Zero-energy buildings – an overview of terminology and policies in leading world regions

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Abstract
To address climate challenges, major regions of the world are developing policies to move toward ultra-low energy buildings. The European Union (EU) Energy Performance of Buildings Directive requires nearly-zero-energy buildings (nZEB) in all EU member countries by 2020. In the United States (U.S.), the move is toward "net-zero-energy buildings" (NZEB). Despite the apparent similarity in these terms, there are significant differences in the definitions, policies, and support mechanisms associated with these and other similar goals. These differences make it difficult to understand and evaluate global progress toward lower-energy buildings and create confusion for other countries such as China that are considering setting similar goals. Such confusion could create barriers to low-energy-building initiatives in developing regions. To support further research and sharing of best practices around the globe, this paper reviews and compares the definitions of key "zero energy" terms in major world regions, with a focus on two jurisdictions at the forefront of zero-energy buildings: Denmark in the EU and the state of California in the U.S. Our analysis summarizes policy activities that are being implemented to promote zero-energy buildings, highlights differences among policy elements and criteria, and assesses the progress in regions that have adopted zero-energy policies. From the current international experience, we consider policy implications for China and other emerging economies that are currently working to develop goals for zero-energy buildings.

Introduction
In the developed world, buildings consume more energy than any other sector. Reducing energy consumption in buildings is essential to mitigating climate change and creating sustainable urban environments (the latter challenge is pressing for developing countries that are in the process of massive urbanization). Given the global challenges of climate change and resource shortages, much more is required than incremental increases in energy efficiency. Currently, The European Union (EU) Energy Performance of Buildings Directive (EPBD) requires nearly-zero-energy buildings (nZEB) in all EU member countries by 2020 while the United States is pursuing "net-zero-energy buildings" (NZEB). Despite the apparent similarity in these terms, there are significant differences in the definitions, policies, and support mechanisms associated with these and other similar goals. These differences make it difficult to understand and evaluate global progress toward ultra-low energy buildings and create confusion for other countries such as China that are considering setting similar goals.

This paper reviews the international experience with "zero-energy building" terminology and policy with the aim of providing information for developing regions that are interested in adopting zero-energy-building goals and policies. For simplicity, in this paper we use the umbrella term "zero-energy building" (ZEB) to refer to all of the various types of low-energy-buildings encompassed in the initiatives we studied.

In the remainder of this paper, we first discuss the major differences among ZEB definitions in the EU and U.S. Next, we briefly describe the general ZEB policies adopted in the EU and the U.S. and elaborate on policy examples from leading regions on the two continents: Denmark in the EU and California in the U.S. Broadly speaking, the zero-energy-building policy framework includes eight components: targets and building codes, certification, economic instruments, compliance enforcement, information tools, demonstration projects, education and training, and research and development (R&D) (Ecofys, Politecnico di Milano, & University of Wuppertal, 2013). We review the building energy-efficiency and renewable-energy (mainly solar photovoltaic [PV]) elements of each of these components. Then, we describe current ZEB activities in China. Finally, based on the EU and the U.S. examples, we describe terminology and policy implications for China and other emerging economies that are considering development of ZEB goals.

This study only addresses new construction because that is where the ZEB concept is usually mandated in the national and regional energy policies. The technical challenges of achieving zero energy consumption by retrofitting existing buildings are generally greater than the challenges in new construction. Despite the challenges associated with retrofits, five EU member states have demonstrated nearly-zero-energy building renovation projects under the ZenN project (2013–2017) (Karlsson et al., 2013) and many other projects.

Definitions

Defining a ZEB concept for policy purposes encompasses wide range of factors specific to the region or jurisdiction, including the technologies to be adopted in ZEBs, the economic viability of ZEBs, the feasibility of implementing ZEB technologies, the impacts on the regional electricity grid, and the benefits to different stakeholders. These conditions, in turn, influence the deployment of the ZEB technologies.

There is currently no universally accepted definition of a ZEB. One of the aims of the joint International Energy Agency (IEA) SHC TASK40/ECBCS Annex 52, was to help illuminate the various different international ZEB definitions. Different definitions of a ZEB exist that correspond to the political and other purposes associated with promoting ZEBs in a given region (Sartori, Napolitano, & Voss, 2012). A key element of the ZEB concept is the balance between weighted energy demand and supply (see Figure 1). Currently, four definitions of this balance are commonly found around the world: net-zero site energy, net-zero source energy, net-zero energy costs, and net-zero energy emissions (see Table 1[1]). In addition to these four types of definitions, the California Energy Commission developed the time-dependent value (TDV) energy metric (California Energy Commission, 2013). The TDV was first used in the 2005 California Building Energy-Efficiency Standards and is included in the proposed ZEB standard. The TDV energy calculation is similar to the site energy consumption calculation except that site energy is converted to TDV energy using hourly TDV factors. In practice, approximately 75 balance methodologies are used around the world. In some jurisdictions, more than one metric is considered (Ecofys et al., 2013). This wide variety of metrics indicates the regional diversity of the interests and motivations of ZEB market actors.

Figure 1 shows the supply and demand balance concept involved in a ZEB. It underscores the importance of energy efficiency in achieving near-zero energy use. The ZEB design concept generally goes beyond passive design strategies.

Table 2 summarizes the differences among the variety of ZEB definitions in selected world regions.

We can see in Table 2 that different regions interpret several factors differently, including the weighting of energy supply and demand, the ZEB boundary (whether on-site or off-site renewable energy are included within the ZEB "footprint" and whether zero energy must be achieved by a single building or can be achieved over a group of buildings), what energy use is accounted for in the ZEB, the minimum requirements, and building types. These interpretations are, in turn, affected by existing required and voluntary building codes, laws and regulations, the practical feasibility for designers and building owners of realizing ZEB goals, electricity grid conditions, the economic viability of the ZEB definition itself, as well as different stakeholder interests. Newly proposed building codes will have to consider existing building codes and voluntary efficiency standards .For example, In Europe, the passive house standard and other voluntary codes are widely disseminated and form a baseline for developing the ZEB concept. In the U.S., the Leadership in Energy-Efficiency Design certificate program has provided lessons on successful marketing strategy that can help disseminate the ZEB concept.

