Journal of Cleaner Production 248 (2020) 119260

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Innovative designs of building energy codes for building decarbonization and their implementation challenges

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ARTICLE INFO

Article history:
Received 30 July 2019
Received in revised form
24 October 2019
Accepted 9 November 2019
Available online 10 November 2019

Handling Editor: Sandro Nizetic

Keywords:
Energy policy
Building energy codes
Building regulation
Building standards
Building decarbonization
Construction sector
Policy design principles

ABSTRACT

Building energy codes—policies that traditionally set minimum requirements for buildings' energy use—have proven effective and efficient for building decarbonization. As researchers and policymakers increasingly recognize the limitations of prevalent building energy codes, discussion turns to innovative designs that could overcome such limitations. Therefore, this study aims to advance the implementation and development of innovative designs of building energy codes by exploring which challenges policymakers face when implementing these designs and, subsequently, by identifying how general code development might learn from these challenges. Evaluating the building energy codes of Denmark, France, England, Switzerland, and Sweden, we present six innovative designs of building energy codes and highlight how they advance building decarbonization by increasing energy efficiency and renewable energies, considering embodied energy, closing the performance gap, and accelerating retrofits. Based on 19 expert interviews with practitioners, regulators, and researchers, we identify real-world challenges that policymakers face when implementing innovative designs of building energy codes. Synthesizing these challenges across the countries, we derive six policy principles for advancing the development and implementation of building energy codes. Policymakers can thus learn valuable lessons from front-runners' experience and steer clear of avoidable pitfalls.

1. Introduction

Energy demand from buildings accounts for about 31% of global final energy demand and 23% of global energy-related carbon emissions (IPCC, 2018). In industrialized countries, these figures are even higher. In Switzerland, for example, buildings contribute to 50% of the primary energy consumption (BFE, 2018) and up to 40% of the country's carbon emissions (IEA, 2012), highlighting the remarkable potential for reducing carbon emissions in construction. Buildings also provide many opportunities to save energy cost-effectively (IEA, 2014). According to Ürge-Vorsatz et al., (2012), energy demand for heating and cooling could be almost halved by 2050 compared to 2005 levels by applying today's best-practice energy-efficient technologies. However, many energy-saving opportunities are not realized, although being already cost-effective (McKinsey and Company, 2009)—which has become to be known as the "energy efficiency gap" (Jaffe and Stavins, 1994).

Literature has long recognized that implementing policies—individually tailored in form, magnitude and timed to address specific market and behavioral failures (Gillingham and Palmer, 2014)—can help to close this gap (Mowery et al., 2010). Policies for energy in buildings have been classified into control and regulatory mechanisms, economic and market-based instruments, fiscal instruments and incentives, and support, information and voluntary action (Ürge-Vorsatz et al., 2007). Most effectively these instruments work in synergy with each other in a so-called policy mix (Kern et al., 2017; Rogge and Reichardt, 2016), as no single one can address all the market and behavioral failures (Lee and Yik, 2004).

Building energy codes[1] (BECs)—control and regulatory mechanisms that traditionally set minimum requirements for energy use and generation in buildings—are seen as one of the most cost-effective policies for closing the energy efficiency gap (Graham et al., 2014; Ürge-Vorsatz et al., 2012), and are thus an essential part of a policy mix. Dating back to as early as 1946 in Sweden, BECs have been introduced since the mid-1970s in most industrialized

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[1] Literature also refers to these policies as 'Building Regulation', 'Technical Energy Regulation', or 'Building Standards'.

https://doi.org/10.1016/j.jclepro.2019.119260
0959-6526/

countries as a reaction to the oil crisis (IEA, 2013). More recently, many countries have included BECs in their climate mitigation actions under the Paris Agreement (Evans et al., 2017). BECs have helped to reduce energy consumption from buildings by up to 6% in Southern European countries and 22% in Germany and Netherlands (IEA, 2013), by 13–22% in China (Yu et al., 2014), and by 42% in India (Tulsyan et al., 2013). They are also expected to continue reducing energy consumption in the future. For example, the US Department of Energy projects the current BECs to contribute to cumulative primary energy savings of 12 EJ by 2040 (Athalye et al., 2016). Further, BECs are seen to be one of the most politically feasible and thus popular policy to promote energy efficiency (Gillingham and Palmer, 2014). They are especially suitable when dealing with a target group that is unwilling to act or difficult to address (e.g., landlord-tenant problem) or when aiming at removing the worst products or services from the market with regard to energy consumption (Harmelink et al., 2007). Consequently, implementing effective BECs has been proposed as a key issue for building decarbonization in the literature (Evans et al., 2018, 2017).

Despite their long history and success, policymakers and researchers increasingly recognize the limitations of current BEC designs. First, BECs traditionally focus on prescriptive requirements such as minimum U-values, yet reducing these further has diminishing returns (Rosenberg et al., 2015). Second, current BECs primarily regulate the energy demand during the use phase of buildings, and thus neglect embodied energy (i.e., energy used to produce construction materials), which makes up to one-third of the energy use of net-zero energy buildings (Goggins et al., 2016). Third, most BECs still allow fossil-fuel heating systems, which are subsequently still the prevalent technology in many industrial countries, despite economically superior energy-efficient alternatives (IEA, 2019). Fourth, most BECs regulate planned values in building design and construction, despite an average difference between calculated and measured energy use of 34% (van Dronkelaar et al., 2016)—termed the ‘performance gap’. Fifth, the impact of current BECs on the existing building stock is limited with retrofitting rates below 1% per year in many countries (Ma et al., 2012). Responding to these limitations and building decarbonization goals (e.g., net-zero energy buildings), policymakers and researchers have begun to discuss new designs of BEC development and implementation that overcome these limitations—which we will refer to as “innovative BEC design” in the following.

Literature on BEC development highlights that the continuous development of BECs is key to keep them effective. For example, Rosenberg et al. (2015) lists central tenets that have remained consistent throughout the evolution of BECs (e.g., the focus on prescriptive requirements and new buildings while neglecting unregulated loads and the actual energy use) and discusses how advances in building technologies (e.g., the rollout of sensors and controls) will leverage more stringent BECs. Another study by Cohan et al. (2010) presents a list of guiding principles (e.g., the inclusion of performance tests, new enforcement mechanisms) that could be applied to general code development, resulting from an assembly of US energy code and policy experts. However, these studies neglect discussing the challenges that policymakers might face when implementing such innovative BEC designs.

