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Past visions, current trends, and future context: A review of building energy, carbon, and sustainability

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ABSTRACT

People spend most of their time inside buildings, and buildings are responsible for approximately one third of total direct and indirect energy-related worldwide carbon emissions. Likewise, buildings in the U.S. account for about 40% of total U.S. energy consumption. Future building development will be driven not only by emerging challenges such as vulnerability to a changing climate and resource scarcity, but also by disruptive innovations and societal changes. Acknowledging the impossibility of predicting future building evolvement, it is imperative to develop a forward-looking vision considering buildings' significant effect on global environment, primary or source energy consumption, and occupant health, productivity, and wellbeing. As a necessary step in the development of a comprehensive vision, which will be published in a separate document, this article provides an understanding of the past, present, and future building paradigms. It presents the possible future context regarding demography, environment, and resources. It also discusses how building development in the past century was shaped by technology leapfrogging and social movements. It reviews today's key technological and social trends that are likely to influence the design and function of buildings of the future.

1. Introduction

The U.S. Department of Energy (DOE) Building Technologies Office, in collaboration with the Pacific Northwest National Laboratory, developed a vision for what U.S. mainstream buildings could become in 100 years, by which time the current building stock in the U.S. will likely be renewed [1,2]. Building service life (i.e., the period in which a building is in use) is affected by numerous factors [3]. A 50-year design life is often used in life cycle assessment [4], and some buildings can last 100 years or more with a comprehensive maintenance and replacement program [5]. A separate vision article discusses the desirable attributes for buildings in the future [186], but as a necessary step of developing a comprehensive vision for the future, this article seeks to review various projections of demographic and resource consumption data that will likely affect building design; review, assess, and learn from past visions of building paradigms; and review, assess, and project current trends in building design and technology. This work focuses broadly on typical buildings in the U.S., both commercial and residential, and accounts for energy and water use, waste streams, the productivity and health of the occupants, sustainability with respect to the building materials, land use, the surrounding natural environment, and interactions between buildings and centralized services such as electricity, natural gas, and water.

There is no doubt that creating a sustainable built environment that supports better living is a common goal in the building community. This goal cannot be reached if design paradigms, strategies, and technical solutions are partial rather than holistic. Many past building paradigms didn't fully consider buildings as components of larger districts or isolate buildings from their historical context. They either created isolated neighborhoods or zones (e.g., Neighborhood Unit [6], Garden City [7,8]) or connected buildings in a highly ordered way that did not fully respect how connectivity should be naturally formed (e.g.,

Abbreviations: DOE, U.S, Department of Energy; R & D, research and development; IEA, International Energy Agency; NASA, National Aeronautics and Space Administration; EIA, U.S. Energy Information Administration; GDP, gross domestic product; PV, photovoltaic; EPA, U.S. Environmental Protection Agency; EU, European Union; RMI, Rocky Mountain Institute; LEED, Leadership in Energy and Environmental Design; IoT, (Internet of Things)

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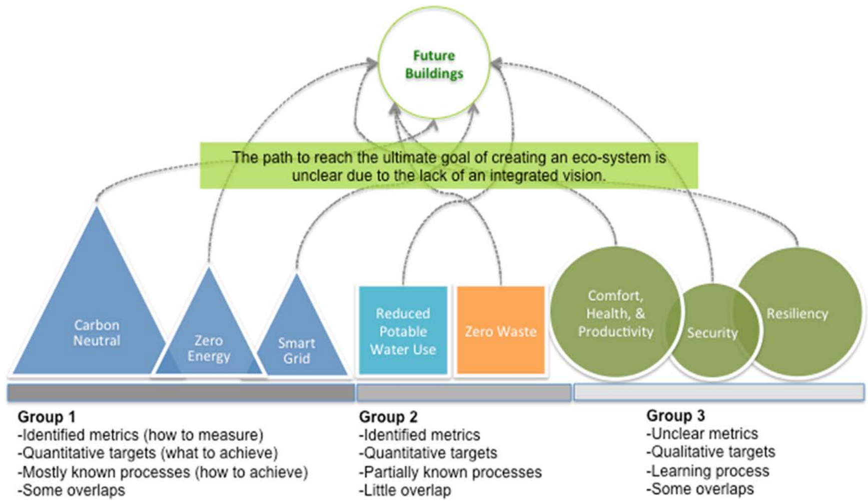

Fig. 1. Building metrics grouped by their level of development.