Some general findings about the range of definitions can be summarized as follows:

- The primary energy metric (source energy) is more commonly used in the EU (this approach suits a national energy system that aims to increase renewable share), while the site energy metric (final energy) is applied extensively in the U.S. (this metric is easier to understand and implement, and appropriate for encouraging energy-efficient design) (Torcellini, Pless, & Deru, 2006).
- Plug loads are generally not included in the European definitions.
- To help meet the EU's long-term climate target, some EU definitions include minimum requirements for energy efficiency and renewable energy integration; renewable energy is less prominent in the U.S. definitions.
- Embodied energy is considered only in Norway's and Switzerland's definitions. When buildings become more efficient, the share of embodied energy from materials and manufacturing can be as high as 62 %, according to a case study in California (Faludi, D. Lepech, & Loisos, 2012). Despite the greater embodied energy from use of more insulation and other energy-efficiency measures, the total lifetime energy use of low-energy buildings is less than that of conventional buildings (IPCC working group III, 2014).
- EU building code requirements have begun gradually shifting from prescriptive to performance- or outcome-based, a major change. In the U.S., codes are generally prescriptive although performance-based codes are options in some states, including California, Massachusetts, and Oregon.

1. Note: m = final energy use at the meter; r = renewable energy produced on site; r0 = renewable energy supply off site; g = energy transmission lost; \$m = bought energy cost; \$r = on-site renewable production sales; CO_{2m} = CO_2 emissions from final energy use; CO_{2r} = offset CO_2 emissions from on-site renewable energy production; CO_{2g} = CO_2 emission offset through carbon trading schemes.

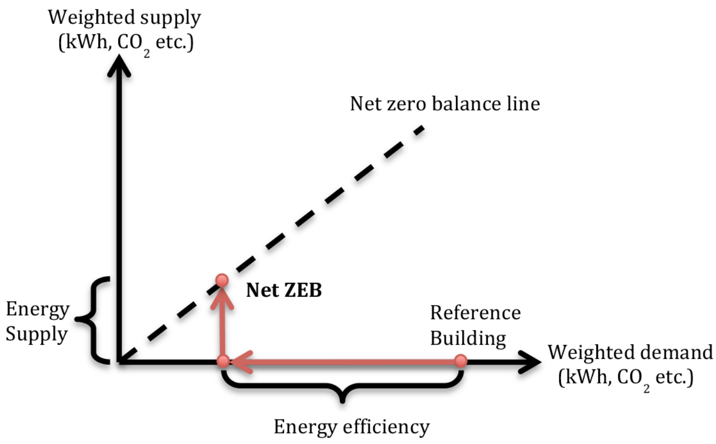

Figure 1. Net ZEB balance concept (Sartori et al., 2012).

Table 1. Common ZEB definitions (Ji & Guo, 2013).

Concept	Definition
Net-Zero Site Energy	m-r-r0 ≤ 0
Net-Zero Source Energy	m+g-r-r0 ≤ 0
Net-Zero Energy Costs	\$m-\$r ≤ 0
Net-Zero Energy Emissions	CO_{2m}- CO_{2r}- CO_{2g} ≤ 0

Context for Zero-Energy Buildings in the European Union and United States

EUROPEAN UNION

Europe aims to drastically reduce building-sector greenhouse gas emission by 88 to 91 % by 2050, compared to 1990 levels (Boermans & Grözinger, 2011). The revised EPBD requires EU member states to ensure that all new buildings occupied and owned by public authorities are nearly zero-energy buildings after 31 December 2018, and all new buildings are nearly zero-energy buildings by 31 December 2020. The EPBD, the Energy-Efficiency Directive (EED) 2012/27/EU, the directive on renewable enegy sources (209/28/EC), and directives on ecodesign and energy labeling (2009/125/EC and 2010/30/EU) provide the legal framework for the EU's ZEB target. Table 3 summarizes the intermediate and future ZEB targets in the EU and selected EU countries.

It is widely recognized that the ZEB definitions in these targets vary, and there is no uniform definition across the European continent. At the same time, in contrast to 2013 when only five member states had a ZEB definition in place (Groezinger et al., 2014), by 2014, a majority of EU member states had adopted or were in the process of approving definitions. The majority of member states target energy use of no more than 45–50 kWh/m^2/yr in new residential buildings, and up to 270 kWh/m^2/yr in hospital and other non-residential buildings (Garcia, 2015). As required by EED Article 4 (2012), member states must establish long-term strategies for mobilizing investment to renovate national building stocks, with emphasis on "deep" renovations. As such, several EU projects (ENTRANZE, COHERENO, and ZEBRA 2020) (Rapf, 2015) have been established to scale up the ZEB renovation market and ensure that the European building stock achieves long-term ZEB targets and associated benefits.

UNITED STATES

In the United States, based on the federal Energy Independence and Security Act of 2007 and Executive Order 13514, the Department of Energy (DOE) has established an aggressive goal of creating the technology and knowledge base for cost-effective zero-energy commercial buildings by 2025. Currently, DOE's proposed ZEB definition is under public review (DOE, 2015).

At the state and local levels, non-binding ZEB goals have been established in several places. For example, the California Energy Commission announced an update to Title 24, the energy-efficiency portion of the California building code, to include the ZEB goal (CPUC, 2008). The states of Massachusetts, Washington, and Oregon, and the cities of Austin, Texas and Seattle, Washington, among others, have mapped pathways toward a ZEB goal; see Table 4 for more details.

The implications of the four different ZEB definitions listed in Table 1 were reviewed by the National Renewable Energy Laboratory (NREL) (Torcellini et al., 2006). The NREL review concluded that a ZEB definition based on energy cost would be the most difficult to achieve. Source ZEB and emission ZEB definitions were found to be most closely related to national energy system planning and green power development but to

Table 2. ZEB definitions in leading world regions.

