, the study can more accurately simulate the energy consumption and production of urban residential buildings and evaluate the potential of SESH2ES in different climate zones.

This study aims to evaluate the level of NZEBs for single-detached houses equipped with SESH$_2$ES in long-term energy management. Hydrogen-based storage systems have proven advantageous in managing seasonal fluctuations and monthly energy storage. Based on the above considerations, an operation strategy is proposed that prioritizes hydrogen-based energy storage systems to reduce reliance on the power grid. When energy production is surplus or deficient, priority is given to hydrogen-based energy storage systems. The operation strategy of SESH$_2$ES is implemented based on a typical year, and the management time interval is set to one month. The energy management optimization methodology was designed to achieve the highest self-sufficiency rate (SSR) for single-detached houses. The objective of the energy management strategy was to minimize the interaction between grid power energy and residential energy networks, as formulated in Eq. (1). The nonlinear objective function (OF) was linearized by introducing auxiliary variables to solve the nonlinear objective function. The objective function was then transformed into Eq. (2), and new constraints were introduced in Eqs. (3) to (4) [11]. By optimizing the energy management strategy, the study can achieve optimal energy utilization, reduce energy costs, and improve the energy self-sufficiency rate of single-detached houses.

$$OF = min\sum_{t=1}^{12}\left|E_t^{Grid,input} - E_t^{Grid,output}\right| \quad (1)$$

$$OF = \min\sum_{t=1}^{12}\left(E_t^{Grid,AV1} + E_t^{Grid,AV2}\right) \quad (2)$$

$$E_t^{Grid,input} - E_t^{Grid,output} + E_t^{Grid,AV1} - E_t^{Grid,AV2} = 0;\ \forall t \in T \quad (3)$$

$$E_t^{Grid,AV1} > 0;\ E_t^{Grid,AV2} > 0;\ \forall t \in T \quad (4)$$

where, $E_t^{Grid,input}$ and $E_t^{Grid,output}$ are the input or output electricity of grid at time *t* (kWh); $E_t^{Grid,AV1}$ and $E_t^{Grid,AV1}$ are auxiliary variables.

The constraint Eq. (5) ensures the electricity balance of SESH$_2$ES at any time.

$$E_t^{PV} + E_t^{FC} + E_t^{Bat,dch} + E_t^{Grid,input} = E_t^{ED} + E_t^{Ely} + E_t^{Bat,ch} + E_t^{Grid,output}; \forall t \in T \quad (5)$$

where, E_t^{PV}, E_t^{FC}, E_t^{ED}, and E_t^{ELy} are corresponding to the electrical energy of energy production, fuel cell, energy demand and electrolyzer (kWh); $E_t^{Bat,dch}$ and $E_t^{Bat,ch}$ are the discharge or charge electricity of battery at time *t* (kWh); $E_t^{Grid,input}$ and $E_t^{Grid,output}$ are the input or output electricity of grid at time *t* (kWh).

Eqs. (6) and (7) force the input and output of grid power to be complementary when grid power interacts with SESH$_2$ES.

$$E_t^{Grid,i} = \delta_t^{Grid,i} \cdot E_t^{Grid,i};\ \forall t \in T \wedge i \in \{input, output\} \quad (6)$$

$$\delta_t^{Grid,input} + \delta_t^{Grid,output} \le 1;\ \forall t\ \in\ T \quad (7)$$

where, $\delta_t^{Grid,input}$ and $\delta_t^{Grid,output}$ are the binary variables for grid input or output at time *t*.

Binary variables are used to describe the state of charge and discharge of the battery. The maximum exchange energy between the battery and grid power is limited by the battery capacity, as indicated in Eq. (8). The state of the battery's capacity is described by Eq. (9), which is restricted by the minimum and maximum allowed state of charge (SoC) to prolong the battery life, as shown in Eq. (10). Finally, Eq. (11) is employed to prevent the simultaneous charging and discharging of the battery.

$$0 \le E_t^{Bat,i} \le \delta_t^{Bat,i} \cdot E^{Bat};\ \forall t \in T \wedge i \in \{ch, dch\} \quad (8)$$

$$S_{t+1}^{BS} = S_t^{BS} + \eta^{Bat,ch}E_t^{Bat,ch} - \frac{E_{s,t}^{Bat,dch}}{\eta^{Bat,dch}}; \forall t \in T \quad (9)$$

$$SoC^{BS,min} \cdot E^{Bat} \le S_{t+1}^{BS} \le SoC^{BS,max} \cdot E^{Bat};\ \forall t \in T \quad (10)$$

$$\delta_t^{Bat,ch} + \delta_t^{Bat,dch} \le 1;\ \forall t\ \in\ T \quad (11)$$

where, S_t^{BS} and S_{t+1}^{BS} are the stored electricity in a battery at time *t* or *t+1* (kWh); $\eta^{\ Bat,ch}$ and $\eta^{\ Bat,dch}$ are the conversion efficiency of battery unit (0.9); $SoC^{BS,min}$ and $SoC^{BS,max}$ are the maximum or minimum storage percentage of battery (0.1~0.9); $\delta_t^{Bat,ch}$ and $\delta_t^{Bat,dch}$ are the binary variables for battery discharge or charge at time *t*.

