Scenarios of energy reduction potential of zero energy building promotion in the Asia-Pacific region to year 2050

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ARTICLE INFO

Article history:
Received 9 May 2020
Received in revised form 7 August 2020
Accepted 3 September 2020
Available online 10 September 2020

Keywords:
Zero energy building
Asia-Pacific region
Future forecast

ABSTRACT

Building energy consumption in the Asia-Pacific region continues to rise. It is important to understand the energy use and future trends of 21 members of Asia-Pacific Economic Cooperation (APEC) and to find more effective ways to achieve APEC’s dual goals of reducing energy intensity by 45% of 2005 levels by 2035 and doubling the share of renewable energy in the energy mix between 2010 and 2030. Recently, promoting building toward ultra-low energy, nearly zero energy and zero energy is becoming a consensus trend. This paper aims to explore how zero energy building promotion could influence the total energy demand in the mid to long term. An EUPP (Economic, Urbanization, Population and Purchasing power parity) model was established to show the relationship between building energy consumption and its influencing factors, and the potential development path of building energy consumption in APEC was predicted by using the model. The results show that in the Business As Usual (BAU) model, building energy demand will increase from 1387.4 Mtoe in 2016 to 2456.8 Mtoe in 2050 while in the CAP model, building energy demand will be constrained to under 2000 Mtoe before 2050. In the ZEB promotion model, 897.8 to 1945.3 Mtoe could be saved separately. The share of end demand supplied by onsite renewable energy production could reach 11% - 54%. The building sector has the potential to become the largest contributor to achieve the APEC energy goal and thus to the climate change goal.

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1. Introduction

Building construction and operations accounted for 36% of global final energy usage and nearly 40% of energy-related carbon dioxide (CO2) emissions in 2017 [1]. The proportion of carbon emissions will increase to 50% if building energy consumption continues to grow at its current rate. In addition, increased adoption of electric vehicles, which are partly charged from buildings, will further increase building energy consumption while reducing emissions from transportation. The current energy security situation and related environmental issues will not be solved by merely increasing the energy supply. Considering the challenges associated with climate change and resource scarcity, there is a great opportunity to improve energy efficiency while maintaining building thermal comfort and cost-effectiveness.

APEC economies are dominated by energy imports, and energy demand continues to increase, which currently accounts for approximately 60% of world energy demand [2]. In 2011, the energy intensity goal approved by all APEC members involved reducing the overall energy intensity by 45% from 2005 levels by 2035 and
rationalizing and phasing out inefficient fossil fuel subsidies that encourage wasteful consumption while still providing essential energy services [3]. In 2014, the goal of doubling the share of renewables in the APEC energy mix between 2010 and 2030 was approved in 22nd APEC Economic Leaders’ Declaration.

At the 2015 United Nations Climate Conference, the Paris Agreement was drafted and adopted by consensus with the main objective of keeping the global average temperature increase in this century to within 2 °C and restricting the global temperature rise to within 1.5 °C above preindustrial levels [2]. Achieving the greenhouse gas (GHG) emissions mitigation potential of the building sector is essential for the world to limit global warming. Studies show that to have a 67% chance of meeting the 1.5 °C target, we must reduce CO₂ emissions by 50%—65% from today’s levels by 2030 and completely phase out fossil fuel CO₂ emissions by 2040 [4].

Recently, Canada, China, Japan, Korea, and the United States have all issued energy policies on carbon emissions reduction and non-fossil fuels; for instance, China aims to achieve a carbon cap in 2030 of 6 billion tons of coal equivalent (tce) with non-fossil fuels accounting for 20% of energy consumption [5]. Policies focused on buildings set targets for the development of Zero Energy Building (ZEB) and provide financial incentives, and subsidies were also issued to encourage best practices at the infant stage. In China, a target of 10 million m² of nearly-zero-energy buildings was set for the period from 2016 to 2020 [6]. In Korea, the 2nd Energy Master Plan requires that all newly constructed buildings should be zero-energy buildings by 2025 [7]. In addition to government goals, pioneer NGOs have also proposed mid-to-long-term goals that are much more ambitious than those of governments. The ambitious goals of the World Green Building Council proposal are that all new buildings must operate at net zero carbon from 2030 to 100% of buildings must operate at net zero carbon by 2050 [8]. METI of Japan [9], China Passive Building Alliance (CPBA) [10] and Architecture 2030 [11] have all set long-term goals of ZEB.

The APEC Zero Energy Building Program has been funded by the APEC Energy Working Group since 2013 with the objective of promoting ZEB in the APEC region as a whole; 3 reports were completed and published on the official APEC website [12-14]. Starting from that point, voluntary standards and guidelines, such as the Nearly Zero Energy Building Technical Standard [15] of China, the ZERO Code [16] developed by Architecture 2030, and the Advanced Energy Design Guide for K-12 School/Small to Medium Office Buildings to Achieve Zero Energy of ASHRAE [17,18] came onto the market with similar definitions and technical requirements. Additionally, different kinds of demonstrations were conducted to show the tremendous energy reductions resulting from ZEB.

