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An international survey of building energy codes and their implementation

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ABSTRACT

Buildings are key to low-carbon development everywhere, and many countries have introduced building energy codes to improve energy efficiency in buildings. Yet, building energy codes can only deliver results when the codes are implemented. For this reason, studies of building energy codes need to consider implementation of building energy codes in a consistent and comprehensive way. This research identifies elements and practices in implementing building energy codes, covering codes in 22 countries that account for 70% of global energy use in buildings. These elements and practices include: comprehensive coverage of buildings by type, age, size, and geographic location; an implementation framework that involves a certified agency to inspect construction at critical stages; and building materials that are independently tested, rated, and labeled. Training and supporting tools are another element of successful code implementation. Some countries have also introduced compliance evaluation studies, which suggested that tightening energy requirements would only be meaningful when also addressing gaps in implementation (Pitt&Sherry, 2014; U.S. DOE, 2016b). This article provides examples of practices that countries have adopted to assist with implementation of building energy codes.

1. Introduction

Buildings are an important element of sustainable development and de-carbonization policies, as buildings account for 1/3 of total final energy consumption globally (IEA, 2015). Population growth, migration to cities, increasing wealth, and changing lifestyles are major factors contributing to increasing energy consumption from buildings (Lucon et al., 2014; Chaturvedi et al., 2014; Eom et al., 2012). However, policies and technologies could help reduce total building energy use.

Building energy code policies are one of the most effective mechanisms to reduce carbon emissions from the building sector in the medium term (Lucon et al., 2014). Studies have shown that building energy codes have helped save 6–22% of average annual energy consumption in buildings of the European Union (IEA, 2013) and 106 million tonnes of oil equivalent between 1992 and 2012 in cumulative energy savings in the United States (Livingston et al., 2014). Similarly, in China building energy codes have the potential to reduce the building sector's energy consumption and CO_2 emissions by 13–22% by 2100 (Yu et al., 2014). A study of the city of Jaipur in India revealed that code implementation could save 17–42% annually, depending on the building type (Tulsyan et al., 2013). Another study of potential energy savings from codes in Gujarat, India, revealed that building energy codes could reduce building electricity use in Gujarat by 20% in 2050 (Yu et al., 2016). Building energy codes are particularly critical in countries with expected construction booms, such as China and India. Because building codes can be effective in reducing carbon emissions from the building sector, dozens of countries pledged to use building energy codes and similar policies as part of their climate mitigation action. Specifically, over 30 countries referenced building energy codes as part of their Nationally Determined Contributions (NDCs) under the Paris Agreement on Climate Change, which entered into force on November 4, 2016.

Aside from being critical to climate mitigation, building energy codes have many co-benefits, such as lower energy bills for consumers, improved energy security, health and comfort, and lower need for energy subsidies. Recognizing these benefits, most

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countries have introduced policies requiring minimum levels of efficiency in new buildings, such as building energy codes and standards. However, access to the full benefits of building energy codes, including their role in climate mitigation, depends on code implementation during building design and construction.

Research focused on building energy codes has stressed the importance of implementation of building energy codes and called for further work in this area (Ellis et al., 2009; IPEEC, 2015). Yet, few academic studies have focused on implementation of building energy codes and none have provided a systematic review of implementation practices globally. At the same time, anecdotal evidence and individual national studies suggest that there are gaps in implementing existing requirements. For example, studies from Australia recommended closing the gaps in implementation of existing codes before tightening energy efficiency requirements (Pitt and Sherry, 2014; DOE, 2016a). Given this research gap, the authors took to researching implementation of building energy codes. The goal for the research is to understand what successful implementation of building energy codes encompasses in different countries. Our research questions, specifically, are: what is the range of implementation practices for building energy codes across countries and how do these practices affect implementation?

Through a systematic review of code implementation in 22 countries, that together account for about 70% of global energy consumption from buildings (based on IEA data, IEA, 2015), this research aims to shed light on implementation systems and practices of building energy codes and inform better design of institutions, incentives, or support, so that codes can deliver on their potential benefits.