Literature on BEC implementation includes implementation mostly as a minor part of a broader BEC evaluation, often across countries (Berardi, 2017; Evans et al., 2009; Huang et al., 2016; Iwaro and Mwasha, 2010; Young, 2014). Only recently—responding to studies that highlight the importance of BEC implementation for capturing the full advantages of BEC design such as by Yu et al. (2014)—researchers started to focus more specifically on BEC implementation. For example, Evans et al. (2017) identify elements and practices of BEC implementation systems (i.e., compliance control and evaluation, training, and support tools) at the national level across 22 countries. Guo et al. (2016) and Evans et al. (2010) analyze BEC implementation in China—one of the biggest success stories in terms of official compliance rates. However, these studies rather evaluate the success of BEC implementation systems in isolation of BEC development.

Therefore, the objective of this study is to link BEC implementation and development by exploring which challenges policymakers face when implementing innovative BEC designs and how general BEC development might learn from these challenges. We approach this by addressing the following three research questions: First, we ask: *How does the status quo of BEC development advances building decarbonization?* We then ask: *How do innovative BEC designs overcome limitations of current BECs designs, and what challenges did policymakers face when implementing them?* Finally—to close the link between BEC development and implementation— we ask: *What can we learn for future BEC development from implementing innovative designs?*

2. Method

To analyze how BECs can advance the ongoing decarbonization of the building sector, we build on the following four components.

Literature review: To identify pathways to advance the ongoing decarbonization of the building sector –which we will refer to in the following as leverage points –we began with Mavromatidis et al. (2016), who highlight the role of *increasing energy efficiency* and *increasing renewable energy* in past building decarbonization. To reflect future priorities, we added three more leverage points: The first is *reducing embodied energy*: net-zero energy buildings have up to half of their lifecycle carbon emissions embodied in their materials (Goggins et al., 2016). Second, c*losing the performance gap* aims to reduce the difference between calculated and measured energy use, which is particularly pronounced in new energy-efficient buildings (van Dronkelaar et al., 2016). Third, *accelerating retrofits* helps to decarbonize the existing building stock by increasing retrofitting rates, which are below 1% per year in industrialized countries (Ma et al., 2012). While literature highlights many other measures that contribute indirectly—for example, extending system boundaries from buildings to increase renewable energy (Grosspietsch et al., 2019)—we consider such measures as BEC designs that pave the way for leverage points.

Case selection: To identify countries that have already implemented innovative BEC designs, we started with the few review studies on BECs (Evans et al., 2018, 2017; IEA, 2013; Rosenberg et al., 2016). We consolidated and extended our findings with a forward and backward search and an independent keyword search on Scopus. We then made a longlist of innovative designs (cf. supplementary information) and narrowed it down with two additional criteria: The country must already be implementing the BEC—as many challenges only occur during their implementation—and all selected cases must have comparable built enviornments (i.e., old building stock with low new construction and renovation rate, long building lifetimes, a high-quality building industry, and long-lasting experience with BECs). Finally, to limit the scope of this study, we selected one innovative BEC design for each leverage point—while we selected two innovative BEC designs for “increasing renewable energies” due to the variety of BEC designs that address this leverage point. Ultimately, we selected Denmark (DK), France (FR), England (ENG), Switzerland (CH), and Sweden (SE). Please note that the selected innovative BEC designs are not a comprehensive review of all innovative BEC design.

Document analysis: To understand the entire BEC of which the innovative design is a part, we analyzed the building regulations of the selected countries (707 pages) in depth and validated our understanding with secondary literature. To compare BEC designs, we developed a categorization framework covering all essential categories of BECs and populated it with the BECs of our selected countries. We discussed and validated our framework with building and energy experts over several iterations (cf. supplementary information).

Semi-structured interviews: To evaluate implementation challenges, we conducted 18 semi-structured expert interviews covering four topics: "design of the innovative approach and BEC," "implementation challenges," "impact on the technology landscape," and "outlook for future designs." To cover different perspectives, we interviewed researchers, practitioners, and policymakers. To select new interview partners we drew on secondary data and asked already interviewed experts for recommendations (i.e., snowball sampling). We conducted the interviews between March 2018 and January 2019. The response rate was 24% (academics 33%, practitioners 20%, regulators 22%). The research went through several rounds of discussion, starting with an in-depth interview (in person or via phone), and continued with written correspondence and review of the case summaries. Table 1 provides an overview of our data sources across cases.

3. Leverage points for building decarbonization and the *status quo* of BEC development

In the following, we outline five leverage points for building decarbonization derived from literature and show how current BECs address each one. Table 2 summarizes the BEC designs selected countries adopted, including innovative designs, which are described in-depth in section 4.

Increasing energy efficiency reduces energy demand during buildings' use phase. Historically, most energy-efficiency gains came from improving thermal insulation and installing energy-efficient technologies for heating, cooling, lighting, and ventilation. Many countries increased energy efficiency through BECs that prescribed individual building parts, such as U-Value (Berry and Marker, 2015; Deason and Hobbs, 2011). However, there are limits to the energy savings that can be achieved by strengthening such prescriptive requirements, resulting in diminishing returns. For example, adding insulation to an un-insulated wall reduces heat loss by about 75%, while adding the same amount again only saves a further 11% (Rosenberg et al., 2016). Therefore, current BECs shifted towards performance metrics for the entire building's energy use—in our cases, mostly primary (i.e., DK, FR, CH, SE) and end-use energy demand (i.e., ENG). However, all cases retained prescriptive requirements for envelope efficiency or individual building technologies. Such a combination helps minimize buildings' energy demand while also minimizing carbon emissions to cover the remaining energy demand. The shift towards performance metrics further allows BECs to consider so-far neglected sources of building energy use, such as plug loads and fixed installed appliances (cf. Table 3), or additional emerging sources, for example, due the diffusion of electric vehicles (IEA, 2018). The energy demand for increased cooling degree days (Frank, 2005) is included in all performance metrics. In addition, Switzerland and Sweden adopted capacity constraints to limit one or more service capacities such as heating power.

Reducing embodied energy is becoming increasingly relevant, as net-zero energy buildings have up to one-third of their energy use, and up to half of their lifecycle carbon emissions, embodied in their materials—compared to conventional buildings with up to 90% of their lifecycle energy use during their use phase (Goggins et al., 2016). Further, there might be a trade-off between embodied energy and energy efficiency, calling for joint regulation of both. For example, some energy-efficient buildings show an increasing amount of energy-intensive materials (Casals, 2006; Chastas et al., 2016). Historical and current BECs, however, concentrate on energy use during the operational phase, and thus neglect to set requirements for embodied energy.