There is no doubt that ZEB will become mainstream in building and construction sector, and the development of ZEB will restructure the energy structure in the building sector. Many developed economics have proposed goals and policies for zero energy buildings (ZEBs) [19,20]. There are many technologies that can reduce energy use in ZEBs, which can be divided between passive and active, and both have been extensively investigated. Luisa F. Cabeza [21] classified the strategies that need to be considered to achieve ZEB, including active/passive energy saving technologies, introducing renewable energy and energy storage technologies. Liu [22,23] analyzed the application prospect of solar thermoelectric cooling technologies and fresh air energy saving technology in ZEBs. Lorenzo Belussi [24] summarized the actual state-of-art of whole performance of ZEBs and the related technical solutions, and analyzed their increasing potential in energy consumption. Cristina Baglivo [25] evaluated cost-optimal levels of minimum energy performance requirements. Yang [26] proposed a three-definition hierarchy of ultra-low energy buildings, nearly-ZEB and ZEB as upgrading goals of the successive building energy codes towards 2050 in China. With the continuous progress of ZEB technology development, the next step is to study the energy saving potential of ZEB buildings in the medium and long term in the future, so as to show that the zero-energy buildings are technically feasible and contribute greatly to the overall energy consumption control. There are some research studies that have established various models to predict the energy and carbon dioxide emission reduction potential in building sector [27-29].

The existing studies on the energy saving potential of ZEB were conducted for single economy, but for the whole Asia-Pacific region, which includes 21 economies (both developed and developing). There is no study to date on how the whole region will be influenced by the promotion of ZEB. The objective of this paper is to study mid-to-long term energy savings potential by promoting ultra-low energy, nearly zero energy and zero energy buildings from successful demonstrations to the mass-market adoption. The following is a brief introduction to the steps of setting up the energy consumption development scenario.

1. Select the factors that have significant impact on building energy consumption. These factors are determined according to the APEC historical building energy consumption Data.
2. According to the factors of economy, urbanization rate and population of each economy, the potential trajectory prediction model of building energy consumption based on purchasing power parity (EUPP Model) was established.
3. Then the paper formulates two scenarios of the development process of building energy consumption in APEC. For each scenario, the trends of all factors used as the EUPP model inputs are projected to 2050.
4. Finally, three possible ZEB development schemes are proposed to explore the peak energy consumption and energy saving potential of the building.

2. Analysis of the medium - to long-term potential trajectory of building energy consumption

2.1. Basic information

In this study, the development trend of building energy consumption in 2050 is predicted by classifying and analyzing the component of the APEC base year statistics.

We categorize 21 APEC economies into 3 groups according to their climate zones:

- Cooling dominated, heating dominated and heating and cooling mixed-climate zones. Eight economies are in heating and cooling...
mixed-climate zones and are denoted as M1 to M8, 11 cooling-dominated economies are denoted as C1 to C11, and there are 2 heating-dominated economies. Detailed information is provided in Table 1. Table 1 shows the basic information of climate zones, GDP, population, and energy consumption, etc.

In APEC, as in virtually all regions of the world, economic development, urbanization, and population are major drivers of building energy consumption. The study uses gross domestic product (GDP) [49] in 2016 USD and purchasing power parity (PPP), from the World Bank for historical data. The GDP(PPP) takes into account the real purchasing power and exchange rate of money, and could be used as a reasonable indicator in the comparison of the economic level of various economies. Historical data on population [50](POP) and urbanization [51] also come from the World Bank. Building final energy consumption (BEC) is measured in the same units used by the IEA [46], and uses standard oil equivalents, which are 1.428 times the calorific value of standard coal. The economy floor areas were derived based on data from APEC [38], the EIA and each economy’s national statistics website; for Russia, South Korea, Singapore and Mexico, these values were based on data from the internet and national statistics websites [30–37,39,45,47,48]. When historical data were not available, floor areas were regressed according to data from similar economic conditions. In this study, buildings are divided into two categories, namely, residential buildings and service buildings. In which service buildings include all buildings except industry and residences and are represented by commercial buildings, offices, schools, hospitals and government buildings. Building energy intensity is calculated from basic information.

In 2016, the energy consumption of the building sector in the 21 APEC economies reached 934.7 million tons of oil equivalent (Mtoe) which accounted for 25.8% of the total energy demand. The United States, China, Canada, Japan, South Korea and Russia together account for 86.5% of total energy consumption in the building sector.

The building energy level of each economy can be reflected by its energy intensity, which can be expressed by two indexes, namely, energy consumption per capita and energy consumption per unit area, which correspond to Energy Intensity-1 (EI-1) and Energy Intensity-2 (EI-2), respectively, in Table 1. Fig. 1a show the relationship between energy consumption and GDP in the 21 APEC economies in 2016. It is very clear that as GDPs grow, Energy Intensity-1 moves toward higher consumption levels in these economies. The US has the highest level of energy consumption in APEC with an Energy Intensity-1 of 1.412 toe/person.

The average level in the traditional developed economies of Japan, South Korea, Australia and New Zealand is 0.72 toe/person. Although the economic levels are advanced in Hong Kong and Singapore, the average level of 0.481 toe/person is due to climate characteristics and restriction of per capita building area caused by the population densities. Energy Intensity-1 is approximately 0.2–0.3 toe/person in developing economies due to their lower economic levels. As show in Fig. 1b, for economies with low per capita consumption, the values of consumption per unit area are also lower.