Country	Definition/ label	Metric			System boundary		End Uses and Life-Cycle Stages Included					Minimum requirements		Single building types	
		Primary (Source) energy	Final (Site) energy	Carbon emissions	On-site	Off-site	HVAC*	DHW*	Lighting	Plug load /Appliance	Embodied energy	EE*	RE* share	New	Existing
EU	EPBD*	✓			✓	✓	✓	✓	✓			✓	✓	✓	✓
DE*	EffizienzhausPlus	✓			✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
DK*	Danish Building regulation 2010 (BR10)	✓			✓	✓	✓	✓	✓			✓		✓	
CH*	Minergie-A	✓			✓		✓	✓	✓	✓	✓	✓		✓	
NO*	Zero-emission building			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
UK*	Zero-carbon standard			✓	✓	✓	✓	✓	✓			✓	✓	✓	
US**	Zero-Net- Energy Building		✓		✓	✓	✓	✓	✓	✓		✓		✓	

* HVAC – heating, ventilation, and air conditioning; DHW – domestic hot water; EE – energy efficiency; RE – renewable energy; EBPD – Energy Performance of Buildings Directive; DE – Germany; DK – Denmark; CH – Switzerland; NO – Norway; UK – United Kingdom.

** In the U.S., California has proposed to use the time-dependent valuation (TDV) metric in a definition of ZEBs.

Notes to table:

- *The definitions/labels listed are provided mostly by public authorities. Other definitions from the research community or voluntary sources are not included here.*
- *The ZEB target is usually required in new buildings.*
- *Building code regulations usually refer to single buildings, however, the ZEB concept can also be realized in cluster of buildings.*
- *End uses and life-cycle stages included (accounting system): electro mobility is generally not included except in DE.*
- *Balance period: this is typically based on the operational year; the life-cycle perspective is only considered by definitions in CH and NO.*
- *Minimum requirements also include indoor climate and comfort elements that are not listed here.*
- *The minimum renewable integration requirements in UK definition are made through carbon compliance minimum levels.*

Sources: (Zhang, Xu, Jiang, Feng, & Sun, 2014), (Ecofys et al., 2013), (Dokka, Sartori, Thyholt, Lien, & Lindberg, 2013), (Atanasiu, Kunkel, & Kouloumpi, 2013), (Zero Carbon Hug, 2014), (UK Green Building Council, 2014).

Table 3. Intermediate and future targets in the EU and selected EU countries.

Region	Intermediate and future targets
EU	New commercial buildings meet ZEB by 2018; all new buildings meet ZEB by 2020.
DE	Energy-efficiency requirements gradually tighten 25 % by 2016. Renewable energy for heating in new buildings is compulsory since 2009 (according to the German Renewable Energy Heat Act).
DK	Expected share of renewable energy in building sector is 44–51 % in 2015 and 51–56 % in 2020. Energy consumed for heating, cooling, ventilation, and hot water limited to 20 kilowatt hours per square meter per year (kwh/m^2/year) by 2020. Additional lighting requirements for non-residential buildings (25 kwh/m^2/year).
CH	Similar to Minergie-A ecological standard by 2020; consider embedded energy below 50 kwh/m^2/year.
NO	Passivhaus standards by 2017; zero emissions for all new buildings by 2020.
UK	New homes to be “zero-carbon homes” by 2016. Public buildings should be zero carbon by 2019.

Sources: (EuroACE, 2013), (Ecofys et al., 2013), (European Commission, 2013b).

Table 4. State and local ZEB plans in the United States (selected regions).

Regions	Targets
California (Hewitt, 2014)	All new residential construction will be net zero energy by 2020; all new commercial buildings will be net zero energy by 2030.
Massachusetts (Hewitt, 2014)	All new buildings will reach net zero energy by 2030 (Massachusetts zero-net-energy-building task force).
City of Austin, Texas (Global Buildings Performance Network, 2014)	Net-zero-energy-capable (designed and built so that PV will be added when it becomes more cost-effective) homes achieved by 2015; citywide net-zero impact on climate change by 2050.
Oregon (U.S. General Services Administration, 2014)	The Energy Trust of Oregon has created a “Path to Net Zero” pilot program. (Oregon Army National Guard, under U.S. Army Net Zero Initiative).
The District of Columbia (District Department of the Environment, 2013)	By 2032, 100 percent of all existing commercial and multi-family buildings should achieve net-zero energy standards. All new development should achieve net-zero energy performance standards (“Sustainable DC”).
Washington (Hewitt, 2014) (U.S. General Services Administration, 2014)	All new buildings incrementally move toward achieving a 70 % reduction in annual net energy consumption by 2031, compared to consumption in 2013. The city of Seattle has a citywide goal of carbon neutrality by the year 2030.
Vermont (Hewitt, 2014)	Incremental improvements to achieve net-zero goal before 2030.
Minnesota (Hewitt, 2014)	Meeting the goals of the Architecture 2030 program to achieve net-zero-energy buildings.

require significant information on site-source conversion and emissions factors. NREL concluded that the “site energy” definition was easy to understand and well accepted among the U.S. building community.

The ZEB concept has recently taken off in the U.S., and technical feasibility studies have been conducted for a variety of building types in the nation’s diverse climate zones. To date, there are 39 verified ZEBs or clusters of buildings that, as a group, achieve zero energy in the U.S. (it has been documented that these projects meet, over the course of a year, all net energy demand through on-site renewable sources of energy (New Building Institute, 2015). Among others about one-third of U.S. ZEBs are located in California, and California has been recognized as a leader in the ZEB market transformation (Cortese, Higgins, Lyles, & Hamilton, 2014).