Increasing renewable energy in buildings minimizes carbon emissions to cover the remaining energy demand of energy-efficient buildings. Historically, the decarbonization of building energy demand was driven by decreases in the carbon intensity of energy supplies such as electricity, while fossil heating systems remained the prevalent technology in many industrial countries (IEA, 2019), despite economically superior low-carbon alternatives. More recently, however, current BECs have begun to regulate renewable energy in buildings. First, all selected countries adopted

Table 1
Data sources across cases.

		Denmark	France	England	Switzerland	Sweden	Total (minutes)
Interviews (duration in minutes)	Researchers	Professor (61)	Assistant professor (53) Lab director (82)	Lab director (40)	(Advisory board meetings of research project, no additional interviews)	Senior expert (65)	301
	Practitioners	Senior specialist in energy and indoor climate (written statement)	Director in social and private housing company (41)	Director of building engineering (54)	Deputy head in building service engineering (34) Founder of energy consultancy (24)	Project manager in building consultancy (63)	216 + written statement
	Regulators	Senior advisor for Danish transport, construction and housing authority (49)	Assistant deputy director of quality and sustainable development in construction (63)	Director of sustainable energy (93)	Head of cantonal energy department (52); Head of cantonal department of energy and environment (54); Head of Cantonal Department Construction, Transport, and Energy (73)	Assignment owner, increased sustainable construction (58)	442
	Total (minutes)	110 + written statement	239	187	237	186	959
Legal Documents (pages)		137	140	167	98	165	707
Secondary data		Scientific publications on regulations addressing the five focal cases, summaries BECs, …					

Table 2
Overview of key leverage points for building decarbonization and related BEC design options.

Key leverage points	BEC designs	DK	FR	ENG	CH	SE
Increasing energy efficiency	- Adopting stringent prescriptive requirements	✓	✓	✓	✓	✓
	- Adopting stringent performance requirements	✓	✓	✓	✓	✓
	- Including capacity constraints				✓	✓
	- Pre-announcing upcoming BECs	☆				
Reducing embodied energy	- Adopting a lifecycle perspective for performance requirements		☆[a]			
	- Adopting requirements for the construction phase		☆[a]			
Increasing renewable energy	- Adopting stringent performance requirements	✓	✓	✓	✓	✓
	- Adopting a performance metric on carbon emissions			☆		
	- Prescribing renewable heating for new buildings and deep retrofits	✓	✓			
	- Prescribing renewable heating during boiler replacement				☆	
	- Prescribing on-site electricity generation				☆	
	- Banning fossil technologies and their infrastructure	✓			✓	
	- Stipulating a technological and economic feasibility test (prescriptive, indirect)	✓		✓		
Closing the performance gap	- Checking compliance during planning and construction	✓	✓	✓	✓	✓
	- Checking compliance during occupancy					☆
Accelerating retrofits	- Adopting less stringent and/or purely prescriptive requirements for retrofitting	✓	✓	✓	✓	
	- Stipulating retrofitting during changes of ownership		☆			
	- Adopting a long-term perspective on retrofitting obligations		☆[b]			

✓: Country implemented this BEC design.
☆: Country implemented this innovative BEC design.
[a] Not part of current regulations, but announced for 2020.
[b] Adopted in law, but not yet implemented by decree; no official timeframe for implementation.

Table 3
Overview of BEC coverage.

	DK	FR	ENG	CH	SE
Heating	✓	✓	✓	✓	✓
Cooling	✓	✓	✓	✓	✓
Domestic Hot Water	✓	✓	✓	✓	✓
Ventilation	✓	✓	✓	✓	✓
Lighting	✓	✓	✓	(✓)[a]	(✓)[b]
Plug-load					
Fix installed appliances					(✓)[c]

[a] Only non-residential buildings.
[b] Only permanently installed lighting of common spaces and utility rooms.
[c] Energy used in heating cables, pumps, fans, motors, control and monitoring equipment.

a performance metric that supports the use of renewables. In addition, all except Sweden adopted additional prescriptive requirements for the use of renewable energy: Denmark, France, and Switzerland directly prescribe the use or a minimum share of renewable energy; Denmark and Switzerland partly ban fossil and high-energy-use technologies; Denmark restricts extending the distribution network of fossil fuels; Denmark and England demand a technological and economic feasibility assessment (if feasibility is proven, buildings must use renewables).

Closing the performance gap aims to reduce the difference between calculated and measured energy use (Glasgo et al., 2017; Gupta and Kotopouleas, 2018; Rosenberg et al., 2016). According to recent studies, this difference amounts to 34% on average (van Dronkelaar et al., 2016) but can increase the calculated energy use by as much as three times (Delzendeh et al., 2017). The main drivers of this "performance gap" (De Wilde, 2014) are inaccurate estimates of occupants' energy-use behavior, deviations from as-planned building properties such as insulation and air permeability, rebound effects (Hens et al., 2010; Sorrell et al., 2009), and occupants' unfamiliarity with new, complex energy-efficient technologies. Since the performance gap is a relatively novel phenomenon, the focus of historical BECs on regulating building design and construction was appropriate. However, also current BECs only continue to check compliance as far as planning and construction.

Accelerating retrofits advances the decarbonization of the existing building stock. With current retrofitting rates below 1% per year in industrialized countries (Ma et al., 2012), many of today's energy-inefficient buildings are likely to still be standing in 2050 and beyond. The reasons for the sluggish retrofitting rate include the split incentive problem for landlords and tenants (Ástmarsson et al., 2013), the high upfront costs of energy-efficiency investments, and the pronounced depreciation of future energy savings (Meijer et al., 2018). While historical BECs initially focused on new buildings, over recent decades they have also adopted requirements for retrofits—albeit less stringent ones than for new buildings, thereby reducing upfront investment costs. Also most current BECs distinguish between regulations for new buildings and retrofits and for example allow latter to comply with purely prescriptive requirements only. From our selected countries, only Sweden adopted similar requirements for new buildings and retrofits.

4. Innovative BEC designs and their implementation challenges

The selected countries already implemented innovative BEC designs to overcome specific limitations of current designs. In this section, we describe how these innovative BEC designs were implemented and outline the challenge of their implementation. Table 4 summarizes the content of this section.

4.1. Increasing energy efficiency by pre-announcing upcoming BECs (Denmark)

Denmark increased energy efficiency by introducing voluntary low-energy classes and announcing far in advance when they would become mandatory, thus providing long-term targets for the construction industry.