However, it would be unacceptable for developing and moderately developed economies to move toward America’s ultrahigh energy consumption model because the trend in building energy will directly affect the control of total energy consumption. Combining the energy consumption levels of other countries outside APEC such as the United Kingdom, France and Italy, it is concluded that Energy Intensity-1 in developed countries usually does not exceed 1 toe/person, which is similar to that of Japan, South Korea and Russia.

Table 1
Basic Information in base year (2016).

| No. | Climate Zone | Economy | Energy consumption (Mtoe) | Energy consumption ratio | Population (Million) and Per Capita GDP (2016 USD) | Energy Intensity-1 (toe/p) | Total Floor Area (Million m²) | Area Per capita (m²) | Energy Intensity-2 (toe/m²) |
|-----|--------------|---------|--------------------------|-------------------------|-----------------------------------------------|---------------------------|-------------------------------|----------------------|--------------------------|
| 1   | M1 USA       | 1073.7  | 146.5                    | 247.3                   | 206.8                                         | 0.38                       | 32.3                          | 81.4                 | 5.08                     |
| 2   | M2 Japan     | 287.3   | 44.3                     | 41.8                    | 9.3                                           | 0.98                       | 32.7                          | 8.3                  | 0.67                     |
| 3   | M3 South Korea | 167.6   | 24.7                    | 20.3                    | 3.1                                           | 0.79                       | 31.3                          | 10.3                 | 0.68                     |
| 4   | M4 Australia | 76.1    | 11.9                    | 11.9                    | 1.9                                           | 0.32                       | 31.1                          | 10.3                 | 0.68                     |
| 5   | M5 New Zealand | 18.4   | 2.7                     | 1.2                     | 0.2                                           | 0.21                       | 30.2                          | 10.3                 | 0.68                     |
| 6   | M6 China     | 1397.5  | 195.0                   | 195.0                   | 27.5                                         | 0.79                       | 34.5                          | 12.0                 | 0.68                     |
| 7   | M7 Chile     | 285.5   | 40.6                    | 40.6                    | 6.0                                           | 0.79                       | 37.6                          | 12.0                 | 0.68                     |
| 8   | M8 Egypt     | 34.4    | 4.8                     | 4.8                     | 0.7                                           | 0.79                       | 34.4                          | 12.0                 | 0.68                     |
| 9   | C1 Argentina | 59.3    | 8.3                     | 8.3                     | 1.2                                           | 0.86                       | 39.0                          | 12.6                 | 0.68                     |
| 10  | C2 Hong Kong | 7.3     | 1.0                     | 1.0                     | 0.1                                           | 0.13                       | 7.3                           | 12.6                 | 0.68                     |
| 11  | C3 China     | 5.5     | 0.7                     | 0.7                     | 0.1                                           | 0.13                       | 5.5                           | 12.6                 | 0.68                     |
| 12  | C4 Malaysia | 92.1    | 12.8                    | 12.8                    | 2.1                                           | 0.13                       | 92.1                          | 12.6                 | 0.68                     |
| 13  | C5 Mexico    | 111.1   | 15.3                    | 15.3                    | 2.6                                           | 0.13                       | 111.1                         | 12.6                 | 0.68                     |
| 14  | C6 Thailand | 177.2   | 24.4                    | 24.4                    | 3.6                                           | 0.13                       | 177.2                         | 12.6                 | 0.68                     |
| 15  | C7 Indonesia | 145.9   | 20.1                    | 20.1                    | 3.0                                           | 0.13                       | 145.9                         | 12.6                 | 0.68                     |
| 16  | C8 Philippines | 31.8  | 4.4                     | 4.4                     | 0.6                                           | 0.13                       | 31.8                          | 12.6                 | 0.68                     |
| 17  | C9 Vietnam | 81.4    | 11.3                    | 11.3                    | 1.7                                           | 0.13                       | 81.4                          | 12.6                 | 0.68                     |
| 18  | C10 India    | 240.3   | 34.6                    | 34.6                    | 5.3                                           | 0.13                       | 240.3                         | 12.6                 | 0.68                     |
| 19  | C11 Pakistan | 2.4     | 0.3                     | 0.3                     | 0.02                                          | 0.13                       | 2.4                           | 12.6                 | 0.68                     |
| 20  | R1 Canada    | 152.3   | 21.7                    | 21.7                    | 3.6                                           | 0.13                       | 152.3                         | 12.6                 | 0.68                     |
| 21  | R2 Russia   | 46.7    | 6.5                     | 6.5                     | 1.0                                           | 0.13                       | 46.7                          | 12.6                 | 0.68                     |
2.2. Influencing factors and potential trajectory

In order to get the possible development trend of building energy consumption, the driving factors behind it must be revealed. Since this paper includes 21 economies rather than a single country’s energy consumption forecast, the data used to build the model include 21 sets of data for 2016 (the base year). Fig. 2 shows the relationship between variables influencing building energy consumption from which the mid-to long-term development trends can be analyzed. The relationship among building energy consumption, GDP (2016 USD PPP) per capita and urbanization rate of all economies in each climate zone is provided in this section. The building energy consumption is divided into residential buildings and service buildings, and the proportional distribution of energy consumption of the two types of buildings is discussed.

2.2.1. Energy intensity

Since the per capita index also includes the impact of per capita floor area on energy demand, it can better reflect the level of building energy consumption in each economy. This section uses Energy Intensity-1 as an index to express the energy levels of different economies.