The initial value of the battery capacity is defined as 20% of the battery capacity at the beginning of the time horizon. To ensure that no additional energy is stored in the battery system at the end of the time horizon, the final battery capacity is forced to be the same as the initial value, as shown in Eq. (12).

$$S_1^{BS} = S_{end}^{BS} = 0.2E^{Bat} \quad (12)$$

The hydrogen storage unit comprises an electrolyzer, a fuel cell, and a hydrogen tank. In the process of mutual transformation between hydrogen and electricity, the energy capacity of the electrolyzer and fuel cell is limited by the hydrogen stored in the hydrogen tank, as shown in Eqs. (13) and (14). The state of the hydrogen storage volume in the hydrogen tank is described by Eq. (15), which is restricted by the minimum and maximum allowed level of hydrogen (LoH), as shown in Eq. (16). Lastly, Eq. (17) forces the water electrolysis and reverse hydrolysis processes in the hydrogen storage unit to be complementary.

$$0 \le E_t^{Ely} \le \delta_t^{Ely} \cdot \eta^{Ely}L^{HS};\ \forall t \in T \quad (13)$$

$$0 \le E_t^{FC} \le \delta_t^{FC} \cdot \eta^{FC}L^{HS};\ \forall t \in T \quad (14)$$

$$L_{t+1}^{HS} = L_t^{HS} + \frac{E_{s,t}^{Ely}}{\eta^{Ely}} - \frac{E_{s,t}^{FC}}{\eta^{FC}}; \forall t\ \in\ T \quad (15)$$

$$LoH^{HS,min} \cdot L^{HS} \le L_{t+1}^{HS} \le LoH^{HS,max} \cdot L^{HS}; \forall t\ \in\ T \quad (16)$$

$$\delta_t^{Ely} + \delta_t^{FC} \le 1; \forall t\ \in\ T \quad (17)$$

where, L_t^{HS} and L_{t+1}^{HS} are the stored hydrogen in a hydrogen storage tank at time *t* or *t+1* (kg); η^{Ely} and η^{FC} are the conversion efficiency of electrolyzer and fuel cell (0.2 and 0.6); $LoH^{HS,min}$ and $LoH^{HS,max}$ are the maximum or minimum storage percentage of hydrogen storage tank (0.1~0.9); δ_t^{Ely} and δ_t^{FC} are the binary variables for electrolyzer and fuel cell at time *t*.

Eq. (18) is similar to Eq. (12). The initial value of the hydrogen volume in the hydrogen tank is set as 20% of the volume of the hydrogen tank, and the hydrogen volume is equal at the beginning and end of the time horizon.

$$L_1^{HS} = L_{end}^{HS} = 0.2L^{HS} \tag{18}$$

Eqs. (19) and (20) are to prevent the energy flow between the battery storage unit and the hydrogen storage unit to restrict energy waste among subunits.

$$\delta_t^{Bat,ch} + \delta_t^{Fc} \leq 1; \forall t \in T \tag{19}$$

$$\delta_t^{Bat,dch} + \delta_t^{Ely} \leq 1; \forall t \in T \tag{20}$$

3 Results and discussion

To ensure a comprehensive analysis of the performance of SESH$_2$ES in urban residential buildings across different regions in Canada, the study selected 20 representative cities from each province and territory based on population quantity. The climate datasets in Canadian cities are critical in predicting energy production and demand in EnergyPlus, so the study utilized the Canadian Weather Energy and Engineering Datasets to estimate the urban energy status in the 20 selected cities.

To further analyze the system performance of SESH$_2$ES in urban residential buildings, the study proposed the hydrogen electricity storage ratio (HESR) to assess the effect of the mixing degree of the two storage carriers on the system's energy performance. A higher HESR indicates a higher proportion of hydrogen storage in the total energy storage capacity. In this study, the hydrogen storage unit is considered the dominant energy storage subunit in the implementation of hydrogen electricity SESH2ES, resulting in an HESR exceeding 1. The total energy storage capacity of SESH2ES in each city was set as the annual surplus energy, ensuring a fair and consistent comparison of the system's performance across different regions and cities in Canada.

Fig. 3 illustrates the impact of the HESR on the SSR of the single-detached houses in the 20 selected cities in Canada. The results show that the house SSR in all cities exhibits a similar trend as the HESR increases in hydrogen electricity SESH$_2$ES implemented in urban residential buildings. The house SSR decreases rapidly as the HESR increases but remains less than 10, whereas the change in the house SSR is less significant as the HESR increases beyond 10. The battery storage unit has a significant impact on the house SSR only when the battery storage capacity is sufficiently high.

The study found that the house SSRs in most Canadian cities range from 75% to 120% when hydrogen electricity SESH$_2$ES is implemented, indicating that these cities can achieve net-zero energy building status. However, the house SSRs were higher than 140% in Victoria and Vancouver, indicating the potential for excess energy generation and storage. Conversely, the house SSRs were lower than 75% in Goose Bay, Whitehorse, Yellowknife, and Iqaluit, suggesting that the implementation of hydrogen electricity SESH$_2$ES may not be suitable for achieving net-zero energy building status in these cities.