2. Background

Countries have developed diverse approaches to implementing building energy codes. Understanding these approaches is an important step to analyzing and distilling best practices in accessing the full benefits of energy-efficient buildings.

To demonstrate compliance with (and implementation of) building energy codes, developers can follow one or more compliance paths (IEA, 2013; IPEEC, 2015). Thus, considering compliance paths, built into codes, could make implementation mechanisms more robust. Building energy codes that offer a *prescriptive* compliance path set performance requirements for each building component. A *simple trade-off* compliance path is similar to the prescriptive one but allows some substitution among code components. A *simulated performance* compliance path relies on building energy simulation software to simulate energy use in a designed building, which is compared either to a reference building or to a specified requirement. A *point system* assigns points for meeting certain requirements, reminiscent of green building rating systems, and often with accompanying incentives for specific levels of above-code compliance. (These four compliance paths are some of the most widely used, though there are other, emerging types, such as using post-construction ratings to demonstrate compliance, or proposals to use actual energy performance for a given period of time as part of the compliance process). Depending on the compliance path, some implementation mechanisms might be more important in one country than others. For example, implementation of building energy codes that rely on simulated performance to establish energy efficiency characteristics requires adequate training to ensure that the software is used properly and that buildings' actual characteristics correspond to the simulated ones. Such training might not be required for prescriptive codes, which are typically easier to implement, albeit with less flexibility. Many countries offer several paths for code compliance to ensure strong compliance among different types of users, including those users who need design flexibility, and those who want to avoid the complexity and expense of conducting high-quality building simulation.

Another factor that affects implementation of building energy codes is that, in some countries, only local or regional governments have the jurisdiction to adopt a building energy code. This is particularly true in countries with a federal form of government such as Canada, the United States, Mexico, and India. Instead, such countries may have model codes developed through expert organizations in partnership with industry, government and other stakeholders. Subnational jurisdictions can then develop their own building energy codes, adopt a model code through a legislative process, often with modifications, or adopt a model code by referencing it. For example, while Canada or the United States could not have mandatory national codes, adoption of some version of the model code is widespread among states and provinces. Other countries have a central form of government and can adopt codes at the national level. These differences in jurisdiction impact how governments design their implementation agencies. Without the authority to make codes mandatory, federal governments at the national level tend to focus on training, supporting tools, and evaluation programs, which become important elements of implementation.

This research focuses on implementation of building energy codes, considering the notion that stricter code requirements will only be meaningful if implementations systems are in place. For this reason, the authors have not compared the *stringency of requirements* beyond those that relate closely to implementation. Stringency of requirements varies between countries and can be quite difficult to compare directly because of differences in climate, construction techniques, and how codes are written. Instead, the researchers chose to focus on the implementation process for existing building energy codes.

3. Literature review

Many researchers have studied building energy codes and have shown that building energy codes can bring significant benefits if they are well-implemented and enforced (Yu et al., 2014; Tulsyan et al., 2013; U.S. DOE, 2013). On the other hand, implementation is key to those benefits; non-compliance and under-compliance, on the other hand, erode gains from energy code development and adoption (Stellberg, 2013).

Few studies have systematically and comprehensively reviewed implementation of building energy codes across countries. Researchers have examined building energy codes in specific countries or localities (Li and Shui, 2015; Salvalai et al., 2015; Travezan et al., 2013), compared individual countries with limited geographic scope (Huang et al., 2016; Evans et al., 2009), or reviewed certain phases of code adoption or implementation (Janda, 2009; Iwaro and Mwasha, 2010). Similarly, Iwaro and Mwasha (2010) include code implementation in their review of building energy codes in 60 developing countries but their assessment has gaps as the metric for implementation includes only two indicators: training and educational aids used and certain characteristics of enforcement bodies. Moreover, the 2010 study does not include such factors as code coverage and availability of labeled and rigorously rated building materials to meet code requirements. Young (2014) begins to incorporate elements of enforcement systems into the review of building energy codes across 15 countries and describes enforcement mechanisms, such as inspections, penalties for noncompliance, and incentives to motivate compliance.