In 1995, the Danish government introduced a "50% voluntary low-energy class," which covered buildings that were 50% more energy-efficient than the minimum defined by the Danish Building Regulation. A decade later, in 2005, the government introduced a "25% voluntary low-energy class." Shortly afterwards, it pre-

Table 4
Benefits and implementation challenges of innovative BEC designs.

Innovative BEC Design	Benefits and implementation challenges
Increasing energy efficiency by pre-announcing upcoming BECs (DK, Section 4.1*)*	+ Strong endorsement for innovation + Provides ambitious building owners a target to aim at + Allows stricter but cost-effective requirements − Increases concerns about higher investment costs
Reducing embodied energy by taking a lifecycle perspective and adopting requirements for the construction phase (FR, Section 4.2*)*	+ Encourages construction industry to use and development low-energy building materials − Requires extensive prior testing and continuous learning
Increasing renewable energy with a carbon emission metric (ENG, Section 4.3*)*	+ Aligns BEC requirements with energy & climate targets + Fosters the adoptions of carbon-friendly technologies − Results in energy-inefficient buildings − Increase electricity demand when grid is decarbonized − EU harmonization efforts push the use of primary energy as a metric
Increasing renewable energy by requiring on-site electricity generation and renewable heating (CH, Section 4.4*)*	+ Very effective in increasing renewable energy − Seen as technology specific − Problematic for all buildings to comply with − Increases upfront investment cost
Closing the performance gap by complying with measured energy demand (SE, Section 4.5*)*	+ Increases matching between calculated and measured requirements (however, has not been proven yet) − Higher soft costs and personnel capacity need for enforcing authority − Sanctioning building owners during occupancy in case of non-compliance is a delicate task
Accelerating retrofits through retrofit obligations (FR, Section 4.6*)*	+ Provides a fair planning horizon for building owners for retrofitting − Increases upfront investment costs − Premise of requirement (i.e., European Performance Certificate) is seen as unreliable − Results in more but less deep retrofits

+: Benefits of implementing the innovative design.
-: Challenges when implementing the innovative design.

announced that both low-energy classes would become mandatory: the 25% class in 2010 and the 50% class in 2015, with both based on 2006 values. At the same time, the government introduced another voluntary "Building Class 2020," which calls for a 75% improvement in energy efficiency, and announced that it would become mandatory in 2020. However, in 2018, the government decided that the 2020 Building Class would remain voluntary even after 2020 (Ministry of Transport Building and Housing, 2018). No long-term targets beyond 2020 have yet been announced.

According to our interviews, the construction industry perceived the announcement of future regulation as a strong endorsement for innovation, and therefore advocated for it. Knowing that a voluntary energy standard would become mandatory, companies had time to develop and exploit investments in new technologies, materials, and construction methods. As one researcher explains, *"Announcing future minimum regulations shows that there will be a market for high-quality products because everybody has to use them."* In particular, large manufacturers of high-quality products advocated for tighter regulation, announced early. As one practitioner underlines, *"Insulation material manufacturers were pushing this. They saw it as an opportunity to sell more of their products due to the tightening of the energy requirements."* Literature confirms such positive perception of pre-announcing future regulation. For example, *Copenhagen Economic (2014)* presents a number of examples of the Danish construction industry related to the pre-announcement of low energy classes and highlight that it provided a competitive advantage in the international market for building technologies and construction concepts.

Investors have varying views on pre-announcement. On the one hand, it gives ambitious investors a target to aim at. As one practitioner explains, *"Customers want their building to be prepared for the future. When the next regulation is only two or three years away, they want to build according to the next regulation. [...] That's exactly what happened between 2010 and 2015. While, in 2010, only a small percentage of the owners built according to the low energy class, in the year before it became mandatory, the percentage increased to 50%. In turn, the market, instead of changing radically, changed gradually and slowly shifted from one set of requirements to another."* Gram-hanssen et al. (2018) confirm these numbers and highlight that low energy classes have been received very well by the building industry with regard to the construction of new buildings. On the other hand, large real-estate investors in particular opposed the announced changes due to concerns about higher costs. However, the Danish government successfully addressed these concerns by referring to the principle of cost-effectiveness as a prerequisite of making a low-energy class mandatory.

In 2018, the Danish government revoked its plan to make the Building Class 2020 mandatory. As one regulator explains, *"We evaluated the Building Class 2020 and it was simply too strict for a minimum requirement. It is easier to cut the first 25% of the building energy consumption than the last 25%. Particularly for non-domestic buildings, the Building Class 2020 is not cost-efficient, not even close."* A further tightening of the energy requirements of the Danish building regulation seems unlikely, but the regulations will still evolve, and Denmark will pre-announce future regulations on embodied energy. As one researcher outlines, "*The next thing is sustainability. We are currently developing a Sustainability Class 2025, including a lifecycle view and a focus on embodied energy. The idea is to introduce this in 2020 as a voluntary class for 2025. We will continue to pre-announce future requirements*."

Pre-announcing upcoming BEC designs resulted in a more innovative Danish construction industry, driving down costs of energy-efficient building technologies. In turn, Denmark was able to define more stringent but cost-effective targets.

4.2. Reducing embodied energy by taking a lifecycle perspective and adopting requirements for the construction phase (France)

France will begin to reduce embodied energy by taking a lifecycle perspective for performance metrics and adopting requirements for the construction phase in the next update of its thermal regulations for buildings, the so-called *Réglementation Environnementale* ("RE"), which will come into force in 2020 (Bordier et al., 2016). To prepare the construction industry, as early as 2016, French policymakers launched the "E+C- program" (ADEME, 2018). The program aims to define cost-effective lifecycle energy performance requirements with voluntary industry participation, forming the basis for RE 2020.

According to our interviews, the current introduction of embodied energy requires extensive prior testing and continuous learning. As one regulator highlights, "*For RE 2020, to include embodied energy, all building developers will have to do a lifecycle analysis for every new building. This has never been done before*." To test this regulatory novelty before a nationwide rollout, French policymakers followed a two-step learning process. One researcher explains the first step as follows, "*We had already started testing the lifecycle approach five years ago. […] Based on those learnings, we launched the E+C- program*." One regulator explains the second step as follows: "*The E+C- program is an experiment for two to four years to test which energy performance level will ultimately become the regulation. We have to try and see what the costs are*." Further, the framework should allow for continuous learning. As one regulator explains, "*We do not yet have a lifecycle analysis for every product and material on the market. To still include a lifecycle perspective, there will be an average value for those products, but with a penalty factor*."