Radiant City [9]). In other cases, new buildings completely rejected the existing cities and communities were rebuilt relying on new technologies at that time such as automobiles (e.g., Broadacre City [10]). These utopian visions intended to resolve a number of social issues by redesigning better buildings and cities; however, they broke links between buildings and their context and left gaps in between.

Current paradigms have improved in this regard. Visionaries no longer start from scratch and they acknowledge the existing conditions of buildings and cities. Yet, fully integrated paradigms still do not exist. Building stakeholders are creating visions piece by piece. A number of building performance metrics and corresponding quantitative goals for future development (such as reductions in greenhouse gas emissions, energy and water use) have been identified. Metrics or explicit targets for many other aspects of built environments (such as health and resilience) have yet to be fully developed. Fig. 1 groups the existing efforts by their level of development. Some areas have widely accepted metrics, well-defined targets, and identified paths forward (Group 1), while others are more qualitative or anecdotal, with many unknowns (Group 3). For example, it is unclear how resilience to changing environmental conditions fits into the current commitments to reduce greenhouse gas emissions. How does one align the energy efficiency goals with water efficiency and waste management? A vision of the future is intended to fit these factors together by creating a model of connectedness. Moreover, buildings must be envisioned as active components of larger districts where urban transportation, utility services, and resource exchange are perhaps equally important.

Acknowledging the unpredictability of the future, we first explore projections of the possible future context that directly influences building development, including projections of population and demography, environmental change, and energy and water consumption. Considering the ways current priorities might influence our sense of what will be needed in the future, we review the current goals and commitments for reducing building energy use and greenhouse gas emissions to mitigate future environmental risks. We discuss why these energy efficiency and carbon reduction goals are inadequate to create a vision for buildings of the future.

Because projections of the future are biased by the priorities of the time in which they are developed, we examine past visions that were intended to guide building development and discuss lessons learned. We investigate the projections of design, technology, and lifestyle changes relative to the most pressing social and technical challenges of their time. By understanding the innovations of these past visions as well as their points of failure, we identify the most promising approaches and key stumbling blocks to a successful vision development. A review of how building development in the past century was shaped by technology leapfrogging and social movements helps us focus our research and development (R & D) activities on the essential topics that can bring value to building stakeholders today and in the future.

Based on the projections of the future and a historical view of the building stock, we review some of the popular economic, environmental, and social views today and discuss the current trends in utility, city infrastructure, and building technology developments. An examination of current R & D activities and building trends is essential to suggesting possible approaches to address current problems and lead to a more efficient, healthy, and productive built environment.

2. Future context: projections of demography, environment, energy, and water in the next century

Population growth, climate change, and resource consumption trends are all important factors that affect building design philosophy and guide the development of today's R & D goals and strategies. We anticipate that these contextual factors will remain critical for future building development.

2.1. Population growth, aging, and urbanization

Population growth increases demand for food, water, energy, land, and other resources. It is a root cause of many environmental problems. Even in the low-fertility scenario projected by the United Nations [11], the world population is projected to increase by over 20% in 50 years.[1] The U.S. population is projected to increase by over 40% in the next century[2] [11–13].

Due to rising life expectancy and declining birth rates, the median age of all countries is expected to rise, especially in developed regions (Fig. 2). The total dependency ratio[3] in the U.S. is estimated to grow from 59% in 2010 to 74% by 2050. [12]. This means that more people will need to work longer to alleviate the increasing economic burden on the working-age population. Both workplace and housing development will need to accommodate the physical and social needs of the growing senior population.

In 2014, 81% of the U.S. population lived in urban areas[4]; by 2050,

[1] From 6.1 billion in 2000 to 7.4 billion [low], 8.9 billion [medium], or 10.6 billion [hig] in 2050.

[2] From 321 million in 2015 to 420 million in 2060 and to 462 million in 2100.

[3] Dependency ratios indicate the potential burden of the dependent population, approximated by those under 18 years and those 65 years and over, on those in the working-age population [12] (p. 9). The peak dependency ratio in the U.S. was 67% in 1960 [15]. The portion of the population aged 65 and over in the United States is projected to grow from 15% in 2015 to over 20% by 2030 [14].

[4] There is no common global definition of an urban settlement. The classification criteria may be based on population density, minimum population threshold, proportion