Adding to this research gap, many studies on codes have somewhat vague definitions regarding building energy codes.

Because governments develop and adopt code policies differently, it is difficult to decipher adoption status without extensive interviews and comprehensive methodologies. As a result, researchers can misinterpret the status of building energy codes in some countries. For example, Allouhi et al. (2015) review building energy code status globally but classify India as having adopted a mandatory building energy code for commercial buildings (the Energy Conservation Building Code). However, India's model national code requires adoption by states, and very few states have adopted the code to-date. Janda (2009) classify countries such as Italy and Mexico as having mandatory building energy codes, yet, prior to 2015, Italy's local building codes covered regions with only 1/3 of the country's population (Salvalai et al., 2015), and Mexico's mandatory and most implemented building energy standards cover only lighting and certain equipment.

Few other studies focused on implementation of building energy codes, and this highlights the importance and challenge of studying implementation systems for building energy codes internationally. Ellis et al. (2009) and IPEEC (2015) stressed this issue and called for further work in this area.

Recognizing the importance of building energy codes and their implementation, the authors chose to bring attention to the many facets of code coverage and implementation and to shed light on the various aspects of code implementation that future researchers might consider. In addition, we offer examples of tools and practices used to improve effectiveness of code implementation. We describe compliance evaluation programs in some countries, such as Australia, China, and the United States, but also other tools to assist code implementation.

4. Methodology

The diversity in building energy codes and implementation practices among countries poses challenges for assessing building energy code implementation and impact. This paper offers a systematic synthesis of building energy code implementation systems, analyzing building energy codes in 22 countries that account for 70% of global energy consumption from buildings. These countries are member economies of the Major Economies Forum on Energy and Climate (MEF) and/or G20, or are G20 guests (such as New Zealand, Singapore, and Spain). The countries include: Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Mexico, New Zealand, Russia, Saudi Arabia, Singapore, South Africa, South Korea, Spain, Turkey, the United Kingdom, and the United States. The authors developed a systematic approach to collecting data on implementation practices and describing elements of implementation systems among these countries to the extent that such information is available, and provide examples of practices for improving the extent of building energy code compliance.

To gather information about current practices in implementation of building energy codes, the research team reviewed the literature including information on government websites and accessed analyses available on institutions, processes, incentives, and support for implementation of building energy codes. As a result of this initial research, the authors arrived at key categories and/or issues at the core of the implementation systems for building energy codes in most countries. The key categories included:

- Code coverage
- Institutional approaches
- Building checks
- Incentive structure
- Training and tools
- Building materials

These categories provided structure for our data collection regarding implementation of building energy codes. However, to ensure systematic collection of information across countries, the research team further developed a detailed information template with annotated explanations that aimed to cover various aspects of key categories. The team shared this list with each country's designated point of contact for peer review. Based on the feedback from country experts, we revised the information template.

Subsequently, the team began research to populate information sheets for 22 countries, to the extent possible, accessing information in local languages. In the process, the researchers found that the information template needed adjustment to better capture the nuances of code implementation practices across countries. With feedback from country experts, we modified the template in a way that would cover the functions in most countries. This required working out definitions of certain concepts and approaches, e.g., mandatory code, to ensure that the research captured country differences, but still offered a cross-cutting look at practices. (Please see the resulting information template in Supporting Information A).

To fill in the gaps in understanding how building energy codes are implemented in different countries, the team identified key experts on building energy codes and their implementation within national government and research institutions and reached out for phone interviews. Between December 2014 and July 2015, experts from 16 countries participated in structured interviews and answered additional questions on building energy code implementation. The response rate was 73%. The researchers went through several rounds of discussion, including, in most cases, at least one in-depth phone interview, but also written correspondence and review. The team collected and categorized the data on a public portal, and the public nature of it incentivized countries to provide careful review: http://www.gbpn.org/laboratory/building-energy-codes-portal.

