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

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Highlights

- Today's BECs include requirements to increase energy efficiency and renewables
- Yet, they fail to address embodied energy, the performance gap, and retrofit rates
- Pioneering countries have therefore begun to implement innovative BEC designs
- Policymakers face universal challenges when implementing innovative BEC designs
- Synthesizing the implementation challenges, we derive six design principles for BECs

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 design limitations of prevalent building energy codes, discussion turns to innovative designs that could overcome such limitations. However, literature lacks an overview of innovative building energy code designs that address leverage points for decarbonization; and, an evaluation of the challenges policymakers face when implementing such innovative designs. This study shows that merely imposing strict requirements to increase energy efficiency and renewable energy prevents countries from making full use of their regulatory power. However, some pioneers have begun to include the remaining leverage points—reducing embodied energy, closing the performance gap, and accelerating retrofits—through innovative building energy code designs. Our results further highlight that policymakers face universal challenges when implementing innovative building energy code designs, which we synthesize into six design principles. We recommend that policymakers apply these principles when implementing innovative building energy code designs to ensure broad acceptance across all actors in the construction sector.

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 the Global Energy Assessment Report (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, despite being economically superior to the status quo. Policies are needed to close this gap (Jaffe and Stavins, 1994) by addressing market failures in the construction sector (Ürge-Vorsatz et al., 2007).

Building energy codes[1] (BECs)—national policies that traditionally set minimum requirements for energy use and generation in buildings—are a promising means for building decarbonization. Literature also highlights the importance of voluntary energy labels and economic incentives (Ürge-Vorsatz et al., 2007). However, although voluntary energy labels have an important role in legislation (Groesser, 2014), their voluntary characteristic makes them less effective. Similarly, economic incentives such as direct subsidies are broadly accepted, but might involve considerable societal cost and distributional effects (Schwarz et al., 2018). Consequently, implementing effective BECs has been proposed as a key issue for building decarbonization in the literature (Evans et al., 2018, 2017).

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

BECs date back to as early as 1946 in Sweden. Since the mid-1970s, industrialized countries have introduced them more broadly 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 22% in Europe and China (IEA, 2013; Yu et al., 2014) and by 42% in India (Tulsyan et al., 2013).

However, despite their long history and success, policymakers and researchers increasingly recognize the limitations of current BEC designs. They often focus on prescriptive requirements for individual building parts, such as U-values for windows, although there are limits to the potential energy savings from stepping up such requirements. Another limitation is the focus on regulating planned values in building design and construction, while neglecting actual energy use and thus causing the "performance gap" (Glasgo et al., 2017; Gupta and Kotopouleas, 2018; Rosenberg et al., 2016).

As a result of these limitations, researchers have begun to discuss individual innovative BEC designs and their potential to overcome prevalent limitations (Cohan et al., 2010; IEA, 2013; Rosenberg et al., 2016; Vine et al., 2017). However, these studies lack an overview of innovative designs and the challenges of implementing them. Policymakers must learn from these implementation challenges if they are to design BECs that work well and enjoy a broad acceptance.

We aim to fill this gap by analyzing several innovative BEC designs and their implementation challenges. First, we ask: *How do state-of-the-art BECs address leverage points to help building decarbonization?* Second, we ask: *How do innovative BEC designs address these leverage points, and what challenges did policymakers face when implementing them?* Finally, we ask: *What general design principles for future BECs can we draw from these innovative designs?*

2. Method

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

(i) Literature review: To identify leverage points for building decarbonization, 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 rather than leverage points.

(ii) Case selection: To identify countries that have already implemented innovative BEC designs, we started with the few reviews on BECs (Evans et al., 2018, 2017; IEA, 2013; Rosenberg et al., 2016), which discuss the limitations of prevalent BEC designs and how they might be overcome. We then 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 implementation— and all selected cases must have comparable climatic conditions. Ultimately, we selected Denmark, France, Switzerland, England, and Sweden.

