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Towards greening the U.S. residential building stock: A system dynamics approach

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ABSTRACT

Energy consumption in residential buildings is one of the major sources of greenhouse gas (GHG) emissions in the U.S. Most of the efforts to minimize these emissions contemplate on construction of new high performance green buildings rather than retrofitting the existing residential building stock, which has the greatest emission reduction potential. In this paper, rapidly increasing GHG emissions trend associated with the U.S. residential building stock is addressed. The objective is to reduce or stabilize the increasing GHG emissions trend as a result of sprawling residential building stock across the country. System Dynamics (SD) is utilized to study the mid and long term impacts of green building related policies on the GHG emissions stock. SD model is built based on stock and flow diagram, which is derived from causal loop diagram that consists of 12 endogenous and 2 exogenous variables and causal relationships. Three important action areas are considered for policy making, namely: high performance green building construction, building retrofitting, and net zero building construction. From the three policy fields, a total of 19 policy strategies (7 single and 12 hybrid) is developed and the impacts of the policies on GHG emissions trend are experimented until 2050. Among the proposed policies, retrofitting-focused policies are found to be more effective on stabilizing the GHG emissions trend compared to the policies related to the construction of new net zero and high performance green buildings. On the other hand, hybrid implementation of policies from the three policy fields provided the greatest reduction in the GHG emissions trend. One of the most important outcomes of this study is that focusing on increasing the construction rate of net zero or high performance green buildings *alone* does not help with stabilizing/reducing the GHG emissions trend unless the retrofitting of existing residential building stock is seriously considered as a strict policy along with green building policies. Analysis results also revealed that the residential green building movement *itself* is found to be far from being the driver policy in stabilizing the rapidly increasing GHG emissions trend in the long run.

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1. Introduction

Environmental concerns have been significantly increasing over the past few decades. Especially, the issues related to global climate change has been addressed by various scientists, researchers, national and international organizations, and policy makers. According to the Intergovernmental Panel on Climate Change (IPCC), the leading international body for the assessment of climate changes, current policies related to mitigating the severe effects of climate change and sustainable development practices will not be able to stop the exponential growth in Greenhouse gas (GHG) emissions over the next few decades since the fossil fuels are expected to be the dominating energy source in the global energy mix until 2030 and beyond [1]. Thus, carbon dioxide (CO_2) emitted from energy consumption are expected to grow in the world. Nonrenewable resource based energy consumption will continue to comprise significant portion of the total GHG emissions in the United States as well.

Among the sources of energy consumption, buildings' energy use is one of the major contributors of the GHG emissions in the U.S. According to the U.S. Department of Energy's recent report, energy use in the U.S. buildings is found to be responsible for 40% of the total GHG emissions in 2011. Among the building categories,

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residential buildings constituted 54% of the building's carbon footprint, while 46% was attributed to commercial buildings [2]. Due to the significant shares of buildings in total GHG emissions, it can be concluded that viable energy efficiency options in buildings can significantly decrease the GHG emissions with economic benefits. However, there are various barriers which could limit this potential such as financing, sustainable building initiatives, higher costs of reliable information, appropriate portfolios of policies and programs, and limitations inherent in building designs [1]. In this regard, the federal government and national agencies put certain goals and initiate action plans toward decreasing or in the very least stabilizing the exponential growth in steeply increasing GHG emissions trend by the middle of the 21st century. For instance, President Obama's Climate action plan targets doubling energy productivity by 2030 relative to 2010 levels. Improving energy productivity means producing more goods and services which uses less energy. Energy productivity saves money, increases jobs, and reduces energy waste, which is basically getting more GDP out of every energy unit consumed [3]. Also, the Department of Energy established new minimum efficiency standards for appliances such as dishwashers, refrigerators, and many other products. In addition, the Department of Housing and Urban Development allocated $23 million of funds to be used by the affordable housing providers, technology firms, academic institutions, and philanthropic organizations. The main objective is to test new practical approaches to be used in delivering cost-effective residential energy. The Better Buildings Challenge, a program of the U.S. Department of Energy, sets a target, which projects commercial and industrial buildings to be at least 20 percent more energy efficient by 2020 [4].