As shown in Figs. 2a and 21 economies are divided into three climatic zones, which still show the trend that the higher the GDP is, the higher the per capita building energy consumption is. In the mixed climate zone, the overall energy consumption of America, Japan, Australia and New Zealand is relatively high. In the main cooling dominant area, Singapore and other places have higher energy consumption. In the heating dominant area, the energy consumption is higher in Canada. Moreover, as the energy demands of buildings in the same climate zone are almost similar and there is a strong correlation between Energy Intensity-1 and per capita GDP, which can be expressed as:

\[ \text{Energy Intensity} = \frac{A G^B_{\text{per capita}, i}}{G_{\text{per capita}}} \]  

(1)

Where A and B are regression coefficients of different regions, i is the different area, and G is GDP per capita.

Take the mixed climate zone as an example. According to Eq. (1), by 2050, the average Energy Intensity-1 level of developing economies will reach the average level of the base year of the traditional developed economies in the same climate zone, and these traditional developed economies will be exactly the same as the level of the US base year. (The forecast data of GDP in the outlook period are from the economic model of APEC [38]). However, considering that the building energy consumption of developed economies is already at a relatively high-comfortable level, and now it is mainly about the development of energy conservation technology. Eq. (1) is only applicable to the stage when developing economies advance to the benchmark annual energy use level of developed economies. Thus, this paper proposes a relatively energy efficient and feasible trend of building energy demand, and look for a more likely development scenario by making assumptions within a reasonable range.

As the per capita energy consumption and per capita area of the United States are significantly higher than those for other developed economies, we assume that in this building energy development model in APEC, Energy Intensity-1 in the US is no longer increasing, as greater improvements in energy efficiency outweigh the impact of small increases in building floor areas. Energy efficiency in other developed economies will also improve as a result of energy-saving measures, but the increase in building areas still leads to small increases in Energy Intensity-1 for the outlook period. Since building areas and energy consumption demands will increase significantly due to the growth of GDP per capita during the outlook period, Energy Intensity-1 of developing economies will approach the level of developed economies in the same climate zone.

2.2.2. Per capita floor area

Fig. 2b shows comparisons of per capita floor areas of APEC economies in 2016. As shown in the figures, there is a strong linear relationship between the demand for floor area and GDP per capita, especially for service buildings. This is because the economic development promotes the improvement of people’s demand for living environment and space, and the increase of purchasing power promotes the development of the tertiary industry, which inevitably leads to the increase of the demand for service floor area. Therefore, the higher the per capita GDP, the higher the per capita floor area. (residence sector and service sector).

At present, the average residential area per capita in western economies ranges from 50 m²/person to 80 m²/person while those of the Asian developing economies are generally below 40 m²/person. After analyzing the current status and development trend, this study assumes that the area per capita of Asian economies such as China, Japan and South Korea will not exceed 40 m²/person in 2050 and Western economies such as Australia and New Zealand will not exceed 80 m²/person. In the outlook period, the service
Floor area will grow rapidly, especially in developing economies, where the per capita service floor area is still less than 10 m²/person and there is much room for improvement. We suppose that by 2050, with the rapid development of economies and urbanization, the building scale of developing economies will also rise to the base-year level of developed countries, while the average area will be controlled to below 18 m²/person. Developed economies will also see a modest increase in floor area in the outlook period.

2.2.3. Ratio of energy consumption of residential building to services building

Building energy demand is divided into residential and service buildings and the share of building energy consumption of the services sector is strongly related to economic status and urbanization rates. Fig. 2c and d show the shares of residential and service energy consumption in the building sector. The ratio of residential building energy consumption to service building energy consumption is abbreviated as the ratio R/S. Lower R/S values represent higher proportions of energy consumption by service buildings. The energy consumption of service buildings is determined by the building function (e.g., dining, swimming, or recreation). By comparing R/S of 21 economies, it is found that this ratio is mainly affected by economic level. The higher the level of GDP per capita in an economy, the higher the proportion of its energy consumption in service buildings, because the economic structure of developed countries is usually dominated by the tertiary sector. In general, a higher proportion of the tertiary sector in the economy means more energy consumption in buildings [52]. Fig. 2c shows that the R/S value of developing economies with low per capita GDP is greatly affected by economic development. Eq. (2) can be used to represent the relationship between these two indicators. However, when per capita GDP reaches approximately 40,000 USD, the R/S value in various economies varies little and generally remains close to 1.

Fig. 2d shows that the slight differences in R/S values among developed economies are caused by differences in urbanization rates. When the per capita GDP exceeds 40,000, the urbanization rate usually increases to about 80%, at which point, R/S is expressed by Eq. (3).

\[
R/S = 3140.3G^{-0.748}, \quad G < 40,000 \quad (2)
\]

\[
R/S = 3 \times 10^{-7}U^{-3.843}, \quad G \geq 40,000 \quad (3)
\]

Where \( U \) is Urbanization rate.