Policy examples from leading jurisdictions: Denmark and California

In addition to the general ZEB policies adopted in the EU and the U.S., the policy examples of Denmark and California could be considered best practices on the two continents. California has been leading the U.S. ZEB market in terms of total built projects, and Denmark, which has among the most progressive and ambitious energy and climate policies in the world, was one of the first two EU member states to establish an official national ZEB plan. Focusing on these two examples allows us to break down their policy frameworks into the eight components identified previously and discuss these components specifically. This section of the paper introduces the general energy policy and role of ZEB targets in these selected jurisdictions.

DENMARK

The ZEB goal in Denmark has been seen as an opportunity to increase the renewable-energy share in the national energy mix (Joanna et al., 2010), and, in the long term, to achieve a fossil-fuel-free country by 2050. Therefore, ZEB policies in Denmark tend to apply to multiple sectors. The ZEB target is accepted by a broad majority in the Parliament and thus has long-term credibility (Low Carbon Transition Unit, 2013). The target is for Denmark's energy and transport system to use 100 % renewable energy by 2050. By 2020, half of traditional electricity consumption will be supplied by wind power, and by 2035, electricity and heating will be fully supplied by renewable energy. Denmark's ZEB goal broadly covers both new and existing buildings as well as the electricity and heat production systems. The Danish government has clearly signaled to the construction industry that the ZEB goal will be mandatory in the building code by 2020. Since 2006, the Danish building code has provided three different performance levels for builders to choose from. This approach makes clear to the industry that it needs to prepare for the future ZEB market. The national policy has inspired several municipalities to adopt more ambitious building performance levels.

The ZEB policy package in Denmark has a regulatory focus (PRC Bouwcentrum International and Delft University of Technology, 2011), consistent with Denmark's history since the oil crisis of the 1970s of levying energy and carbon taxes and establishing building regulations to mandate energy efficiency. In general, since the 1970s, Denmark's financial mechanism to encourage energy-efficient buildings has been a heavy tax on energy and carbon (rather than subsidies). Today, Denmark has a comprehensive set of taxes, charges, and other fiscal instruments applicable to energy, transportation, pollution, and resources (these levies represented about 4 % of Denmark's GDP in 2011). Most of these taxes and charges flow into the general governmental budget. The "public service obligation" (a levy charged on every kilowatt-hour of electricity sold in Denmark) is classified as tariff and therefore is not collected by the Danish government but by a state-owned non-profit enterprise (Energinet.dk). The funds are used to subsidize renewable energy deployment (The Danish Ecological Council, 2013). The public service obligation is an innovative financial tool in that it is independent of the government budget. Renewable-energy deployment in the building sector is supported by a feed-in tariff mechanism and by net metering rules (Ministry of Climate Energy and Building of Denmark, 2013). In 2012, solar energy experienced exponential growth, and Denmark achieved its 2020 solar goal in just one year (Solarplaza, 2013). Since then, the solar subsidy program (based on net-metering rules) has been revised. Solar PV systems are only one of the renewable alternatives for achieving ZEBs in Denmark. Both on- and off-site renewable options are proposed in the ZEB definition. Regarding plug loads, Danish appliance energy-efficiency standards generally depend on the EU codes (The Danish Government, 2011). Therefore, for Denmark to impose an appliance standard that is sufficiently stringent to achieve ZEB goals, the EU would have to adopt the same stringent standard.

Overall, the ZEB policy package in Denmark is balanced, relying on both top-down and bottom-up strategies. The general energy policies are influenced by neoclassic economic and "innovative democratic" approach (we will describe more about these approaches in the "Policy Implications" section) (Mendonça, Lacey, & Hvelplund, 2009). Stakeholders have been extensively involved and formally consulted during the process of establishing the ZEB policies. This has helped to elicit high-level political support and unified action (World Green Building Council, 2013).

CALIFORNIA

As a frontrunner in U.S. energy efficiency and renewable-energy policy and technology deployment, California already has an existing policy framework and substantial policy package supporting ZEBs, as explicitly outlined in California's ZEB action plans (CPUC, 2012 & 2013). In addition, the state's mild climate and mature solar market help make ZEBs technically and financially feasible. The state's targets are zero-energy new residential buildings by 2020 and zero-energy new commercial buildings by 2030. In addition, the California Renewable Portfolio Standard requires that all electricity retailers in the state must supply 33 % of retail sales from renewables by the end of 2020. To date, the California Energy commission and California Public Utility Commission (CPUC) have, together with stakeholders, developed ZEB action plans for research and technology; codes and standards; heating, ventilation, and air conditioning (HVAC); lighting; and other areas (CPUC, 2013; CPUC, 2012).

California's overarching goal is bottom-up, market-driven development and deployment of the ZEB concept. Currently, the state's ZEB action plans focus on R&D, information tools, education and training, and demonstration of the ZEB concept. The market-based approach is evident in the economic instruments devised to support ZEBs, e.g., tax credits, rebates etc.

California's ZEB action plan focuses on four key research and technology areas initially: integrated building design, market intelligence and consumer acceptance, plug loads, and advanced HVAC technologies. From the financial perspective, commercial ZEBs in some cases paid no extra up-front costs (PG&E, 2012) when integrated design trade-offs were made appropriately. From the regulatory perspective, there are still barriers to mandating a ZEB goal. The California Energy Commission can only use the building energy-efficiency standard, Title 24, as a regulatory vehicle for this mandate if the measures needed to achieve the ZEB goal are deemed cost effective (Heschong Mahone Group Inc., 2012). Therefore, the ZEB goal is currently not legally binding. In addition, revisions to the appliance standard, Title 20, to achieve ZEBs also face legal challenges because California's appliance standard is subject to federal pre-emption (Chase, McHugh, & Eilert, 2012).

SUMMARY OF DENMARK'S AND CALIFORNIA'S ZEB POLICIES AND IMPLEMENTATION

In this section we focus on the overall ZEB approaches and strategies that are relevant to the building energy-efficiency and PV sectors in Denmark and California. Table 5 summarizes the ZEB policy frameworks in these two jurisdictions (This table is intended as a summary only, not intended a comparison of the policies).