Understanding code implementations requires a clear definition of what constitutes a building energy code and what does not. Experts in various countries often do not have the same definition of building energy codes. For example, many building energy practitioners and code experts consider building energy performance labels to be a building code, even if these labels do not mandate specific performance levels. This is true in Mexico, Brazil, and some European countries. This study defined building energy codes as a set of rules and requirements for designing and constructing energy-efficient buildings. This is similar to International Energy Agency's definition of a building energy code as “a set of mandatory minimum energy performance requirements designed to regulate energy use in buildings” (IEA, 2013).

5. Results: implementation systems for building energy codes

This research analyzed the range of implementation practices across countries, and how these practices affect implementation globally. Effective implementation of building energy codes includes many interconnected elements such as the extent of code coverage; the institutional set-up for building plan review and site inspections; training programs and supporting infrastructure, such as software tools; meaningful penalties and incentives for better compliance; and building material testing, rating, and labeling systems that help quickly assess materials for code compliance. In addition, a number of countries have implemented programs to evaluate the effectiveness of building energy codes.

The sections below contain results regarding implementation in each of these categories. These detailed elements of

Table 1
Examples of comprehensiveness of coverage of building energy codes in different countries.

Building type	Building renovations	Building size threshold	Building elements and measures	Geographic coverage	Country example
Residential and commercial	Yes	None for new; for renovations >2000 m^2	Envelope, HVAC, service water heating, lighting, electric power, renewable energy, maintenance	Entire country	Singapore
Residential and commercial	Yes	None	Envelope, HVAC, service water heating, lighting, electric power, renewable energy	42 states adopted statewide codes; the remaining eight rely on either county or municipal codes	United States
Residential and commercial, but simple structures excluded	Yes, for renovations affecting more than 25% of the building area	None	Envelope, HVAC, service water heating, lighting, electric power, renewable energy	Entire country	Spain
Residential and commercial	Yes	None	Envelope, HVAC, service water heating, electric power, renewable energy; lighting is in a separate code	Entire country, but rural residential code is voluntary (about 45% of population is rural)	China
Residential and commercial	Yes, if affects more than 15% of area	None for new; separate requirements for renovations	Envelope; buildings larger than 20,000 m^2 must use renewable energy or co-generation	Entire country	Turkey
Residential and Commercial	Yes	Residential >50 house-holds; commercial >2000 m^2	Envelope, HVAC, service water heating, lighting, electric power, renewable energy, maintenance	Entire country	South Korea
Commercial	New and additions	>1000 m^2 (approximately)	Envelope, HVAC, service water heating, lighting, electric power	8 states (about 25% of total population); most central government public buildings and some state government	India

Sources: GBPN et al., 2015; Cort and Butner, 2012; Tan et al., 2016.

implementation systems can indicate how comprehensive implementation is likely to be.

5.1. Code coverage

Code coverage is the first step in ensuring that building energy efficiency requirements apply to a significant portion of buildings and have an impact on energy-intensive buildings. Countries have diverse practices when it comes to what a code covers (see Table 1). Depending on the country, the code may only apply to certain types or sizes of buildings; it may cover a broad range of energy uses or only the building envelope. It may or may not apply to planned renovations. The code many also only be in force for specific towns, regions, or states. As coverage and implementation grow, the number of new buildings that will be included each year will also grow, which in turn can result in significant energy savings. Ideally, a code will cover a comprehensive range of types and sizes of buildings, geographic locations, as well as elements within buildings. Subsequently, implementation institutions and processes should be designed considering the breadth and the scope of the code. It is also important to note that code coverage is one way to consider the extent of implementation. One example of the linkage between coverage and implementation is when a country has a seemingly robust implementation system, but its code only covers large buildings or only thermal insulation. Both limited coverage and limited implementation present missed opportunities.