Taking a lifecycle perspective and adopting requirements for the construction phase is expected to transform the French construction industry. As one regulator underlines, *"Including a lifecycle perspective for buildings will probably change the face of the construction industry—it changes everything."* However, the direction of this change is seen as uncertain. As the same regulator adds, *"The timber industry lobbied for a lifecycle perspective. Interestingly, the cement industry did not oppose it."*

Taking a lifecycle perspective and adopting requirements for the construction phase is the necessary step to regulate the entire carbon footprint of buildings and, thus, advance building decarbonization in the long run.

4.3. Increasing renewable energy with a carbon emission metric (England)

In 2006, England adopted carbon emissions as the key performance metric in its building regulation (HM Government, 2016). This metric calculates carbon emissions by multiplying the demand for different energy carriers such as electricity and heating oil by their respective "Carbon Emission Factors." The lower the carbon emission factor, the higher the allowed consumption of the respective carrier while still complying with the performance requirement.

According to our interviews, the motivation for adopting a carbon emission metric was to align buildings requirements with national targets and international commitments strategically. As one regulator explains, *"England has international commitments to reduce carbon emissions. When you have concerns about the environment, the carbon emission metric is more relevant. When you have more concerns about resources, then you might shift into primary energy."* Further, one researcher notes, *"The carbon emission metric was an attempt to increase public understanding of how much carbon emissions can be saved through building regulations, and how these savings contribute to England's reduction targets."*

Requirements for buildings' carbon emissions are perceived to have affected the technology landscape in England. As one regulator emphasizes, "*Carbon-friendly technologies have been heavily adopted on the back of a carbon metric. Examples are biomass, biofuels, and combined heat and power systems*." For example, the installed capacity of combined heat and power systems in the UK almost doubled between 1998 and 2018, amounting to 600 MWe in the building sector (UK Government, 2018). In the near future, the decarbonization of the electricity mix will re-direct this effect towards technologies using electricity. As one regulator explains, *"The carbon emission factor of the electricity grid is going down very heavily; soon it will be similar to the factor of natural gas. This will have huge implications for building technologies and their building demand for electricity."* Defining the carbon emission factors, however, is challenging, with far-reaching implications for the industry. As one regulator notes, "*It is critical to consider the timelines of the factors, because a new building lasts 60 years and a heating system 15–20 years*."

The carbon emission metric is increasingly seen in a critical light, prompting regulators to act. As one regulator notes, "*In the new regulation cycle, we will shift from a pure carbon emission metric to a combination of a primary energy and a carbon emissions metric*." Interviewees indicated three arguments that support this assertion. First, reducing carbon emissions does not necessarily result in energy-efficient buildings, as one practitioner explains: "*Technologies using low-carbon electricity might be more carbon-friendly but less energy-efficient than a fossil-fuel-based technology. An additional energy metric would increase buildings' energy efficiency*." Second, primary energy factors are more stable than carbon emission factors. As one regulator explains, "*The primary energy factor of the electricity grid is more stable and not yet as close to gas*." Third, the EU promotes the use of a primary energy metric (EU, 2018).

While a primary energy metric also serves other policy goals such as energy security and electricity reliability, a carbon emission metric is directly linked with the goal of climate change mitigation. A switch towards a carbon emission metric might thus leverage low-carbon technologies.

4.4. Increasing renewable energy by requiring on-site electricity generation and renewable heating (Switzerland)

Swiss model regulations—aimed at harmonizing BECs across the Swiss cantons—define two prescriptive requirements that aim to increase renewable energy in buildings (EnDK and EnFK, 2015). First, they stipulate that new buildings must produce a certain amount of electricity on-site. Second, they require the 1.1 million Swiss residential buildings that have an oil or gas boiler to install a heating system based on at least 10% renewable energy in case of a boiler replacement.

According to our interviews, both requirements are heavily debated in the implementing cantons. Mandatory on-site electricity generation raises two issues. First, construction experts regard this requirement as technology-specific. As one practitioner points out, "*The requirement […] should be technology-neutral, but the alternatives to solar photovoltaics are all very exotic solutions. So far, we have always installed rooftop solar photovoltaics*." Second, on-site electricity generation might be difficult to achieve for some buildings. As one regulator notes, "*Compact buildings cannot install the required number of photovoltaic panels on the rooftop. Should the building owner, in this case, install expensive façade photovoltaics?*" However, one practitioner disagrees: "*We have never had the problem that the rooftop area is insufficient because the required power generation is limited*."

The debate on renewable heating in case of a boiler replacement centers on two issues. First, the requirement might increase investment costs. As one regulator highlights, "*Many owners will be financially overwhelmed by the investments. Particularly problematic are buildings with multiple and heterogeneous owners. Also, many older people are neither willing nor able to invest much money in retrofitting their homes*." This argument is supported by the limited technology choices for some existing buildings, as one practitioner explains: "*Existing buildings can be limited due to previous technology choices, leading to more expensive solutions. For example, buildings with radiators require high flow temperatures, which heat pumps cannot deliver.*" Second, biogas might pose difficulties in compliance control, as one regulator explains: "*Historically, compliance is checked at the time of the issuance of building permits or the installation of technologies because it is much easier to adhere to than periodical compliance checks during building operation. Accepting biogas as a renewable energy would require checking periodically whether it is actually being delivered or not.*"

Despite these criticisms, both requirements are seen as very effective in increasing renewable energy in buildings. As one practitioner explains, "*Architects try to avoid single photovoltaic modules on the rooftop. That is why the required 10 W/m^2 already has a big impact, because then the whole roof is usually filled.*" A regulator adds, "*Due to the 10 per cent renewable energy in case of a boiler replacement, one can only continue installing a gas or oil boiler when adding solar thermal energy, which is quite expensive. Then, other heat sources such as the heat pumps become cheaper than the combination of a gas boiler plus solar thermal energy*". These excerpts show that both requirements result in more renewables than actually stipulated.

In sum, requiring both on-site electricity generation and renewable heating reduce the net demand of buildings for fossil fuels, which, ultimately advances building decarbonization.

4.5. Closing the performance gap by complying with measured energy demand (Sweden)

The Swedish building regulation aims to close the performance gap by checking compliance based on measured building performance. For each building, the local municipality decides whether compliance will be checked based on measured or calculated building performance. If the municipality opts for measurement, but the building exceeds the minimum requirements two years after occupation, it can fine the owners, demand additional energy-efficiency measures, or even withdraw the final building permit.