Zero-energy-building activities in China

In 2013, nearly 3.9 billion square meters (m^2) of new buildings were added in China (National Bureau of Statistics of China, 2014). This represents about half of the world's annual new con-

Table 5. Summary of ZEB policies in Denmark and California.

Policy Instruments	Denmark (EU)	California (U.S.)
Targets and building codes	Mandate ZEB target for new buildings by 2020 (Building class 2020). Building code has three performance levels. National energy plan is for fossil-fuel-free country by 2050. Danish appliance standard depends on EU regulations.	Zero-net-energy (ZNE) goals are proposed (not yet mandatory) for new residential buildings by 2020 and for new commercial buildings by 2030 (Title 24). Appliance standard Title 20 is proposed to be updated to meet ZNE goal but is subject to federal pre-emption. Renewable portfolio standard requires 33 % renewable-energy electricity retail sales by 2020.
Certification	Energy Performance Label is mandated by governments and verified by third party (European Commission, 2013a).	In the Home Energy and Commercial Building Energy Asset Rating Systems, ZEBs are rated at 0. The Living Building Challenge Certification Program also provides ZEB certification (International Living Future Institute, 2014).
Economic instruments	High energy-use/carbon taxes (proportionally more than half of electricity bills) result in highest electricity prices in Europe (European Commission, 2014). Other instruments include the public service obligation levied by state-owned enterprises on energy use, a tax rebate for energy-efficiency measures, and subsidies to replace oil/coal/natural gas heat boilers. For solar PV deployment, net-metering rules and feed-in-tariffs were adopted (IEA, 2013).	Market-based approach. Substantial federal and state financial support for both building energy efficiency and solar PV (e.g., tax credits, rebates, grants, and low-interest mortgages). For solar net-metering rules, feed-in-tariff (tied to the market rate) and "Go Solar California" incentives were adopted. Solar system costs are expected to drop and incentives offered through the program to decline (California Advanced Homes Program, 2014) (CPUC, 2014).
Compliance	Through a mandatory "Energy Performance scheme" (EPC) initiated in 1997, an energy audit is performed and an energy label issued. There is a fine for violating EPC rules (European Commission, 2013a).	ZEB targets are not legally binding. Currently, compliance is required only with the current building code, Title 24. The current Title 24's on-site inspection requirement forms the baseline to be encompassed into future ZEB requirements. Efforts to ensure code compliance come from simplifying the regulatory process and training offered by the California Energy Commission and utilities to building professionals, other stakeholders and the public. (California Energy Commission, 2014). A certificate (Living Building Challenge) from the International Living Future Institute requires submission of an annual energy bill to verify that the building meets ZEB targets.
Information tools	The Danish Energy Agency launched a campaign to promote energy savings and the EPC scheme. Utilities, which have an obligation to save energy, actively distributed campaign materials to the public, and a "knowledge center for energy savings in buildings" was established to disseminate technical and regulatory information to building professionals (Mccormick & Neij, 2009) .	Informational tools are a current focus of the ZNE action plan. They are being developed by non-governmental organizations (NGOs), governments, and utilities with the participation of all ZEB market actors. Early adopter networks were established. The New Building Institute, CPUC, California ZNE Homes, and utility websites provide abundant ZEB information. Commercial building benchmarking and disclosure are mandated.
Demonstration	The first ZEB was built in the late 1970s. By 2012, about 10 Bolig+ and "active house" demonstration projects had been built (Musall, 2013). These demonstrations are seen as mainstream practices rather than futuristic experiments (Low Carbon Transition Unit, 2013).	Increasing ZEB demonstration is a current focus of the ZNE action plan. In 2014, about 47 ZEB projects had been built in California, although the energy supply and demand balance have not been verified in every case. These projects are mostly public buildings (Cortese et al., 2014).
Education and training	ZEB education is conducted by major Danish universities and the "knowledge center for energy savings in buildings."	Educational tools are a current focus of the ZNE action plan and take a variety of forms, including design training and competitions; and seminars held by utilities, NGOs, and the government. In addition, the free "Saving by Design" program (SavingsByDesign Program, 2014) was set up to assist designers in applying an integrated design approach during the early stages of a building's development.
R&D	The "strategic research center for zero-energy buildings" was established in 2009 through joint collaboration of two Danish universities (Alborg and Danish Technical) (Joanna et al., 2010) with the aim of building a technical basis for developing the ZEB concept. However, most of the practical and technical solutions for improving energy performance are developed in private sector.	The federal research and development agenda identifies several key ZNE solutions and technologies: integrated design, efficient appliances, and building- and community-scale energy supply (National Science and Technology Council USA, 2008). Technical (Pacific Gas & Electric Company, 2012), economic (PG&E, 2012) and policy (Heschong Mahone Group Inc., 2012) studies have been completed for California.
Overall approach	Balanced policy package combining top-down and bottom-up approaches. General energy policies are influenced by neoclassical economic and "innovative democratic" approaches (Mendonça et al., 2009).	Bottom-up market-driven strategy to create awareness among builders and homeowners. Neo-liberal principles at the core of economic policy.

struction. Chinese efficiency standards for buildings have three tiers. Relative to an energy baseline from the early 1980s, the codes require 30 %, 50 %, and finally 65 % total energy savings to be achieved by specified milestone years. Currently, national building codes require that both commercial and residential buildings be 65 % more efficient than the baseline; some province and city codes are even stricter, requiring a 75 % energy-efficiency improvement. Now that the most stringent of the three efficiency levels in the national and local building codes is in effect, China must choose the next direction for building-sector energy requirements. The new targets that are chosen will have significant implications in relation to the recent U.S.-China joint announcement on climate change, which stated that China's CO_2 emissions will peak around 2030 and that the country will make best efforts to reach the peak earlier than that (Office of the Press Secretary of The White House, 2014). ZEBs are a good opportunity for China's building industry to avoid locking in unsustainable consumption levels and ongoing contributions to global climate change. The international climate change commitment as well as pressure to address domestic air pollution have initiated discussion of a ZEB roadmap by 2030 within China's Ministry of Housing, Urban and Rural Development (MOHURD) and among leaders in the building community.