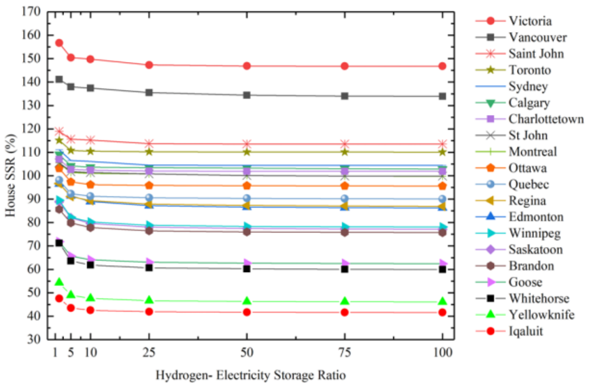

Fig. 3. The optimal house SSRs of 20 selected cities under seven types of HESR.

Fig. 8 presents the potential energy policy for achieving NZEBs in residential buildings in different Canadian cities. The optimal SSR was used to quantify the application potential of SESH2ES for achieving NZEB status in each city. Based on the house SSR, the cities were categorized into three types: (1) net zero emission cities (NZECs) with an SSR higher than 100%, (2) nearly zero emission cities (nZECs) with an SSR between 90% and 100%, and (3) non-net zero emission cities (NNZECs) with an SSR lower than 90%.

SESH2ES should be developed for all cities in Canada as all were NNZECs without storage systems. Victoria, Vancouver, Saint John, Toronto, Sydney, Calgary, and Charlottetown were NZECs, and hydrogen-only SESH$_2$ES could achieve NZEB status in these cities. Therefore, these cities could explore hydrogen applications such as hydrogen vehicles using hydrogen-only SESH$_2$ES. St John, Montreal, and Ottawa were nZECs, and hydrogen electricity SESH$_2$ES could be used to achieve NZEB status, provided the HESR was less than 10. Ottawa became an NZEC only when the HESR of hydrogen electricity SESH$_2$ES decreased to 1. The HESR of hydrogen electricity SESH$_2$ES in these cities should be adjusted to balance energy performance and environmental burden. Quebec, Regina, Edmonton, Winnipeg, Saskatoon, Brandon, Goose Bay, Whitehorse, Yellowknife, and Iqaluit were NNZECs and required additional energy inputs, such as electricity from the power grid and hydrogen from the market, to achieve NZEB status. The integration of diverse forms of renewable energy, such as wind, biomass, or hydropower, should be considered in these cities.

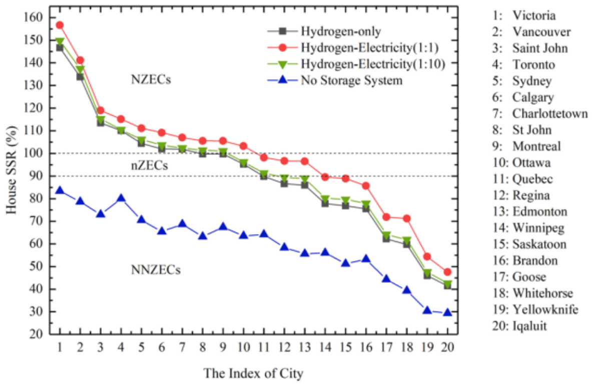

Fig. 4. The application potential comparison of 20 selected cities under different types of SESH$_2$ES.

4 Conclusion

In this study, we presented an application potential evaluation method that considers urban energy differences to effectively evaluate the energy performance of SESH2ES for urban residential buildings in Canada. This method fully considers the differences in energy production and demand caused by urban geographical conditions. We applied this energy evaluation method to assess the application potential of SESH$_2$ES for NZEBs in different Canadian cities. The results will enable planners to formulate a hydrogen policy for NZEBs based on the urban energy status. The main conclusions are summarized below:

Firstly, none of the cities can achieve NZEB status without implementing SESH$_2$ES. SESH$_2$ES can effectively improve the house SSR by storing and transferring surplus energy. The scale of improvement in house SSR depends on the annual net energy of each city.

Secondly, we classified the 20 representative cities in Canada into NZECs, nZECs, and NNZECs based on the house SSR. We recommended the adoption of hydrogen-only SESH$_2$ES, hydrogen electricity SESH$_2$ES, and diverse renewable energy resources for these cities, respectively, to achieve NZEB status for urban residential buildings.

Lastly, the HESR is crucial in determining the system performance of hydrogen electricity SESH$_2$ES. The HESR has a threshold that discriminates the degree of influence on the house SSR. Only a large battery storage capacity significantly affects the house SSR, which implies that the HESR significantly affects the house SSR when it is lower than the threshold. Therefore, we recommended that the HESR should be lower than 10 when implementing hydrogen electricity SESH$_2$ES to achieve NZEBs in each Canadian city.

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