According to our interviews, the motivation for introducing a measured compliance path was indeed to close the performance gap. As one regulator notes, "*Before 2006, in Sweden, we only had a calculated compliance path. However, when comparing calculated and measured building performance, it became evident that measured energy use was sometimes 250% higher than calculated. We wanted to change this, so we began to define regulation based on measured performance.*" Boverket, the Swedish entity responsible for compliance control, confirms that actual and calculated energy consumption of buildings could differ up to this number (Boverket, 2016).

Building owners and municipalities have different views of this compliance path. One researcher explains the owners' perspective: "*Professional owners prefer measurement because they see the benefits of getting a good building. Conversely, less competent owners are less interested because they only see the additional cost.*" A practitioner adds the perspective for municipalities: "*Mostly, municipalities prefer the calculated compliance path because then they can close the file after the building has been constructed.*" However, municipalities differ in their evaluation. As one researcher highlights, "*Larger municipalities have the personnel capacity to follow regulatory changes and check compliance. Smaller municipalities, however, are often unaware of regulatory changes and thus do not know how to check compliance correctly.*" These excerpts show that actor size plays a significant role for the compliance–path preference. Larger actors seem to prefer measurement over calculation, and vice versa for smaller actors. Yet, despite the drawbacks for smaller actors, the regulator pushes for the compliance path based on measured values.

In our interviews, two major challenges of the measured compliance path have become evident. First, data is lacking is available—particularly for residential buildings. As one researcher explains, "*It seems contradictory, but the less complex the building, the less information. For residential buildings, often the only data available is total energy use or total electricity use. In turn, the responsible authority has to make a lot of estimates, which makes the values used for the measured compliance check very uncertain.*" Second, punishing building owners for non-compliance two years after the building's occupation is delicate. As one practitioner points out, "*So far, the municipality has rarely penalized the building owner in case of non-compliance.*"

The shift from compliance with calculated to compliance with measured energy demand requires the construction industry to refocus on as-built performance. Boverket (2016) highlights that the introduction of compliance with measured data resulted subsequently in lower energy use in buildings.

4.6. Accelerating retrofits through retrofit obligations (France)

In 2015, France adopted the Energy Transition Law for Green Growth, which comprises two targets and one obligation for accelerating the retrofitting of the French building stock (Assemblé Nationale et le Sénat, 2015; Republique Française, 2016). The first target aims at accelerating the rate of thermal retrofits to 1.5% per year, amounting to 500,000 dwellings. Half of these should be low-income households, delivering a 15% reduction of energy poverty by 2020. The second target aims at achieving a higher energy-efficiency level for the whole building stock by 2050. The so-called "retrofit obligation" aims to support the latter target and requires all private residential buildings that consume more than 330 kW h/m^2.yr (affecting approximately 15% of the building stock) to retrofit by 2025. The obligation will be tightened every 10 years (Dreyfus and Allemand, 2018; Rüdinger, 2015).

According to our interviews, turning the targets and the retrofit obligation into specific policy measures is challenging. As one researcher notes, *"The government is defining very ambitious targets, but it does not provide or explain the means to achieve them."* Even four years after its adoption, the retrofit obligation is only partially implemented in decrees; so far, it covers the social housing sector only, prohibiting the sale of high energy-use social housing (Legifrance, 2015).

Experts in this field highlight three reasons for the lack of decrees. First, the obligation triggers additional upfront costs for homeowners, as one practitioner notes, *"Some building owners simply cannot afford to retrofit their buildings."* Second, the obligation is based on the French Energy Performance Certificate, which is perceived as unreliable by the population. As one researcher adds, *"If you are designing a law around something that is not reliable, then the new law has also a problem of acceptability."* Also literature highlights the minor impact of the Energy Performance Certificate on the property value in France. For example, Santos et al. (2016) show that only in one-third of the cases low-energy performance ratings affect rent-prices. Third, the obligation is perceived to result in more light retrofits, as one researcher notes, *"If the building consumes slightly more than the retrofit obligation allows, the owner can simply replace one element and achieve compliance. However, this might result in lock-ins and missed opportunities. The obligation should, therefore, prioritize major retrofits instead."* For example, Sebi and Schleich (2018) *highlight that despite 3.5 million retrofits in France, less than 41% improved more than one building element, and less than 10% were major retrofits.*

In sum, retrofit obligations address the most energy-demanding buildings and can, thus, strongly contribute to the decarbonization of the existing building stock.

5. Six principles for innovative BEC design

By synthesizing the implementation challenges across our five case studies, we now derive and discuss six policy design principles for BECs. These are generally applicable and ensure BECs function effectively—thus often separating the successful BEC implementations from the failures (BigEE, 2013; Harvey et al., 2018; UN, 2017; UNDP, 2010). We argue that the benefits and drawbacks of innovative BEC designs become particularly salient when policymakers face new challenges during their implementation. This allows us to derive policy implications for how to design BECs that contribute to building decarbonization. We recommend that policymakers apply these principles when implementing innovative BEC designs to ensure broad acceptance across all actors in the construction sector—particularly important in view of BECs' mandatory nature. Table 5 provides an overview of our six BEC design principles and outlines examples illustrating how to follow them.

5.1. Keep additional burdens for building owners light

To lighten the load for building owners, policymakers should design BECs that only require cost-effective measures that are economically beneficial to consumers. In many countries, cost-effectiveness is already a guiding principle for the design of BECs (EU, 2010). Yet, literature highlights the limitations of the cost-effective principle: First, it limits the possible pace for decarbonizing the building stock and thus climate change mitigation (Berry and Davidson, 2016). Second, the co-benefits of energy efficiency measures such as health and comfort improvements are typically neglected in homeowners' cost-benefit analysis—despite having a direct impact on them (Almeida and Ferreira, 2018; Fawcett and Killip, 2019). Third, due to the landlord-tenant dilemma and the resulting split incentives, energy-efficiency measures might be cost-effective for a single-actor investment, but not for a multi-actor investment—when one actor bears all the costs, but another reaps all the benefits (Ástmarsson et al., 2013).