(iii) 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 (five overarching categories with 63 indicators) 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).

(iv) 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 views, we interviewed researchers, practitioners, and policymakers. To select interview partners we drew on secondary data and asked existing participants 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.

Table 1: Data sources across cases

		Denmark	**France**	**Switzerland**	**England**	**Sweden**	Total
Interviews (duration in minutes)	Researchers	Professor (61)	Assistant professor (53) Lab director (82)	(Advisory board meetings of research project)	Lab director (40)	Senior expert (65)	301
	Practitioners	Senior specialist in energy and indoor climate (written statement)	Director in social and private housing company (41)	Deputy head in building service engineering (34) Founder of energy consultancy (24)	Director of building engineering (54)	Project manager in building consultancy (63)	216 + written statement
	Regulators	Senior advisor for Danish transport, construction and housing authority (49 minutes)	Assistant deputy director of quality and sustainable development in construction (63)	Head of cantonal energy department (52) Head of cantonal department of energy and environment (54 minutes) Head of Cantonal Department Construction, Transport, and Energy (73 minutes)	Director of sustainable energy (93)	Assignment owner, increased sustainable construction (58)	442
	Total	110 + written statement	239	237	187	186	959
Legal Documents (pages)		137	140	98	167	165	707
Secondary data		Scientific publications on regulations addressing the five focal cases, summaries BECs, …					

3. Leverage points for building decarbonization and state-of-the-art BEC designs

In the following, we outline five leverage points for building decarbonization derived from literature (Kaya, 1990; Mavromatidis et al., 2016) and show how state-of-the-art BEC designs address each one. We define a "state-of-the-art" BEC design as one that most of our selected countries adopted. Table 2 summarizes the BEC designs these countries adopted, including innovative designs (i.e., adopted by just one country), which are covered 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, state-of-the-art 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, or additional emerging sources, for example, due to increased cooling degree days (Frank, 2005) and the diffusion of electric vehicles (IEA, 2018). 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 state-of-the-art 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, state-of-the-art BECs have begun to regulate renewable energy in buildings. First, all selected countries adopted 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 ban fossil and high-energy-use technology; 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 state-of-the-art 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. State-of-the-art BECs do similar (except Sweden) and for example allow retrofits to comply with purely prescriptive requirements.

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	- More stringent prescriptive requirements	✓	✓	✓	✓	✓
	- More stringent performance requirements	✓	✓	✓	✓	✓
	- Including capacity constraints				✓	✓
	- Pre-announcing upcoming BECs	☆				
Reducing embodied energy	- Adopting a lifecycle perspective for performance requirements		☆*			
	- Adopting requirements for the construction phase		☆*			
Increasing renewable energy	- More 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	- Check compliance during planning and construction	✓	✓	✓	✓	✓
	- Check compliance during occupancy					☆
Accelerating retrofits	- Adopting less stringent and/or purely prescriptive requirements for retrofitting	✓	✓	✓	✓	
	- Stipulate retrofitting during changes of ownership		☆			
	- Adopting a long-term perspective on retrofitting obligations		☆**			

✓: Country implemented this state-of-the-art BEC design

☆: Country implemented this innovative BEC design

*: Not part of current regulations, but announced for 2020

**: Adopted in law, but not yet implemented by decree; no official timeframe for implementation

4. Innovative BEC designs and their implementation challenges

The selected countries implemented innovative BEC designs as well as state-of-the-art ones. In this section, we describe how these innovative BEC designs were implemented and the challenges involved. Table 3 below summarizes the content of this section.

Table 3: 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

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-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."

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." 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."

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 RE2020.

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."

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." In the near future, the decarbonization of the electricity mix will accentuate this effect. 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 to 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 indicate three arguments 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.

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 10W/m^2 already brings a lot, 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 are actually stipulated.

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 buildings' 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."

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 in 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, insufficient data 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."