5.2. Institutional approaches to enforcement

Enforcement can occur at both the design and construction stages. At the design stage, an enforcement agency verifies that the plan for the building meets the specified energy efficiency requirements, while at the construction stage the code official checks that construction matches the code-compliant design. As-built changes may also go through design review and on-site inspection. Not all countries inspect buildings for compliance with energy efficiency requirements at both stages, though most countries that have codes do have some type of plan review. Enforcing institutions can be national, regional/local, or private/third party. In some instances, countries allowed self-certification, which, by itself, is not a robust form of enforcement (see Table 2).

5.3. Types of building checks

Checking compliance of building energy codes at various stages of construction gives inspectors an opportunity to see if components, such as insulation, are properly installed. Multiple inspections might be required during construction to see components before they are sealed and hidden from view. Therefore, most comprehensive building checks consist of the following stages: desk review, site inspection at several construction stages, and final site inspection. Table 3 provides examples of the types of building checks that exist at the design and construction stages.

Aside from inspections during critical stages of construction, some countries have end-of-pipe tests. Such tests help ensure that building components operate as planned, and thus, end-of-pipe tests are often incorporated into the process of obtaining the occupancy certificate. This is the case in France, the United States, Singapore, and other countries, where blower-door tests are required. However, several countries rely on end-of-pipe tests because they do not have resources for systematic inspections or to verify key components.

In addition to differences in the types of inspections they require, countries have adopted diverse sampling approaches. In some countries, enforcment agencies might not inspect all buildings, choosing only a sample of buildings instead.

Table 2
Institutional approaches to enforcement of building energy codes.

Design stage enforcement	Construction stage enforcement	Country examples
National government	National government	Singapore
National government	Regional/local government	South Korea
Regional/local government	Regional/local government	United States, Spain, New Zealand, Canada, Australia, Indonesia
Regional/local government	Private/third party	Italy
Regional/local government	Self-certification/None	Russia, New Zealand (for certain installations)
Private/third party	Private/third party	China, France, Germany (in some states)
Private/third party	Self-certification/None	Germany (in some states)
Self-certification/None	Self-certification/None	Japan

Source: GBPN et al., 2015.

Table 3
Examples of types of building checks for energy efficiency requirements during design and construction.

Plan review	Site inspection at key construction stages: all or sample of buildings only	Final Site inspection	Example
Yes	Varies by state	Yes, mandatory in some states	Germany
Yes	All states with code	Yes	United States
Yes	Sample	No, except for blower door test	France
Yes	None	No	Japan
Yes	All	Yes	China
In some cases, where code is enforced	Sample	No	India

Source: GBPN et al., 2015.

5.4. Incentives for implementation

Incentives and penalties ensure that stakeholders' interests are aligned with the desired policy outcome, such as code implementation. Traditionally, national and local governments employ "sticks", or penalties, to achieve compliance. The most rigorous is denying construction and occupancy permits; other examples include fines for non-compliances, or suspending the license of third-parties who have failed to properly enforce the code. However, a number of countries have also explored "carrots", or incentives to improve compliance, particularly where it might be difficult to require comprehensive compliance through local governments, given current capacity and willingness, or where they are seeking to encourage beyond-code construction. In the United States, utilities in some states use their resources to help improve compliance in new construction with the goal of meeting their regulatory energy efficiency requirements; the efforts to statistically evaluate compliance levels will help utilities quantify the impact of their interventions. In India, several cities offer to relax zoning requirements for green or code-compliant buildings (see Table 4 for examples of penalties and incentives).

5.5. Tools and training

Tools and training are important to code implementation. Training local officials can help ensure that they understand the importance of building energy codes and how to enforce them. Architects need training to help ensure their designs meets code requirements, while construction companies need help understanding how to implement code requirements. Training might also be needed for inspectors, if building energy efficiency is not their main area of expertise, and they have to pick up the skills necessary for ensuring that buildings meet energy efficiency requirements. Ongoing opportunities for training can ensure that building professionals stay up to date as building requirements and

Table 4
Examples of penalties and incentives in various countries to improve compliance.