In practice, a variety of demonstration projects across China's climate zones have adopted different ZEB definitions. The most common terms used are "net-zero site energy" and "net-zero energy emissions." Currently the term "net-zero-energy building" ("Jing Ling Neng Hao Jian Zhu" in Chinese Pinyin) is widely used. However, a clear, official definition is still lacking although there have been a few attempts in the research community to define a concept tailored to the Chinese context (Zhang et al., 2013).

Table 6 summarizes China's existing policies relevant to ZEBs. Because ZEBs have just appeared in the Chinese market, policy instruments such as certification, information tools, demonstration projects, education and training, and R&D are lacking. In general, China's building energy-efficiency policies rely on regulations that grow increasingly stringent. As noted above, incrementally stricter regulations have saved substantial building-sector energy over the past 30 years ("reduction" in this context means slowing the building energy consumption growth rate rather than decreasing absolute consumption). Studies (Shui & Li, 2012) have shown a lack of energy-efficiency policy transparency, insufficient financial support, and the need for market-based instruments. For PV solar, the most relevant policies are MOHURD subsidies initiated in 2006 for building-integrated renewables, the Golden Sun demonstration subsidy program launched by the Ministry of Finance and National Development and Reform Commission (NDRC) in 2009, and the feed-in-tariff for renewables. Traditionally, China's renewable energy policy has paid more attention to wind than solar, and the PV policy has mostly been formulated from the supply side, triggered by the European and American export markets. Solar PV projects did not achieve large scale in China until 2009. Challenged by international trade barriers to Chinese PV products, policies are shifting slowly to expand the domestic market, in particular toward distributed PV systems. The overall goal for China's PV industry is to install a gross capacity of 1,050 GW by 2030. At the end of 2012, the gross installed capacity was 6.5 GW (Sun, Zhi, Wang, Yao, & Su, 2014). In 2014, simplified net-metering rules were introduced to assist PV owners in selling excess electricity to the grid. Currently, uncertainties remain for distributed PV owners renting commercial roofs; these include lack of clarity about commercial roof ownership and the risk associated with future electricity sale from rental roof depending on the stability of the business occupying the building. However, decreasing solar prices are likely to positively contribute to progress of the ZEB concept in China. An example of decreasing prices is the conservative estimate that the levelized cost of electricity of large scale solar PV in China will drop from 4.8–11.7 EUR_{2014}cost/kWh (2015) to 3.6–9.3 EUR_{2014}cost/kWh (2025). Today the large ground-mounted PV systems have already achieved significant lower system cost of approximately €700/kW in different regions including China (Fraunhofer ISE, 2015).

Terminology and policy implications for China

ZEB TERMINOLOGY IN THE CHINESE CONTEXT

Table 2 shows a broad range of ZEB definitions used in the U.S. and Europe. This range of definitions tailored to local conditions suggests that China could develop its own ZEB definitions to suit the country's diverse climate zones and societal goals such as emissions reductions. Currently, increasing numbers of ZEB projects in China have adopted the "site energy" definition with on-site renewables only. However, it is important to study the pros and cons of different definitions in the Chinese context before committing to any definition.

Several aspects of ZEBs in China might differ from features of other international examples. These aspects, discussed below, should be considered in the process of officially defining the ZEB concept.

First, ZEBs in urban areas will be challenging if the "site energy" metric is adopted. This is because of the predominance in urban areas of high-rise buildings that have limited roof area for PV panels. The ratio of roof area to floor area matters in achieving the NZEB goal in an individual building. In Abu Dhabi, for example, it is possible for commercial buildings up to five stories to be ZEBs if internal loads are aggressively reduced (Phillips, Beyers, & Good, 2009). This suggests the difficulty of achieving ZEB status for larger high rises. To address this challenge, the ZEB definition could take into account energy use at the neighborhood or community level rather than the individual building level, it could allow renewable-energy credits to offset energy use in urban high rises, or it could allow for other, diverse alternative energy sources. A preliminary technical study by Chinese researchers using the site-energy ZEB definition shows that, in theory, it is possible to build an 8- to 10-story commercial ZEB, and a 9- to 11-story residential ZEB, in China's three climate zones (Beijing, Shanghai, and Guangzhou) (Huang, 2014).

Second, it will be challenging to impose a consistent ZEB definition across China, given the diverse climate zones and management and technical calculation approaches in each of the regions and provinces. This regional diversity also suggests that the building community might experiment with different ZEB concepts. Local definitions could be developed based on feedback from experimentation with different concepts.

Table 6. Summary of ZEB policies in China.

Policy Instruments	China
Targets and building codes	Building energy policies focus solely on building codes, which require phased 30 %, 50 %, and finally 65 % total energy savings compared to a consumption baseline from the early 1980s. Code updates are not institutionalized, and the next energy strategy in the building sector after achievement of the code's final 65 % energy reduction is unclear. A ZEB roadmap by 2030 is under consideration by MOHURD to guide future development of the building energy-efficiency industry.
Certification	Existing Chinese green building certificate and voluntary passive house standard.
Economic instruments	Overall, building energy-efficiency funding is insufficient (Shui & Li, 2012). Financial support for PV deployment has recently begun to receive attention. Important policies include building-integrated PV subsidies, a feed-in-tariff, and the Golden Sun solar subsidy program. PV policy has traditionally focused on supply side (Zhi, Sun, Li, Xu, & Su, 2014). Net-metering rules are currently simplified, and financial support for consumers has recently been established.
Compliance	Compliance is mainly verified through the "building energy conservation inspection and supervision" program, managed by MOHURD since 2005 (annual random inspections, results released publicly).
Information tools	Information-sharing is limited to professionals. Public outreach is generally lacking. China's passive house network was established in 2013. The ZEB technology innovation association was established in 2014 by the China Academy of Building Research (CABR) and 32 energy-saving companies.
Demonstration	Various existing demonstration projects feature green buildings, low-carbon cities, passive houses, and building-integrated renewables. Currently, only a handful of ZEB projects have been completed in different climate zones.
Education and training	Domestic education is highly regional. At the national level, Tsinghua University and CABR conduct extensive civil engineering and building policy research.
R&D	ZEB R&D is still in very early stages; only a few studies have been done on ZEB definitions and empirical lesson from demonstration projects (Zhang et al., 2014).
Overall approach	Mainly top-down approach complemented by local experiments (namely "Regionally Decentralized Authoritarianism"). Policy focuses solely on building regulations.