In 2015, the Leaders of APEC, called for the development of a strategic and long-term Services Competitiveness Roadmap with actions and mutually agreed targets [53]. This decision will greatly promote the development of the tertiary sector in APEC. Since the GDP share of tertiary sector in developed economies has little room for improvement, the transformation of industrial structure in developing economies will make a large contribution to this goal. R/S can represent the trend of energy consumption in buildings due to economic development. Therefore, as an economy develops, the share of service building energy consumption in developing economies will inevitably increase toward the level seen for developed economies in the outlook period, while the share in developed economies will barely change.
3. Methodologies

By analyzing the historical data of 21 economies, it is found that building energy consumption is a function of economy, urbanization rate and population. According to the factors of economy, urbanization rate and population of each economy, the potential trajectory prediction model of building energy consumption based on purchasing power parity (EUPP Model) was established. Fig. 3 shows the flow of the model to predict building energy consumption.

In the basic situation, the development trend of per capita energy consumption is used to predict the total building energy consumption, and unit area building energy consumption is calculated according to the total building energy consumption and building area forecast data. Based on the assumption of the possibility of developing ZEB scenario, the energy saving potential of higher zero energy consumption target in the future is obtained.

3.1. Development of building energy consumption until 2050

Energy consumption in the building sector ultimately serves the people in the building, and the demand of the people affected by per-capita GDP is the dominant factor in energy consumption. According to the economic development model in APEC 2050 Outlook 7th Edition [38], per-capita GDPs in developing economies will match or exceed the base-year levels in developed economies by 2050, so there is ample evidence that Energy Intensity-1 of developing economies, driven by per-capita GDP, will rise to the current average of developed economies. Population predictions in this study are from the United Nations Department of Economic and Social Affairs (UNDESA) [54]. The total building energy consumption can be expressed as:

\[
E = \sum_{i} e_{\text{per capita},i} \cdot \text{pop}_i
\]  

where \(E\) is total building energy use; \(e\) is the Energy Intensity-1, determined by eq. (1); Pop is the population; and \(i\) stands for the different area.

3.2. Move toward the ZEB scenario

By 2050, the zero-energy building area will inevitably continue to expand, and its proportion in the total building area depends on efforts of promotion and levels of recognition of ZEB. Since the strict index of nearly zero energy buildings is energy consumption per unit building area, the calculation of energy consumption under the zero-energy development path covered in this paper is based on building areas and Energy Intensity-2. The buildings consist of existing buildings, ultra-low energy buildings, nearly ZEBs and ZEBs. The total building energy consumption is measured as final energy demand, which can be expressed as follows:

\[
E = \sum_{i} \sum_{k} e_{\text{existing},i,k} \cdot A_{i,k} \cdot f_{\text{existing}} + e_{\text{ultra-low},i,k} \cdot A_{i,k} \cdot f_{\text{ultra-low}} + e_{\text{NZEB},i,k} \cdot A_{i,k} \cdot f_{\text{NZEB}} + e_{\text{ZEB},i,k} \cdot A_{i,k} \cdot f_{\text{ZEB}}
\]  

where \(E\) is total building energy use; \(e\) is the Energy Intensity-2, determined by eq. (6) and eq. (7); \(A\) is the building area; \(k\) is the building type, e.g., residential or service building; \(i\) is the climate zone; and \(f\) is the area percentage of different building types, including existing buildings, ultra-low-energy buildings, near-zero-energy buildings and zero-energy buildings.

Through the forecast of total building energy demand, R/S and building area for BAU, the temporal variations of energy intensity...
can be expressed as follows:

\[ \text{Energy Intensity}_{\text{residential}} = \frac{|E_{\text{BAU}} - E_{\text{BAU}}|}{(R/S + 1)} / A_{\text{residential}} \]  

(6)

\[ \text{Energy Intensity}_{\text{services}} = \frac{|E_{\text{BAU}}|}{(R/S + 1)} / A_{\text{service}} \]  

(7)

4. Projection energy consumption results and analysis in 2050

4.1. Potential energy consumption development trajectory

According to the trends shown in Fig. 2a, two building energy consumption scenarios were constructed by adjusting the development degree of Energy Intensity-1. These two scenarios represent the latest energy trends in APEC and potential future trajectories in building sector energy between 2016 and 2050. The energy projections in this section are demand-driven, and the two scenarios use a consistent set of assumptions for population, GDP, and floor area. The specific details of these two scenarios are shown in Table 2.

The first scenario (Business As Usual, BAU) assumes that all building energy saving measures are generally promoted at their existing levels, but it does not consider relevant policies that directly constrain the response to climate change, environmental pollution, building energy consumption intensity and total quantity control and does not guide residential lifestyles. In mixed-climate zones, Energy Intensity-1 in developed economies will increase by 2050 to the average value of Japan, South Korea, Australia and New Zealand in 2016. In cooling-dominated zones, the average Energy Intensity-1 of all economies by 2050 will be the same as the average value of Singapore, Hong Kong and Taiwan in 2016. In areas dominated by heating, Russia will move toward Canadian levels. In developed economies, will not increase unlimitedly according to the growth mode of Eq. (1), since building energy consumption per unit area has been declining in recent years Energy Intensity-1s due to the development of energy-saving technologies. In this paper, Energy Intensity growth rate of developed economies is adjusted within a reasonable range to ensure that the development trend of energy consumption per unit area is more in line with the reality. This scenario provides a baseline assumption against which other scenarios can be compared.

The second scenario (CAP) considers the APEC Leaders’ aspirational goal to reduce the region’s energy intensity (e.g. toe per 2016 USD million PPP) by 45% from 2005 levels by 2035. To achieve this goal, all industries need to control the total amount of energy consumption. The total volume control target for the building sector needs to be kept below 2000 Mtoe during the outlook period, which is similar to the prediction in Asia Pacific Energy Research Centre (APEC) [38]. A key benefit of such modeling, as mentioned above, is that it enables comparisons of feasible trends against what needs to change to meet particular targets.