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 kWh/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.

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." Third, it 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."

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 4 provides an overview of our six BEC design principles and outlines examples illustrating how to follow them.

Table 4: 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 feasibility and cost-effectiveness tests - Combine BECs with additional policies such as zero-interest financing to lighten the burden of upfront investment
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 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

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 limitations of the cost-effective principle. First, it limits the possible pace for decarbonizing the building stock and thus climate change mitigation. 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 or principal-agent problem 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. 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). Further, we encourage policymakers to (ii) add targeted support to cope with the possible additional upfront costs. Cost-effective requirements typically require high capital investment, 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 (Hall 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

Creating 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. Literature highlights that in the absence of regulatory certainty, firms are likely to postpone major investments until the future becomes clearer (Hugh Courtney et al., 1997) or try to mitigate regulatory uncertainty—for example, by increasing the strategic flexibility of the firm

(Engau and Hoffmann, 2009). However, for most actors in the construction industry, regulatory certainty is favorable: 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). 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.

To create long-term regulatory certainty, we recommend that policymakers (i) make BECs part of a clear, transparent, and easy to understand national policy roadmap, including realistic goals with a long enough lifetime (BigEE, 2013; UNDP, 2010). Many countries define ambitious policy goals but fail to achieve them, as implementing them into specific measures is challenging (cf. France), thus making policies unreliable. 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). To firm up the regulatory certainty around BECs, we further encourage policymakers to (ii) pre-announce upcoming BECs and (iii) integrate a continuous improvement process in the BEC design. While the former has proved successful (cf. Denmark), the latter institutionalizes this success, for example, by mandating a tightening of the BEC over time according to a fixed schedule.

5.3. Beware 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 reduction 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. This makes it more likely that all buildings will be able to comply with the BEC (cf. Switzerland). 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 know enough about the innovative design of BECs before they are implemented helps policymakers improve those 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 innovative design, we recommend that policymakers (i) pre-announce the upcoming BEC several years before its implementation (cf. Denmark) and (ii) conduct test programs that are geographically localized or confined to a number of industry participants (cf. France). Both these measures allow the construction industry, building owners, and municipalities to test innovative BECs voluntarily before these regulations become 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. Voluntary energy labels have often been a frontrunner for new BECs and—when build upon—increased BECs 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. Heterogeneous regulatory landscapes 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. First, policymakers should 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. Second, policymakers should set stringency levels appropriately in view of the level and pace of the ongoing decarbonization of the electricity grid. In comparison to a carbon-heavy grid, a decarbonized electricity grid allows buildings to demand more grid-electricity while still complying with the same BEC (cf. England). Third, by 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). Fourth, 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). Fifth, it is becoming more and more 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 individual politicians in power heavily influence the design of stringent BECs, and the likelihood of implementing them.

6. Conclusion

Historically, BECs that set minimum requirements for the energy use of buildings have proven effective and efficient for building decarbonization. However, researchers increasingly recognize the design limitations of prevalent BECs. This study, therefore, aimed to evaluate innovative BEC designs that address leverage points for building decarbonization.

We identify five leverage points for building decarbonization: *increasing energy efficiency*, *increasing renewable energy*, *considering embodied energy*, *closing the performance gap,* and *accelerating retrofits*. We show that state-of-the-art BECs mostly include strict requirements for only the first two of these leverage points, and thus fail to make full use of their regulatory power. However, our selected case countries have already taken their first steps towards addressing the remaining leverage points by implementing innovative BEC designs, as we have outlined (cf. Table 3).

Our results further highlight that, when policymakers implement such innovative BEC designs, they often face challenges. Synthesizing these implementations challenges across our case studies, we derived six principles (cf. Table 4) that policymakers can keep in mind when designing 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 apply more for regions with a similar climate and political context. Further, as this study is limited to one policy instrument, future research should evaluate BECs as part of a broader policy mix.

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