Third, many regions in Europe developed ZEB definitions based on existing codes, e.g., Minergie-A in Switzerland, or as a progression from the passive house standard. In China, MOHURD has already gained significant experience implementing green building codes and has recently started to experiment with the passive house concept. These experiences could be considered in developing the Chinese ZEB concept.

Fourth, most definitions adopt one operational year as the balance period for determining net energy use. This suggests that the Chinese code needs to move from being prescriptive to being performance- and outcome-based. Integrated design support is also needed to develop building simulation programs that can predict energy use, and monitoring and maintenance mechanisms need to be established.

Finally, ZEBs and their energy infrastructure need to be designed, built, and operated taking into account local culture, norms, and occupant behavior. For buildings whose occupants do not share the cultural assumptions on which the standard is based, costs and emissions would increase without an improvement in living standards. For example, some-energy saving technologies are only effective when the entire living space is heated or cooled continuously, 24 hours per day, 7 days per week. Specifying such technologies would prevent even greater energy savings by occupant behavior. This discrepancy was found in a number of low energy building demonstration projects in China through international collaborations (IPCC working group III, 2014).

POLICY IMPLICATIONS FOR CHINA AND OTHER EMERGING ECONOMIES

Numerous examples of policy instruments and approaches can be drawn from ZEB experiences in other regions. These measures are often tailored to local institutions, so some policy instruments are primarily applicable in a specific region. We categorized international policy experience into three areas: building-sector policy instruments specifically aiming at a ZEB target, the energy policy environment outside of building regulations, and the macro political and economic factors rooted in regional energy policy designs. Each of these topics is discussed in a separate subsection below. In some cases, our analysis is organized around policy implications for the Chinese ZEB effort. We focus on policies that address building energy efficiency and general renewable-energy integration issues.

Policies aimed specifically at a ZEB target

Specifying multiple performance levels in the building code: The Danish building code offers builders with three performance levels, making clear the most stringent target to which jurisdictions should aspire. This code structure also inspires local governments to adopt more ambitious goals than the code prescribes.

Defining ZEB concept at the district level, allowing renewable-energy credits to offset energy usage in urban areas: In urban areas where rooftop PV systems might not be feasible, defining ZEBs at a district rather than an individual-building level might help achieve the ZEB goal. Also, the site energy metric is only one of many ZEB definition options. An alternative to site energy could be renewable-energy credits that offset energy usage when a building cannot attain the zero-energy goal because, for example, of limited space or other barriers to on-site renewable energy.

Encouraging "design-build" contracts rather than "design-bid-build": "Design-build" is a project delivery system in which design and construction services are performed by a single entity. Compared with the "design-bid-build" approach, in which one entity designs a project and other entities bid for the opportunity to build it, a design-build approach can minimize risks and principal-agent problems for project owners and help ensure that the final product is the ZEB that was envisioned. The design-build approach was used for the NREL Research Support Facility, which is a ZEB in the U.S.. The project was built at a cost comparable to that of other similar local buildings (as mentioned earlier, some commercial ZEBs have been built with no extra up-front costs).

Defining ZEBs to suit regional conditions: A ZEB standard will be different from a traditional building code because it includes elements such as renewable-energy and plug-load requirements that are traditionally not part of building codes. Our review of international ZEB definitions shows regions have adopted definitions based on local conditions, such as climate, existing building codes, general renewable-energy targets, renewable-energy grid-connection issues, and local building traditions. ZEB definitions are also strongly affected by the local economic and political context.

Defining ZEBs in relation to broad societal benefits: Research might be needed to understand how a ZEB goal relates to broad societal benefits. In the EU, the cost-optimal framework helps balance financial, energy, and environmental goals and offers a means to evaluate the relevance of regulatory goals to ZEB targets. An economic analysis framework for ZEBs should consider long-term societal costs, not just short-term financial savings, and should consider the gap between proposed "cost-optimal" building code requirements and what is needed to achieve ZEBs.

Considering legislative barriers: In many regions, building code requirements must be cost-effective in order to be approved by legislative authorities. Proposed ZEB requirements might not be considered cost effective from a current financial point of view and thus face a barrier in being incorporated into building code requirements. Therefore a long-term economic analysis is needed that takes into account broader benefits of ZEBs, and legislative action is needed to mandate ZEBs and thereby help increase their penetration.

Addressing appliance standards: Plug loads will be the dominant energy-consuming end use during the operational life of a ZEB. Therefore, it is important to address plug loads in ZEB standards even though these loads have not traditionally been included in building codes. For the two regions whose ZEB status we examined in depth, Denmark and California, appliance standards are regulated by the higher authority of the respective regional or national government. An option for reducing plug load in a ZEB would be to require more stringent appliance standards at the higher levels of building performance that are specified in the ZEB code.