4.2. Analysis of building energy consumption until 2050

Based on the above forecast of population and energy consumption modes, the development of building energy is initially analyzed.

Fig. 4a shows the energy consumption predictions from 2020 to 2050 for BAU. The United States, China, Canada, Japan, South Korea and Russia still dominate building energy demand in 2050 and in total represent 80.04% of the total building sector demand in APEC. Over the outlook period for BAU, APEC building demand increases from 1387.4 Mtoe in 2016 to 2456.8 Mtoe in 2050, which is primarily driven by energy demand growth in developing economies. Rising demand is driven by the two-pronged effect of growing populations, which pushes up demand for residential dwellings as well as services, and economic growth in APEC’s developing economies, which increases the population’s ability to supply and consume energy services. It can be seen under the relatively energy-saving development model that reaches to the moderately developed level, building energy demand will still increase significantly in the outlook period. Given that there is still much room for improvement in GDP, urbanization, and living standards in developing economies, building energy may grow to this level if people’s increasing energy demands are met without continuing to push for stronger building efficiency efforts, policies and regulations.

Fig. 4b shows building energy consumption under the CAP model. To fulfill the APEC Leaders’ ambitious goal of reducing total energy intensity by 45% in 2035 compared with 2005, the building demand should be controlled under 1770.46 Mtoe in 2035 and then it will still increase reach to no more than 2000 Mtoe in 2050. In this scenario, the energy demand of the building sector by 2050 will reach 1922.6 Mtoe, which is a 25% reduction compared to the BAU model. Comparing the two development models, it can be seen that the growth trend of energy consumption for the CAP model is obviously slowing down. The offset of end uses in buildings compared with BAU depends on the APEC economies starting to move toward more energy-saving technologies and beginning to adopt more energy-efficient building codes and appliance standards, which are reflected in a decline in Energy Intensity-2.

Since the two scenarios both considered the continuous development of energy-efficiency technology and upgrading of living standard, the potential temporal variations of the Energy Intensity-2 in BAU and CAP modes in developed economies and developing economies we assumed can be found in Fig. 5. The 21 economies

| Climate Zone | Economy | Population (Million) | Energy Intensity-1 (toe/person) | Residential Area Per capita (m²/person) | Services Area Per capita (m²/person) |
|--------------|---------|----------------------|---------------------------------|---------------------------------------|-------------------------------------|
| Mixed        | 1 US    | 389.59               | 1.142                           | 1.1298                                | 80.00                               |
|              | 2 Japan, South Korea, Australia, New Zealand | 198.15 | 0.8346 | 0.7455 | 60.00 |
|              | 3 China, Chile, and Peru | 1426.80 | 0.724 | 0.5792 | 40.00 |
| Cooling      | 1–3 Hong Kong, China, Singapore, and Chinese Taipei | 37.60 | 0.5743 | 0.481 | 31.670 |
| dominant     | 4 Other economies | 873.26 | 0.480 | 0.388 | 30.000 |
| Heating      | 1 Canada | 132.73 | 1.8936 | 1.7358 | 70.000 |
| dominant     | 2 Russia | 44.95 | 1.578 | 1.2624 | 35.000 |
|              | 3 Japan, South Korea, Australia, New Zealand | 198.15 | 0.8346 | 0.7455 | 60.00 |
|              | 4 Other economies | 873.26 | 0.480 | 0.388 | 30.000 |
are divided into two parts: the developed and the developing. According to the two development trajectories of building energy consumption, the overall energy consumption intensity of the building sector in each part can be obtained.

In BAU model, the Energy Intensity-2 of the developed economies will decline due to slight improvements in energy efficiency while Energy Intensity-2 in the developing economies will increase due to the increase of floor area and energy demand and will eventually converge to the same level. In CAP, the energy efficiency of the developing economies also improves while the building areas and energy demands also increase, so Energy Intensity-2 is almost unchanged. Compared with BAU, the average level of Energy Intensity-2 for the developed and developing economies needs to drop by 12.5% and 20%, respectively, in 2050. Therefore, the building sector needs to find more efficient energy saving paths to ensure that the overall APEC energy consumption targets are met.

5. Energy reduction potential of higher targets toward zero energy in future

In addition to the goal of reducing total energy intensity by 45% by 2035, the APEC energy ministers issued a joint statement in 2014, in which they agreed to achieve the goal of “doubling the share of renewables in the APEC energy mix, by 2030 from 2010 levels.” (All biomass in the residential and services sectors is not counted toward the doubling goal) [55] As a result, all industries must improve energy efficiency (thereby reducing demand) and promote renewables. Under the APEC goals, the building sector faces the dual challenges of improving Energy Intensity-2 and increasing its share of renewable energy.

In this section, the different scenarios of building energy consumption in the medium-to-long term in the APEC region were predicted. In addition, according to the prospect of higher ambitious targets toward net zero energy by government documents and building energy alliances, the energy reduction potential of ZEB promotion was analyzed.