To implement cost-effectiveness as a guiding principle successfully, we recommend that policymakers (i) include a technical and economic feasibility test for building owners (cf. Denmark). This accounts for the enormous variety of building types and designs, and permits owners to have the requirement waived if they can demonstrate that it is technically or economically unfeasible for them due to the individual characteristics of their building (e.g., existing heating system, building design) and/or contextual factors (e.g., technology cost). Yet, one drawback of economic feasibility tests for building owners is the definition of parameters that typically vary between homeowners, for example, the discount factor. Further, we suggest policymakers to (ii) expand the range of factors covered in economic feasibility tests, for example, occupant health and well-being. This would increase the cost-effectiveness of low-carbon technologies and, subsequently, support further stringency improvements (Berry and Davidson, 2016). Ultimately, we encourage policymakers to (iii) add targeted support to cope with additional upfront costs (cf. Switzerland). Cost-effective requirements typically require high capital expenditures, while their benefits accrue over time. Further, building owners strongly depreciate future energy savings (Meijer et al., 2018). In turn, they oppose cost-effective BECs, as they fear being financially overwhelmed when retrofitting. To lower the upfront costs of energy-efficiency investments, policymakers can offer, among other measures, interest-free loans and lump-sum grants (Harvey et al., 2018). Such support should target in particular vulnerable end users such as low-income households (BigEE, 2013; UNDP, 2010).

5.2. Create long-term regulatory certainty

Long-term regulatory certainty provides a fair planning horizon for the construction industry. This, in turn, spurs innovation, drives down technology costs and, ultimately, allows for stricter BECs. Large manufacturers of high-quality products can invest in innovative activities, implement innovative processes, or release innovative products in the knowledge that there will be a market for them (Blind et al., 2017). In the absence of regulatory certainty, manufacturers are likely to postpone major investments until the future becomes clearer (Hugh Courtney et al., 1997). In addition, architects and engineers benefit from a long planning horizon, since the process of selecting a building site, acquiring permits, obtaining financing, and actual construction can extend over many years.

However, policymakers should balance long-term regulatory certainty with short-term flexibility. This allows for learning and

Table 5
Overview of BEC design principles and design examples.

BEC design principle	BEC design examples
Keep additional burdens for building owners light (Section 5.1)	- Include technical and economic feasibility test - Expand the range of factors covered in economic feasibility test - Add targeted support to cope with additional upfront costs
Create long-term regulatory certainty (Section 5.2)	- Align BECs with national energy and climate targets - Pre-announce upcoming BECs - Integrate continuous improvement processes
Beware of technology-specific requirements (Section 5.3)	- Ensure that multiple technology options are available
Anticipate the impact of new regulations on smaller actors (Section 5.4)	- Support small firms by reducing unnecessary soft costs - Help small authorities by removing the burden of capacity-intensive compliance control
Promote knowledge of innovative design (Section 5.5)	- Pre-announce upcoming BECs - Conduct test programs - Build upon voluntary labels - Learn from frontrunner legislation
Integrate BECs in the local context (Section 5.6)	- Leverage the existing infrastructure - Consider the level and pace of ongoing grid decarbonization - Leverage domestic resources - Consider the quality of the domestic construction industry - Check political feasibility

responding to changes in human knowledge and values (Hoppmann et al., 2014; Lindblom, 1959) such as societal expectations of carbon emission reductions, knowledge of the economics of energy-efficient design and construction, and knowledge of the multiple benefits of energy-efficiency. Particularly, the latter triggered a shift away from the traditional view of energy efficiency as merely reducing energy demand towards a holistic view that recognizes the full potential including health improvements and boosting industrial productivity (IEA, 2014). If such multiple benefits of energy efficiency would be included in future evaluations of BECs, policymakers could justify more stringent designs.

To balance long-term regulatory certainty and short-term flexibility, we encourage policymakers to (i) pre-announce upcoming but conditional BECs—policymakers define criteria that have to be fulfilled before implementing the BEC. For example, Denmark pre-announced upcoming BECs while tying their implementation to the condition of being cost-effective. As a result, Denmark revoked its 2020 BEC design update because it could not prove cost-effectiveness. To ensure that BECs stay effective, we further recommend to (ii) integrate a continuous improvement process in the BEC design. Policymakers thus should mandate a tightening of the BEC over time according to a fixed schedule. Ultimately, to provide a long-term outlook for the industry, we recommend that policymakers (iii) make BECs part of a clear, transparent, and easy to understand national policy roadmap, including realistic goals with a long enough lifetime (cf. France) (BigEE, 2013; UNDP, 2010). Many countries define ambitious policy goals but fail to implement specific measures. Particularly in countries with fragmented building regulations, national goals and regional BECs are at odds with each other, providing a challenging regulatory environment for firms that are active nationwide (cf. Switzerland).

5.3. Beware of technology-specific requirements

Reducing buildings carbon emissions by directly mandating renewable energies or banning fossil fuel technologies seems a promising option. However, policymakers should be aware of the drawbacks such technology-specific requirements might entail. Literature criticizes technology-specific requirements for causing higher societal costs for carbon emission reductions than technology-neutral requirements (Lehmann and Söderholm, 2018). However, scholars also highlight that this effect might be reversed for emerging technologies with a high expected learning rate, as they might help to avoid lock-ins to current dominant technologies (Hoppmann et al., 2013).

Recognizing these contrasting views, but also the mandatory nature of BECs, we recommend that policymakers (i) ensure the availability of multiple technology options when designing BECs that include technology-specific requirements (cf. Switzerland). This makes it more likely that all buildings will be able to comply with the BEC. Policymakers should keep in mind that even performance-based requirements—which typically give building developers maximum leeway to find technologies that achieve compliance at least cost (Harvey et al., 2018)—can become technology-specific (de Mello Santana, 2016). One recent example is the requirement for new buildings to be near-zero energy. Such buildings must often produce electricity on-site, obliging developers to install solar photovoltaics (cf. Switzerland) because there are no technologically and economically feasible alternatives.

Banning a single technology is also technology specific, but allows policymakers to ensure the availability of multiple alternatives. Some countries have therefore begun to ban fossil heating systems: As early as 2013, Denmark imposed a ban on fossil-fuel boilers for buildings that are not connected to the natural gas grid or a district-heating network (Andersen, 2019; Dansk Fjernvarme, 2013). Austria plans to ban oil-fired heating for new buildings by 2020 and existing oil-boilers older than 25 years starting in 2025 (BMNT, 2018), and the Netherlands aims to replace all gas boilers in all buildings over the next three decades, affecting all but one percent of houses (Rijksoverheid, 2018).

