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Housing stock in cold-climate countries: Conversion challenges for net zero emission buildings

S. Rasoul Asaee, Amir Sharafian, Omar E. Herrera, Paul Blomerus, Walter Mérida*

Clean Energy Research Centre, The University of British Columbia, 2360 East Mall, Vancouver, BC V6T 1Z3, Canada

HIGHLIGHTS

- The challenges to convert housing stock to net zero emissions is investigated.
- About 70% of existing houses were built in the absence of energy efficiency measures.
- In cold climates, over 80% of residential energy consumption is from heating.
- Complete electrification of heating will not fulfill the net zero emissions requirement.
- Retrofits and decarbonization of energy are required to achieve the net zero emission targets.

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ABSTRACT

The residential sector is responsible for 11.7% of global greenhouse gas (GHG) emissions. Space and domestic hot water (DHW) heating accounts for about 80% of the energy consumption of households in cold-climate regions. This study investigates the status of the housing stock in a set of cold-climate countries (i.e., Northern Europe and Canada) with the goal of identifying the barriers to achieving net zero emission (NZEm) status in the residential sector. Several parameters are analyzed, including vintage, energy mixture for onsite heating and offsite electricity generation, energy use, and GHG emissions intensities. Potential scenarios of energy supply and their impact on energy consumption and GHG emissions of the residential sector are discussed. Results show that the existing houses are not energy efficient, and it will be a challenge to reduce the GHG emissions of the residential sector. The energy outlooks indicate that the carbon intensity of grid electricity would not be zero due to reliance on fossil fuels. Therefore, an existing household could not achieve NZEm status by solely using grid electricity. Deep energy retrofits, renewable energy technologies, and reducing the carbon intensity of energy sources are measures to be implemented to achieve NZEm status for the residential sector.

1. Introduction

Environmental challenges and growing public awareness put pressure on countries to move toward a low-carbon economy. Policies to limit greenhouse gas (GHG) emissions include using renewable/alternative energy technologies, retrofitting existing energy systems, and changing consumers' behavior [1]. In preparation for the 2015 Conference of Parties (COP21), countries communicated their intended nationally determined contributions (INDCs) toward achieving the objectives of the United Nations Framework Convention on Climate Change (UNFCCC) [2]. The Intergovernmental Panel on Climate Change (IPCC) classified sectoral GHG emissions into six categories: (i) energy, (ii) industrial processes, (iii) solvent and other product use, (iv) agriculture, (v) land-use change and forestry, and (vi) waste [3]. According to the INDCs, most countries considered GHG emissions reduction in all IPCC sectors. However, the policies to achieve the GHG emissions reduction targets, and their impact on the economy and energy market are not well understood [4]. In 2010, the residential sector (categorized under the IPCC energy sector) generated 5.68 Gt of CO_{2e} emissions, accounting for 11.7% of the global GHG emissions [5]. Energy demand for space conditioning and domestic hot water (DHW) heating has the largest share (about 60%–70%) in household energy use worldwide [5,6]. Energy consumption for space and DHW heating exceeds 80% of households' energy use in countries with cold climates, such as Canada and northern European countries [7,8]. Therefore, strategies to reduce residential GHG emissions should focus on heating technologies, especially in cold-climate regions.

The decarbonization of energy systems including the residential

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* Corresponding author.

E-mail address: walter.merida@ubc.ca (W. Mérida).

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sector was the topic of several papers. Kannan and Strachan [9] used a system wide energy-economy model to study the impact of decarbonization scenarios on the housing stock in the UK. They suggested alternate decarbonization scenarios based on the assumptions related to future of the UK housing stock. In another study, Dodds [10] incorporated a simplified housing stock model in an existing energy system model to assess the impact of decarbonization scenarios in the UK. The revised model provided a more detailed insight regarding the consumer behavior, government policies, and technology trends impacts on the residential heating than the original model. Shi et al. [11] studied the impact of renewable energy utilization and technical progress on the Chinese residential sector energy consumption. They concluded that energy conservation practices can reduce up to 10% of residential energy consumption by 2050. Vaillancourt et al. [12] investigated the impact of decarbonization scenarios to limit the temperature rise below 2 °C by 2100 on the energy systems in Canada. They concluded that the energy efficiency improvements and decarbonizing electricity generation were the mandatory steps to achieve the GHG emissions reduction targets by 2100. Morvaj et al. [13] studied the impact of decarbonizing electricity supply on GHG emissions of urban districts. Their results showed that the share of renewable energy sources for utility electricity generation strongly affects the decarbonization scenarios. Above 70% renewable share would be required to approach the Switzerland's GHG emissions reduction targets using heat pump systems. Pietzcker et al. [14] assessed the feasibility of solar energy technologies to achieve the decarbonization targets. They used an energy-economic-climate model to determine the solar technology which will be dominant from the economic perspective during 2020 and 2100. Their results indicated that the photovoltaic (PV) technology and concentrating solar power would be the dominant options in the short- and long-terms, respectively. Hargreaves et al. [15] presented a method to compare the economic viability of energy efficiency and decentralized energy supply at building and community scale. The results of a case study for the southeast regions of England indicated that a ground source heat pump system is a more suitable option for low density development scenarios than high density ones.