In addition to organizational efforts at the federal and state levels, there are also private and voluntary actions taken towards minimizing the environmental impacts of the buildings in the U.S. In this sense, increased knowledge and consciousness of the environmental footprint and global climate change boost the prevalence and importance of green building movement [5]. The green building concept gained its acceptance in the early 21st century and continues to shape construction and design processes of buildings [6]. There are various ways to achieve a high performance green building, which is mostly expected to function more efficient in terms of energy consumption. In general, green buildings aim to maximize the performance of the buildings by reducing consumption of energy and nonrenewable resources. To illustrate, adoption of whole building design approach [7], passive design strategies, careful selection of low environmental impact construction materials [8], optimizing daylight use, easy access to public transportation, encompassing proper location for buildings, and efficient building operation and waste management systems can be listed as some of the important applications to achieve a high performance green building (HPGB) [6]. Besides, economic savings owing to green buildings is a significant motivating factor for the construction market stakeholders and residents. As green buildings' popularity is increased and the initial implementation costs are reduced, it is expected that traditional buildings (TB) will be eventually replaced by HPGBs [9]. On the other hand, the term "Green Building" needs to be described, quantified, and understood profoundly, so that implementation of it can be successful. This need paves the way for establishment of some building assessment frameworks such as Leadership in Energy and Environmental Design (LEED), Green Globes, Living Building Challenge, CASBEE, DGNB/BNB. Among these, LEED has been identified as the most popular building rating system in United States [6].

The green building movement is a rapidly increasing trend in the U.S. Green Construction market has generated $173 billion dollars in GDP, supported over 2.4 million jobs, and provided $123 billion dollars in labor earnings [10]. The number of LEED certified buildings is projected to be almost half of the all new, nonresidential buildings by 2015 [6]. National Science and Technology Council (NSTC) aims to increase number of net-zero energy buildings (NZB). The ultimate goal is to transform the entire commercial building stock from traditional to NZB by 2050 across the nation [11]. Green Building Initiative (GBI) became the first green building organization that was accredited by American National Standards Institute (ANSI). This may also boost number of green buildings certified by Green Globes [12]. However, there is still less focus on greening the residential buildings, although the environmental impacts of residential buildings are more than that of commercial buildings [2,13–15]. The green construction market share of new green single and multifamily structures is only 7%, while the market share of nonresidential structures is approximately 93% of the total green construction market in the U.S. [10]. Thus, policies aiming to increase the share of green residential construction applications should be enhanced to assist reducing carbon footprint of residential energy use in the U.S.

There are numerous studies focusing on how to reduce carbon footprint of residential buildings as well as households. To name a few, Balaras et al. [16] studied various energy conservation options and their impact on reducing carbon footprint of European residential building stock. Dall'O et al. [17] developed a methodology to evaluate feasible retrofitting options to reduce energy use and carbon footprint of residential building stock in the European Union (EU). Uihlein and Eder [18] studied different policy options towards increasing energy efficiency of residential building stock in the EU. Jones and Kammen [19] quantified various carbon footprint reduction strategies for the U.S. households. Dietz et al. [20] used a behavioral approach to evaluate potential near-term reduction strategies by adoption of available technologies in the U.S. households. There are mainly two distinct modeling approach applied to residential sector energy consumption: top-down and bottom-up. For more information about modeling techniques and their applications to residential sector, please see the referred review studies [21,22]. In this manner, the model proposed in this study might be classified as a top-down model where historic aggregate data and macroeconomic indicators are utilized at national scale. However, the definition of top-down modeling approach does not completely fit to proposed model in this study.

Most of the studies found in literature contemplate on specific energy efficiency options or technologies and related emission reduction strategies. Furthermore, efforts on increasing the energy performance of residential buildings mostly contemplate on the new buildings [23]. On the other hand, many researchers have analyzed the performance of green buildings and stressed the drawbacks and benefits of green building applications. In these works, either a very little or no attention was paid on the long-term effects of such strategies on carbon footprint reduction at the national scale [24–26]. Although there are various ongoing strategies, policies, and researches targeting carbon footprint reduction of U.S. residential buildings, no study has been found which addresses how these targets will be achieved considering the dynamic structure of the U.S. residential building stock such as varying end-use energy shares, population, economic indicators, existing number of TBs, new construction rates of HPGBs and TBs, retrofitting applications, and temporal aspects of these variables, etc. Thus, a dynamic modeling framework is necessary to test mid to long term policies aiming to reduce energy related GHG emissions of the U.S. residential stock. Furthermore, dynamic modeling framework will allow us to estimate the impacts of transformation of TB stock to HPGBs. In this regard, current research has the following objectives:

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