Energy policy environment for ZEBs

Evolving ZEB policies: The policy activities described in this report are a snapshot in time, corresponding to the current degree of penetration of ZEBs and development of ZEB technologies in the respective regions. However, like other energy-efficiency policies, ZEB policies have evolved and will continue to do so. It is important to plan for updating ZEB policies as ZEB technologies and the market change. Thus, the policy implications described in this paper should not be considered fixed recommendations but starting points in a rapidly changing policy environment. Both Denmark and California have a long history of developing energy-efficiency and renewable-energy policies, starting during the oil crisis of the 1970s, and those policies have continued to evolve. For example, as described earlier, an energy tax was Denmark's primary policy instrument previously, but now a comprehensive set of financial instruments has been established.

Establishing stable, long-term targets: One important reason that Denmark and California are leaders in adopting the ZEB concept is that both jurisdictions set stable, long-term ZEB targets.

Mandating and incentivizing utilities to participate in energy efficiency: As previously noted, a ZEB target is different from traditional building codes and requires effort from multiple sectors. Utilities, in particular, play key roles in supporting market adoption of ZEBs in Denmark and California. In both places, utilities are incentivized to reduce the demand for power. In California, utilities' profits have been decoupled from electricity sales since the 1980s, and Denmark's district heating sector is non-profit so that, in both cases, utilities can pursue energy efficiency without undermining their own economic interests (IEA, 2009). In addition, "integrated resource planning" mandated in Denmark in 1994 allowed utilities to select energy efficiency as the least-cost resource in the long term. Utilities in both jurisdictions are obligated to save energy and promote renewable-energy deployment.

Considering net-metering rules: Denmark and California have adopted net-metering rules and feed-in tariffs to support small-scale renewable energy production. These mechanisms help foster private investment in renewable energy and are particularly attractive to owners of "positive-energy buildings" – ZEBs that produce excess electricity on an annual basis.

Political and economic factors

Relying on different factors from political economics: The financial mechanisms and instruments adopted to support ZEBs in California and Denmark reflect different theories of political economics, as described earlier.

Denmark's renewable-energy policy arises from both a neoclassical economic and an "innovative democratic" approach (Mendonça, Lacey, & Hvelplund, 2009). The neoclassical theory (mainstream economics) asserts that energy and carbon taxes internalize environmental effects in market prices. The "innovative democratic" approach perceives that lobbyists (for example those representing fossil-fuel companies) influence the Parliament; therefore, new, independent actors are needed in the energy market to support a move toward renewable energy and reduced energy consumption. Both of these approaches have influenced Danish energy policy during the past 30 years.

In the U.S., economic policy rests on neo-liberal economic principles (Keppley, 2012). Neo-liberalism emphasizes protecting the market from distortionary intervention by the state. This approach underlies the policy instruments adopted in California, such as tax credits, rebates, and a renewable-energy portfolio standard. Feed-in tariffs for renewable energy are tied to market rates and are compatible with deregulated retail electricity markets.

Combining bottom-up and top-down approaches: As discussed previously, Denmark's ZEB policy package focuses on regulatory strategies and is balanced between bottom-up and top-down approach. Building regulations and enforcement have a long tradition in Denmark, dating from the oil crisis of the 1970s. In contrast, the overarching ZEB policy approach in California is a bottom-up market-driven strategy. The approaches in these two jurisdictions are influenced by the political and economic outlooks described in the previous subsection.

Implementing policy in the context of social principles and economic development: Denmark and California are both democracies with well-developed industrial sectors. Their democratic processes formally involve stakeholders and local jurisdictions in decisions about policies and codes such as those relevant to ZEBs, which helps to address different stakeholder interests and ensure local acceptance of new regulations. In less-developed and non-democratic jurisdictions, implementation of ZEB standards will look different. This issue is beyond the scope of this study, but the lessons from these jurisdictions merit consideration when policy experiments are designed at the regional level in China.

Conclusions

Based on our review of ZEB terminology and policy instruments in leading world regions and of the status of ZEB activities in China, we draw the following conclusions regarding ZEB efforts in China and other emerging economies:

1. *ZEB definitions* should be outcome based and consider the diversity among local regions, including typical building size and distinct local lifestyles, as well as the broad, long-term societal benefits of ZEBs. In China, a ZEB definition could be based on existing voluntary codes, e.g., the Chinese green building codes and passive house standard.
2. Jurisdictions that are at the forefront of ZEB adoption use several approaches that have the following policy implications that China and other emerging economies could consider:
   - Gradually moving building codes toward being performance based and providing several performance levels that become incrementally more strict (historically, Chinese building code targets have been phased in using three steps). A phased approach could help ensure a stable, long-term ZEB target toward which the building industry can aim.
   - Adopting ZEB definitions at a district level, or enabling renewable-energy credits to offset building energy usage in urban areas.
   - Developing policies that evolve as ZEB technology penetrates the market.
   - Shifting traditional regulatory-based policy frameworks to balanced policy packages that combine top-down and bottom-up development of standards. China's decentralized authoritarian system could combine top-down and bottom-up approaches to facilitate ZEB technology deployment. The political economics of China's energy sector is highly complex and constantly reforming and evolving. During the current transition, China's energy governance is seen as "pragmatically flexible" (Green & Kryman, 2014), creating an opportunity to adopt strategies from other regions.
3. *Structural challenges that create barriers to ZEBs need to be addressed:* Building regulations alone cannot address all key ZEB issues, including building energy efficiency, renewable energy, plug loads, and grid integration. This range of issues indicates the need for inter-ministry coordination. In China, fragmentation of government activities creates a barrier to ZEB implementation. For instance, at the national level, building regulations and renewable-energy targets are overseen by different institutions, and local (city) building authorities answer to both provincial building agencies and local governments. In addition, an implementation gap remains between the central and local governments. These institutional barriers will be discussed further in a future paper.

Because of the broad international scope (in terms of both geography and complexity) of ZEB policies and activities, there are examples and strategies that are not covered in this paper. Our purpose is to provide a snapshot of the current status of the ZEB industry in leading jurisdictions and to point out key policy issues to be considered by policy makers and technology adopters who are developing ZEB programs in China and elsewhere. Our future research will study, in depth, the structural challenges to deploying the ZEB concept in China.

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