A net zero energy building (NZEB) was defined by the US Department of Energy (USDOE) as "an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy" [16]. Other definitions for NZEBs have also been recommended in the literature [17–21]. The USDOE definition is widely accepted as a common definition for NZEBs [16]. However, a collective definition for a net zero emission building (NZEmB) has not been defined so far. In an earlier study, Torcellini et al. [17] defined a NZEmB as a building that produces equal or more emission-free energy as it uses from emission-producing energy sources. Kibert and Mirhadi Fard [22] reviewed the net zero energy, renewable energy, low energy, and low-carbon building definitions in the literature and identified conflicts and gaps in those definitions. A series of recommendations was provided to facilitate the international collaborations for refining policy and investment in collaborative research on high-performance buildings. They argued that the net zero energy concept can be extended to other resources such as water, materials, and land. In this paper, the NZEmB is considered as a target for the housing stock. Adopting a widely accepted definition for NZEmB is a first step to defining and implementing policies to convert housing stock into a carbon-neutral sector. In this study, a NZEmB is defined as a building that on an annual basis generates less or equal GHG emissions than the GHG emissions avoided by producing carbon-neutral energy sources.

So far, studies have focused on design requirements and policies to promote NZEBs for new construction. For example, Szalay and Zöld [23] introduced a methodology to define primary energy requirements using a large sample of houses in contrast with the conventional method of regulating energy-saving measures based on reference buildings. The methodology was used to develop requirements for new NZEBs in Hungary. Their results indicated that one- and two-storey single detached case study houses with favorable solar design parameters, including surface to volume, surface to floor area, and proper orientation, can fulfill the NZEB requirements. Berry and Davidson [24] studied a case study house and showed that the NZEB is an economically feasible building energy standard for new homes in the warm temperate range of Australia. High-performance energy technologies such as high-performance glazing, insulation, solar water heater, and solar PV technology were used to achieve the NZE status for the case study house. Asaee et al. [25–33] studied a series of retrofit scenarios for existing Canadian houses and developed strategies to facilitate the conversion of Canadian housing stock into NZEBs. They developed numerous retrofit scenarios involving various technologies for each Canadian province. The performance of retrofit scenarios was determined based on the post-retrofit source energy intensity and GHG emission intensity of Canadian houses. Results indicated that converting a large number of existing houses to NZEBs was not feasible without other improvements in energy infrastructure. Several barriers, including the design and geometry of existing houses and the availability of energy sources, limited the possibility of achieving NZE status for existing Canadian houses. However, with careful selection of retrofit options, achieving near-NZE status was a realistic goal for a large percentage of Canadian houses. For example, a retrofit scenario that includes building an integrated photovoltaic and thermal (BIPV/T) system, making envelope modifications, and upgrading appliances and lighting yields the lowest post-retrofit source energy intensity in seven provinces in Canada. Timmons et al. [34] presented an approach for minimizing the cost of decarbonizing building energy use. They showed that the total cost of residential building energy use could be minimized by equating the cost of conserved energy and the carbon-free energy obtained. The authors claimed that the carbon tax and carbon limit could have a lower cost to society for decarbonizing building energy than subsidies for renewable energy and traditional prescriptive building codes. They argued that homeowners may not respond to subsidies and building codes in an optimized manner: some may underinvest in energy conservation while others may overinvest.

Some authors focused on the socioeconomic impact of energy conservation policies in the building sector. Broin et al. [35] conducted an empirical analysis to evaluate the effects of policies on the energy demand for residential heating in Europe. They concluded that the regulatory policies have stronger impact on reductions in residential heating demand than the financial policies. Yeatts et al. [36] reviewed the barriers and potential strategies to overcome the challenges of wide use of energy-efficient technologies in design, construction, operation, and demolition of buildings. Knowledge, access, and intent were identified as the three main barriers to using energy-efficient technologies. They concluded that the same strategy cannot work in all countries, and further research is required. Urge-Vorsatz et al. [6] reviewed the main sustainability challenges regarding thermal energy use in buildings. Their study showed that building energy consumption affects national energy security, especially in countries where power generation and heating rely heavily on imported energy. For example, 40% of energy consumption in the European Union's (EU's) building sector is imported, and building energy savings improve energy security. In addition, fuel poverty, which is defined as the inability of households to afford energy services, was related to the energy inefficiency of dwellings in several countries. They concluded that close to 80% of the thermal energy demand of buildings in 2005 will be locked in unless ambitious performance improvement scenarios in the building sector are adopted. Cooper [37] conducted a study to identify the underlying reasons for the low impact of social sciences on energy policy making. The analysis revealed that the limited use of technical data in social studies of energy resulted in low impact of those studies. It is possible to develop practical but problematic energy policy solely based on technical data; however, making realistic energy policies only on the basis of social studies proved to be impractical. Therefore, they