5.1. ZEB scenario setting

It is difficult to transition building energy directly from the current situation to zero energy, for which a two or three step plan of building energy codes being upgraded to achieve zero energy is feasible. From a global perspective, building toward zero energy is the ultimate global goal in response and makes contributions to addressing climate change and extreme weather. To explore possible pathways and policy options for building energy efficiency and emission reductions in APEC, three scenarios are defined. Under these three scenarios, the total volume of ultra-low, nearly zero and zero energy buildings will reach 50%, 75% and 100%, respectively, by 2050. Table 3 provides detailed definitions of the scenarios.

Building energy consumption is related to energy intensity and building area. Thus, both temporal variations of intensity and building area must be studied. In Table 4, the building floor areas are predicted and will increase 1.5 times in the outlook period (e.g., from 124.8 billion square meters in 2016 to 195.0 billion square meters in 2050), of which the residential building area increased by 32.27% and the service building area increased by more than 100%, which is similar to the prediction results of APERC [55]. Floor areas in the services sector grow more quickly than in residential buildings because increasing population and increasing urbanization drive up demand for services such as schools, health care facilities and commercial spaces at the same time that the economic structure is shifting, particularly in developing economics.

Even the energy consumption could be influenced by different factors, but the energy quota requirement in building standards and the actual consumption in the best practices are in the same range. For the energy consumption of ultra-low energy buildings and nearly ZEBs, the average energy intensity value that used in the model prediction was derived from previous research outcome on best practice analysis [13]. The energy intensity of ultra-low and nearly zero residential building are 0.0059 toe/m² and 0.0022 toe/m² (68 kWh/m² and 26 kWh/m²), respectively. The energy consumption could be influenced by different factors, but the energy quota requirement in building standards and the actual consumption in the best practices are in the same range.
intensity of ultra-low and nearly zero service buildings are 0.0073 toe/m² and 0.0028 toe/m² (85 kWh/m² and 32.5 kWh/m²), respectively. For ZEBs, in which the total amount of energy used by the buildings is roughly equal to the amount of renewable energy created, the energy consumption intensity is 0. For the energy consumption of ultra-low and nearly ZEBs buildings, the average energy consumption intensity after removing the generated renewable energy derived from the best practice is used here.

For residential buildings, both heating and cooling demands vary greatly in different climate zones. However, in total, the building energy consumption intensity for ultra-low energy buildings and nearly ZEBs for different climate zones are similar.

### Table 3

Percentages of different building types for the study scenarios.

| ZEB-1  | Existing | 100% | 95% | 85% | 70% | 50% |
|--------|----------|------|-----|-----|-----|-----|
| Ultra-low energy | 0% | 5% | 10% | 15% | 25% |
| Nearly ZEB | 0% | 0% | 5% | 10% | 15% |
| ZEB | 0% | 0% | 0% | 5% | 10% |

| ZEB-2  | Existing | 100% | 90% | 75% | 50% | 25% |
|--------|----------|------|-----|-----|-----|-----|
| Ultra-low energy | 0% | 10% | 15% | 20% | 30% |
| Nearly ZEB | 0% | 0% | 5% | 20% | 20% |
| ZEB | 0% | 0% | 5% | 10% | 25% |

| ZEB-3  | Existing | 100% | 90% | 60% | 30% | 0% |
|--------|----------|------|-----|-----|-----|-----|
| Ultra-low energy | 0% | 5% | 20% | 25% | 30% |
| Nearly ZEB | 0% | 5% | 15% | 30% | 30% |
| ZEB | 0% | 0% | 5% | 15% | 40% |

### Table 4

Energy Intensity-2 and floor area of existing buildings and their development toward 2050 in different climate zones for BAU.

| Climate Zone | 2016 | 2020 | 2030 | 2040 | 2050 |
|--------------|------|------|------|------|------|
| Total building floor area (Million m²) | Residential | Mixed | 81093.10 | 84800.04 | 90933.35 | 95160.64 | 97211.04 |
| | Cooling dominant | 16562.67 | 18470.07 | 22769.26 | 26991.13 | 30969.88 |
| | Heating dominant | 5463.97 | 5784.53 | 6504.37 | 7140.89 | 7791.98 |
| | Heating dominant | 16830.21 | 18944.49 | 25544.82 | 33524.10 | 44441.37 |
| | Cooling dominant | 2606.20 | 3119.90 | 4673.47 | 6567.88 | 9766.75 |
| Energy Intensity 2 (toe/m²) | Residential | Mix | 0.0084 | 0.0084 | 0.0085 | 0.0086 | 0.0086 |
| | Cooling dominant | 0.0072 | 0.0073 | 0.0077 | 0.0079 | 0.0080 |
| | Heating dominant | 0.0246 | 0.0242 | 0.0235 | 0.0228 | 0.0224 |
| | Heating dominant | 0.0185 | 0.0184 | 0.0184 | 0.0182 | 0.0180 |
| | Heating dominant | 0.0170 | 0.0166 | 0.0169 | 0.0172 | 0.0176 |
| | Heating dominant | 0.0281 | 0.0277 | 0.0271 | 0.0266 | 0.0262 |