5.4. Anticipate the impact of new regulations on smaller actors

Anticipating the impact that adopting new BECs might have on actors throughout the construction sector is crucial for a broad acceptance of the regulatory change. Our results highlight that smaller actors are likely to be most affected. Small firms might lack the financial capacity to cover the increase in costs for compliance and to develop new energy-efficient technologies; small municipalities might not have the personnel capacity to deal with new and increasingly complex BECs. Literature also highlights that environmental regulation increases firms' costs—for example, through copious paperwork to apply for rebates, burdensome environmental quality studies, and costly lifecycle assessments for products (Harvey et al., 2018). For smaller firms, however, such costs may cause a unit-cost disadvantage due to economies of scale; their costs per unit of output increase relatively more than those of larger firms (Chittenden et al., 2003; Dixon et al., 2007).

To cushion the blow for smaller firms, we recommend that policymakers (i) support the building industry by reducing soft costs—for example, by creating a public LCA database (cf. France) or adopting financial subsidies. To free smaller enforcing authorities from capacity-intensive compliance control, we also recommend that policymakers (ii) support smaller enforcing authorities, for example, by shifting compliance control to third-party energy experts (cf. Sweden).

5.5. Promote knowledge of innovative design

Ensuring that actors have enough knowledge about the innovative BEC design before it is implemented helps policymakers to improve the designs, for example, by identifying cost-effective stringency levels. Further, it enables policymakers to justify the design's implementation, for example, by referring to front-runners who demonstrate that the design is adequate and that households can meet its requirements cost-effectively.

To promote knowledge of the innovative BEC design, we recommend that policymakers (i) pre-announce the upcoming BEC several years before its implementation (cf. Denmark) and (ii) conduct pilots that are geographically localized or confined to a number of industry participants (cf. France). Both measures allow the construction industry, building owners, and municipalities to test the innovative BEC design voluntarily before it becomes binding. The former is suited for incremental design changes, and might result in high proportions of new buildings that are tested and constructed according to the forthcoming BEC (UNDP, 2010). The latter is suited for radical design changes and allows for extensive prior testing and continuous learning before a nationwide rollout. Further, we encourage policymakers to (iii) build upon broadly accepted voluntary energy labels (cf. Switzerland). Voluntary energy labels have often been a frontrunner for new BECs and, when build upon, increased BEC's acceptance (Groesser, 2014). However, the opposite is also true if the instrument on which the BEC builds is perceived as unreliable (cf. France). Finally, we recommend that policymakers (iv) learn from other frontrunner legislation (cf. Switzerland). A heterogeneous regulatory landscape on a global, national, and state-level allow policymakers to identify best practices and implementation challenges they must overcome.

5.6. Integrate BECs in the local context

While learning from frontrunners can help to secure broad acceptance, policymakers have to adapt these learnings to the local context to make BECs practically feasible and ensure compliance (Bachtrögler et al., 2019). Our results highlight five aspects of the local context that should be taken into account. Policymakers should (i) leverage the existing infrastructure—the natural gas grid, electricity grid, and district heating networks—for example, by banning oil boilers in areas with a natural gas grid, and gas boilers in areas with a district heating network (cf. Denmark). Recognizing the available infrastructure helps to ensure that multiple technology alternatives are available. (ii) Policymakers should set stringency levels appropriately in view of the level and pace of the ongoing decarbonization of the one. In comparison to a carbon-heavy grid, a decarbonization of the electricity grid allows buildings to demand more grid-electricity while still complying with the same BEC (cf. England). By (iii) leveraging locally available resources such as biogas, firewood, and renewable energy sources, policymakers can reduce carbon emissions and increase energy security. However, local resources might be scarce or already dedicated to other uses, for example, for biofuels (cf. Switzerland). (iv) Understanding the quality of the construction industry is crucial when determining stringency levels. For example, a high-quality local construction industry is likely to benefit from stringent BECs, as this creates additional market barriers for low-quality imports (cf. Denmark). (v) It is becoming increasingly important to consider political feasibility when designing new BECs, as they have shifted from being a technical regulation to a political instrument (cf. Switzerland). In turn, the political landscape and politicians in power heavily influence the design of BECs and the likelihood of implementing them.

6. Conclusion

Historically, BECs—policies that traditionally set minimum requirements for energy use and generation in buildings—have proven effective and efficient for advancing building decarbonization. However, researchers increasingly recognize the limitations of prevalent BEC designs and have thus begun to discuss the development and implementation of BECs that overcome these limitations—termed here "innovative" BEC designs.

This study contributes to the understanding of innovative BEC designs by exploring the challenges that policymaker face when implementing them and identifying how general BEC development might learn from these implementation challenges. To analyze how BECs can advance building decarbonization, we outlined five possible pathways to reduce energy consumption and carbon emissions of the building sector, so-called leverage points: *increasing energy efficiency*, *increasing renewable energy*, *considering embodied energy*, *closing the performance gap,* and *accelerating retrofits*. From the five countries we evaluate in this study (i.e., Denmark, France, England, Switzerland, Sweden), we show that most of the BECs include requirements only for the first two of these leverage points, and thus fail to make full use of their regulatory power. However, the selected countries have already taken first steps towards addressing the remaining leverage points by implementing innovative BEC designs (cf. Table 2). Our results further demonstrate the challenges policymakers face when implementing such innovative BEC designs (cf. Table 4). Synthesizing these implementation challenges across the countries, we derived six principles (cf. Table 5) that policymakers can keep in mind when developing BECs and planning their implementation. Policymakers can thus learn valuable lessons from front-runners' experience and steer clear of avoidable pitfalls.

The insights presented in this study might be limited to countries with a similar built environment. As BEC designs might perform only given a specific feature (e.g., gas boiler phase-out only when a district heating network is widely available), future research should pay particularly focus on the built environment when comparing BECs across countries. This will support policymakers in adapting future learnings to their local context (Bachtrögler et al., 2019). Further, this study is limited to one policy instrument, but future research should evaluate BECs as part of a broader policy mix (Kern et al., 2017). Ultimately, we explored only innovative BEC designs that advance building decarbonization, but neglected designs that advance occupant's comfort. For example, recent heatwaves and their expected increased frequency due to climate change triggered concerns about overheating in the summer. While France and the UK already include requirements to reduce solar gains and the maximum temperature in the summer, future research should emphasize BEC designs for occupant's comfort.

Acknowledgements

This research is part of the project 'The role of technical regulation in the transformation of the building stock and its integration in the future energy system' (IMES-BP 407040-153894/2) in the Energy Turnaround NRP70 Research Program. Funding for this research is provided by the Swiss National Science Foundation (SNF). We would like to thank Simon Liebi, Catharina Bening, Alexander Langguth, Jakob Prüß, and Johannes Meuer for their valuable input on earlier drafts of this article. Further, we are grateful for the comments by the five reviewers and the editor on the initial submission.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.119260.

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