Penalties/Incentives	Examples
Denying construction permits	Australia, Canada, China, Germany, South Africa, Singapore, United States
Suspension or loss of license	Australia, Canada, China, Germany, New Zealand, Singapore, United Kingdom, United States
Programs to go beyond the minimum requirements (benchmarking, awards, subsidized loans, tax credits)	Australia, Germany, Canada, France, Italy, Japan, New Zealand, Spain, United States, Singapore
Permission to build a larger building than zoning otherwise allows, if construction exceeds code	China, South Korea, United States

Source: GBPN et al., 2015.

Table 5
Examples of training and tools in various countries to enable implementation of building energy codes.

Training and tools	Examples
Training programs for local governments on code requirements and compliance	China, Canada, Japan, New Zealand, Singapore, Spain, United States
Software and software training	Australia, Canada, France, New Zealand, Singapore, Spain, United States
Code compliance resource kits	Australia, Canada, China, France, Germany, Italy, New Zealand, Mexico, Singapore, United States
Training and certificate programs for building inspectors	China, Italy, Germany, New Zealand, Spain, Singapore, United States
Sponsored university degree programs on building energy efficiency	Singapore

Source: GBPN et al., 2015.

Table 6
Examples of systems in place in selected countries for building envelope material testing, rating, and labeling.

Types of building materials available with labeled energy properties	Test protocols exist	Building materials are tested by independent and certified labs	Building materials are clearly labeled with performance characteristics	Example
Windows, doors, skylights, insulation, air sealing, roofing	Yes	Yes	Yes	United States
Windows, doors, insulation, roofing	Yes	Yes	No, construction companies send samples of materials for testing	China
Windows	Yes	In some cases	No, building designer must certify that buildings meet requirements	Australia
Windows, insulation, doors	Yes	Yes	No, available upon request	Germany
None	Unknown	No	No	Brazil, India, Indonesia

Source: Yu, Evans, and Shi, 2014; Evans et al., 2015; GBPN et al., 2015.

technologies evolve.

Tools, such as compliance software, can mainstream and ease compliance; other types of tools are user guides, examples of code-compliant designs and other resources (see Table 5).

5.6. Building material testing and labeling

Designers and construction companies can more easily comply with energy efficiency requirements if they have access to building materials with labels that clearly state their tested energy performance properties. Code officials can also more easily verify that materials match the code-compliant design, if tested and labeled materials are used. Thus, having a system for testing, rating, and labeling energy properties of materials makes it easier for everyone to ensure buildings are made from high-performance products.

Countries have varying numbers of products and rigor in their testing, rating, and labeling systems (see Table 6). Products that are commonly labeled are appliances, lighting, windows, doors, and insulation. The most comprehensive systems include the following components: test protocols for specific building materials; test laboratories that are certified by an independent certification body; and labels that provide users with specific performance characteristics.

5.7. Compliance evaluation programs

Evaluating compliance programs can also improve enforcement. Compliance evaluation also allows policymakers to design better implementation systems based on hard data.

Countries have pursued several options to evaluate compliance. Some options include statistical sampling of the actual construction; review of permits pulled; review of other types of indicators, like sales of compliant materials on the market as a proxy; and finally, assessing actual energy use in buildings and comparing it to the design projections (see Table 7).

6. Discussion

We reviewed the existing systems to implement building energy codes in 22 countries. These countries include the largest economies in the world and represent both developed and developing economies. Together, these countries account for about 70% of global energy consumption from buildings (based on IEA data, IEA, 2015). Of the countries evaluated, three (Argentina, Brazil, and Mexico) did not have a formal code at the time of the survey. Some countries have formal codes, but have either scaled them up recently or have not yet demonstrated a commitment to implementation. For example, Italy recently developed its national code to harmonize Italian laws with EU directives. Thus, in 2015, Italy's national government adopted three new decrees unifying its national building energy codes and requiring adoption of the national model code in municipalities that do not have local codes. Prior to 2015, regional building regulations had been adopted in 12% of Italian municipalities with a combined population of over 21 million people (out of the country's 60 million) (Salvalai et al., 2015). Indonesia has technically mandated design requirements to limit building energy consumption since 2005, but in practical terms it does not require compliance. At the same time, Indonesia's Jakarta Province has recently issued the first mandatory green building regulation in the country. The remaining countries have adopted residential and/or commercial building energy codes at the national (e.g., France and Japan) or subnational levels where codes also cover the majority of the population (e.g., Australia, Canada and the United States).