5.2. Analysis of energy consumption in the ZEB scenarios of 2050

Different building development strategies deliver very different futures. Fig. 6 presents three possible building energy pathways toward 2050. In 2016, energy consumption of buildings was 1394.7 Mtoe, excluding the energy demand of industrial buildings. As shown in Fig. 6a, in BAU and CAP, building energy consumption continues to increase over the outlook period and reaches 2456.8 Mtoe and 1992.6 Mtoe, respectively, by 2050. For the three ZEB scenarios, building energy consumption first increases and then decreases. In the ZEB-3 development scenario in which ultra-low energy, nearly ZEBs and ZEBs will begin to develop in 2020 and all buildings in APEC will be ultra-low energy, nearly ZEBs and ZEBs by 2050, the peak will occur in 2020. In general, only if the total percentage of ultra-low energy buildings, nearly ZEBs and ZEBs is greater than 40% does the building energy consumption begin to drop. The cumulative building energy savings increase dramatically. Fig. 6b presents the cumulative energy saving compared to the BAU scenario. From 2016 to 2050, scenarios CAP and ZEB 1, 2
and 3 substantially reduce traditional energy consumption by 464.2, 897.8, 1402.5 and 1945.3 Mtoe, respectively, with the supply of renewable energy also counted as energy reduction.

Fig. 7 shows the proportion of building energy offset by renewables in ZEB scenario. Since one of the characteristics of a zero energy building is to reduce traditional energy consumption by producing onsite renewables, the energy structure remodeling of the building sector can be achieved through the development of zero energy buildings. For existing buildings, there is little potential for modern renewable energy capacity. In 2010, renewable energy was only 22 Mtoe and accounted for 1.69% of building total energy demand [55]. Thus, under the BAU and CAP models, this proportion will barely change, while through the development of zero-energy buildings, this could produce 11%, 27% and 54% onsite renewable energy by 2050, respectively. In the ZEB-3 scenario, renewable energy generation reaches 560 Mtoe by 2050 and the goal of doubling modern renewable energy by 2030 can be achieved by the building sector alone. Ultimately, the building sector has the potential to become the largest contributor to the APEC goal of doubling renewables due to development of ZEBs.

6. Conclusions

Zero-energy buildings have become a hot topic for research to reduce fossil energy consumption and greenhouse gas emissions in the building sector and are widely discussed as a form of high-performance future buildings that are also resilient to crises such as COVID-19 by integrating high energy performance with a healthy and comfortable indoor environment. This paper analyzed the relationship between energy intensity, R/S ratio, urbanization rates, per capita floor areas and per capita GDPs in both developed and developing economies; predicted the future growth of building floor areas in both residential and service buildings; and set up a BAU model according to historical data and a CAP model according to the APEC energy intensity goal, together with 3 ZEB models to see the energy reduction capacity of ZEBs promoted. The main conclusions are as follows:

(1) Building energy demands will inevitably increase following economic growth in developing economies and will be driven by increases of urbanization rates and the pursuit of more comfortable indoor environments. As the per capita GDP increases, the ratio of residential building energy consumption to service building energy consumption will decrease, especially when per capita GDP increases to more than 40,000 USD, the R/S ratio will reach 1 and become stable, which means that when economies become wealthy, more service buildings than residential buildings will be constructed. In the BAU scenario, when there is no more upgrading of building energy code requirements, APEC...
building demand will continue to increase and will reach 2456.8 Mtoe in 2050 with no peak before that.

(2) To fulfill the APEC Leaders’ ambitious goal of reducing total energy intensity by 45% in 2035 compared with 2005, building energy demand should be kept under 1770.46 Mtoe in 2035 and it will still increase and reach no more than 2000 Mtoe in 2050 but still with no peak before 2050. To achieve this goal, the EI-2 of the building sector in developed and developing economies would need to be reduced by 12.5% and 20%, respectively, compared with the BAU scenario. Therefore, the building sector needs to find more efficient energy saving paths to ensure that the overall APEC energy consumption targets are met.

(3) Mid-to long-term goal for ZEBs from governments and NGOs all encourage market growth. The ZEB promotions can meet the total energy consumption control requirements of the building sector in order to achieve APEC Leaders’ ambitious goal. Different scenarios of ZEB promotion substantially reduce energy consumption by 897.8, 1402.52 and 1945.3 Mtoe, respectively. The share of end demand supplied by onsite renewable energy production could reach 11%–54%. With accelerated rates of ZEB development, building energy consumption will begin to drop only if the total percentage of ultra-low energy buildings, nearly ZEBs and ZEBs is greater than 40% of total building stock.

(4) This paper presents a potential building energy consumption trajectory prediction model, which shows that economic development is the main driving factor of building energy demand. The results of the energy forecasting model can make comparison between different economies, so that a single economy can use the energy use levels of more advanced economies in the same climate zone to predict its own future trends. Then, the development paths of building energy consumption within different ZEB scenarios could provide reference for both single economies and the entire APEC region to set mid -to- long term goals, for example, lowering peak building energy demand in 2030–2040 while maintaining economic growth simultaneously. To achieve these long-term results, policy actions need to take place in the short term because buildings constructed now will be consuming energy for many decades. Future work is needed to assess specific technical roadmaps in different climate zones and for different building types. The gap between operation and design also needs to be tracked to prove the energy reduction potential of ZEBs.

Financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Optimization and Demand Response Research of Energy Storage System in Nearly Zero Energy Community, No.2019YFE0193100, Key Program for International S&T Cooperation Projects of China; APEC Energy Working Group, No. EWG-15-2016A, Asia-Pacific Economic Cooperation.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.energy.2020.118792.

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