The extent of energy code coverage varies significantly between countries. For example, South Korea's building energy code focuses on large buildings with high energy loads, whereas in the United States and France, the code applies to virtually all buildings. Some countries require that the code applies to all renovated spaces, while others are silent on the issue of renovations, as is the case with New Zealand. Some codes may cover a broad array of building systems, such as lighting systems, envelope, and HVAC, while others, such as in Russia, focus on building envelope. Overall, more and more countries are adopting building energy codes, countries

Table 7
Examples of building energy code evaluation programs.

Building energy code evaluation	Example
Sampling of a statistically significant number of buildings under construction within a state to assess compliance	United States (for individual states)
A national study of discrepancies between building design and construction, points of non-compliance with the code, and variations across jurisdictions	Australia
Annual inspection of selected buildings across the country by a national agency (non-compliant buildings are fixed during the study, so reported compliance rates may not be indicative)	China
Assessment of the level of compliance of building plans	Japan

Sources: U.S. DOE, 2016b; Pitt and Sherry, 2014; GBPN et al., 2015.

are expanding coverage, and the requirements are becoming stricter over time (Janda, 2009; Evans et al., 2009). For example, Australia introduced its building energy code in 2003 and has revised it a number of times since to improve energy efficiency requirements. Indonesia and Mexico have been actively working to introduce full building energy codes that cover many aspects of building energy consumption, and to improve implementation. In 2008, Singapore mandated that all new and retrofitted buildings must meet the minimum standards of the country's previously voluntary green building scheme, with stricter requirements for public buildings and buildings in key districts. Germany and France have regularly adopted stricter energy efficiency requirements for new buildings and have expanded code coverage to include renovations. Since 2013, new and renovated buildings in Spain must use solar hot water heaters.

As our results show, there are several institutional approaches to enforcing building energy codes. Commonly, local governments are in charge of enforcement, but in many cases, they rely on third parties to expand the capacity for enforcement. This is important to consider when designing capacity building programs, since such programs should target the implementing institutions. During interviews, many countries noted a lack of capacity to inspect buildings for energy requirements and challenges with reviewing design changes during construction. In countries that rely on third-party enforcement, careful design of checks and balances can minimize conflicts of interests and improve results. For example, this could mean having some government oversight of inspection documentation, or having additional random checks by qualified inspectors not associated with the project.

How code officials carry out compliance checks during construction can also impact the degree of compliance. Usually, it is important to have multiple inspections during construction to see components before they are sealed and hidden from view; this is particularly true for multi-story buildings. On-site compliance checks at various stages of construction can ensure that compliance becomes routine. Yet, very few countries have such practices. Most countries that do inspect during construction, in fact, only inspect a random sample of buildings, and often only once. Thus, inspection represents an opportunity to make compliance more comprehensive.

Developers and builders are motivated to comply when they face meaningful penalties for non-compliance. Fines alone might not prove to be a strong incentive, whereas denying a construction permit does serve as a strong incentive. In addition, some countries have experimented with positive incentives for compliance, although such incentives are most common to encourage beyond-code compliance. For example, China allows construction of larger buildings than zoning might otherwise permit, while Australia and many U.S. jurisdictions allow fast-tracking of permitting procedures for above-code buildings. In those cases, studies have found that rewards for going beyond minimum compliance can also ensure high compliance rates (Pitt and Sherry, 2014).

Lack of training and tools can undermine both enforcement and compliance. On the other hand, use of software tools is correlated with higher compliance rates, but training helps ensure that tools are used properly (Gowri and Williams, 2014). Training is particularly important when it comes to performance-based codes. Many countries are switching to performance-based codes; such codes can be more complex, requiring more training and analytical understanding to demonstrate compliance via whole-building simulation. In other words, this compliance path requires a solid understanding and experience with whole-building simulation. For example, one U.S.-based study has observed large discrepancies between information entered into the software and conditions seen in the field (Gowri and Williams, 2014), potentially pointing to the need for training. Additionally, this study has also found “significant confusion and lack of understanding of the energy code requirements among code officials and field inspectors.” Many countries offer more than one type of tools and training opportunities, and, for instance, Singapore sponsors university degree programs that focus on building energy efficiency.

The role of building materials with labeled energy properties in code implementation is often overlooked. Young (2014) provides a wide-reaching review of building energy codes internationally, but this study did not cover building material testing, rating, and labeling as they relate to codes. Ideally, systems include labeling, test protocols, rating procedures, independently certified test laboratories, and checks against “gaming” to ensure its reputation, such as testing random samples from the market (Evans et al., 2015). Testing, rating, and labelling of a broad array of building materials can strengthen the market for energy-efficient materials and make implementation of building energy codes and other policies much easier. Imported materials can also create challenges where there are not clearly enforced rules on labeling according to domestic standards; foreign test results might not be compatible with domestic requirements, making it hard to assess material properties. Uneven implementation of building material standards could create disincentives for manufacturers to test, rate, and label materials, and/or limit the market value of high performance materials when labels do not match performance. In summary, access to building materials with labeled energy properties facilitates code implementation.

Most countries have very limited compliance evaluation programs. However, the few studies that have evaluated implementation of building energy codes can reveal important lessons. For example, a study in the United States showed that, on average, residential buildings performed slightly better than the code in the states surveyed, though there are still opportunities for improvement (U.S. DOE, 2013; U.S. DOE, 2016a). Another example comes from Australia, which conducted studies to review discrepancies in compliance in building design and construction (Pitt and Sherry, 2014). Other countries, such as France, are launching similar evaluations. Such studies help identify areas of non-compliance and under-compliance, gaps in industry knowledge, and deficiencies in enforcement. At the same time, if more and more countries rely on simulation for compliance, it is important to ensure that design engineers are using simulations correctly. Thus, compliance evaluation can help improve the effectiveness of implementation. International collaboration on methodologies for compliance evaluation could help countries further develop such programs.

7. Conclusions

Energy-efficient buildings are essential to attaining a low-carbon future. Building energy codes create a blueprint for achieving energy-efficient new buildings, but effective implementation systems are what will deliver results. Policymakers are increasingly recognizing the need for stronger implementation frameworks to achieve their climate and energy goals in the buildings sector. There is thus a shift in emphasis from adopting more stringent requirements to supporting implementation of existing requirements.

A review of practices reveals that there are significant differences in implementation across countries, and that robust implementation typically has many interconnected elements. This study analyzes building energy codes across 22 countries and characterized key elements of implementation systems. Codes are more likely to deliver energy savings if they provide widespread coverage of buildings, regardless of type, age, size, and geographic location. It is important that countries dedicate or certify an agency to inspect construction for code compliance. Since enforcement is usually done by local authorities that might not have uniform capabilities, engaging code enforcers in training programs is essential, while offering compliance resources will ensure that stakeholders understand how to comply with the code. This is particularly important, given the trend toward increasing complexity of building energy codes. Penalties and incentives need to be meaningful and align with desired outcomes. Independently rated, tested, and labeled building materials should be available to developers and construction companies, and systems for their testing, rating, and labeling should be rigorous and consistent in recognizing high-performance materials. Finally, compliance program evaluation will help policymakers understand gaps in compliance and improve implementation of building energy codes.

This research highlights the importance of code implementation to energy savings, emission reductions, and codes' other benefits. By better understanding the range of practices in implementing building energy codes, policymakers can improve the effectiveness of their code implementation systems.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.01.007.

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