Journal Pre-proof

Research on policy strategies for implementing energy retrofits in the residential buildings

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PII: S2352-7102(21)01019-6

DOI: https://doi.org/10.1016/j.jobe.2021.103161

Reference: JOBE 103161

To appear in: *Journal of Building Engineering*

Received Date: 11 May 2021

Revised Date: 16 August 2021

Accepted Date: 18 August 2021

Please cite this article as: H. Zhang, K. Hewage, H. Karunathilake, H. Feng, R. Sadiq, Research on policy strategies for implementing energy retrofits in the residential buildings, *Journal of Building Engineering* (2021), doi: https://doi.org/10.1016/j.jobe.2021.103161.

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Abstract

Energy retrofits are significant in improving the energy efficiency of existing residential buildings (ERB) and mitigating greenhouse gas emissions. While many countries have introduced relevant retrofit policy instruments (RPIs), retrofit rates are still relatively low due to various complications in practical implementation. This study aims to organize the scattered information related to RPIs and their implementation, success, and obstacles across different countries and provide valuable references for retrofit strategy development. This article examined various RPIs for ERB in 11 selected countries. The investigated RPIs were grouped into four categories: direction and command, assessment and disclosure, research and service, and financial incentives. The RPIs implementation approaches in the surveyed countries were summarized and compared. Furthermore, obstacles to the uptake of retrofit schemes were identified. Finally, policy recommendations to overcome the obstacles and improve the penetration of retrofit schemes were proposed. This study can assist policy makers and other stakeholders in gaining a holistic view of RPIs and their implementation in different countries, understanding the barriers to the uptake of retrofit schemes, and developing more efficient RPIs in the future.

Key words: *energy retrofits, policy instruments, building energy efficiency, existing residential buildings, retrofit programs*

Nomenclature

AD	Assessment and Disclosure
BEE	Building Energy Efficiency
DC	Direction and Command
EnEV	Energy Conservation Regulations
EPC	Energy Performance Certificate
EPBD	European Energy Performance of Buildings Directive
ERB	Existing Residential Buildings
EU	European Union
FI	Financial Incentives
GHG	Greenhouse Gas
GIS	Geographic Information System
HVAC	Heating Ventilation and Air Conditioning
IEA	International Energy Agency
LSRP	Large Scale Residential Retrofit Program
NRCan	Natural Resources Canada
RPI	Retrofit Policy instruments
RS	Research and Service

Countries

AU	Australia
CA	Canada
CN	China
DE	Germany
ES	Spain
FR	France
JP	Japan
SG	Singapore
NZ	New Zealand
UK	United Kingdom
USA	United States of America

1 Introduction

Energy use is a main factor influencing the environmental sustainability of the building sector, and has received much attention with the ongoing climate action initiatives [1]. The existing buildings and building construction sectors together are responsible for over one-third of the total global energy consumption and nearly 40% of total direct and indirect greenhouse gas (GHG) emissions as per the International Energy Agency (IEA). The energy consumption and associated GHG emissions in the building sector may double and even triple by 2050. [2]. Poor energy performance of aging buildings in many countries makes a major contribution towards the said emissions. For example, according to the data from European Parliament, around 75% of existing buildings in Europe are energy inefficient [1]. In Canada, over 50% of Canadian residential buildings aged more than 30 years, and over 20% aged 50 years or more [3]. Old buildings mainly use non-renewable energy options and undergo material and component deterioration [4–6]. Thus, this older building stock consumes more energy and consequently emits more GHGs as compared to new construction [7,8]. Moreover, most of aging buildings do not comply with the latest energy-efficiency requirements [9,10].

However, the energy-efficient retrofit rates still remain low across the world. For example, retrofit rate is at an average of 1% in Germany [11], 1.0–3.0% in the UK [12], and 0.4-1.2% in Europe per annum [13]. In order to meet the target of emission reductions and the requirements of the latest energy-efficiency codes, immediate actions need to be taken to reduce the environmental impacts of the aging building stock [14]. As such, retrofit that involves modifications to envelope components and energy systems of existing buildings has garnered more attention in many countries [15]. In other literature, the "retrofit" is also described by other jargons, such as "refurbishment", "renovation", "upgrade", "transformation", "rehabilitation", "adaptation", "repairs" and "renewal" on existing buildings [16–18].

Government-administered policy instruments are necessary to support the reduction of energy consumption and GHG emissions in the building sector [19]. In reality, retrofitting is an activity that involves multiple stakeholders, making it necessary to streamline and coordinate this process via regulation and policies [20,21]. Renovators and homeowners are mainly responsible for implementing retrofit measures for residential buildings, and there is a possibility of obtaining positive outcomes through retrofits. However, the various economic, environmental, and social issues associated with the entire process have to be addressed by the local or federal governments [22]. Homeowners might not embark on retrofitting without external economic support, especially when they plan to lease or sell their homes [23,24]. Furthermore, selecting the best retrofit options for a given context can vary significantly due to many factors, such as retrofit objectives, building types, climate contexts, technical issues, and stakeholder interests [25]. The benefits of retrofit policies in addressing the above issues are highlighted by literature [26–29]. For example, building assessment and certification policies can assist householders in understanding the energy performance of their homes and the retrofit benefits to their homes. In addition, financial incentives can reduce economic burdens on homeowners and encourage them to start retrofits [30–33].

Several qualitative studies have been conducted to investigate energy retrofit policies. Some of them focus on one specific country. For example, Pombo et al. [34] illustrated the main effect of sustainable retrofit policies based on 3245 real renovation solutions in Spain. Galvin et al. [35] summarized regulations and subsidies of retrofits and highlighted the optimization paths of retrofit policies in Germany. Liu et al. [36] identified retrofit policies implemented during 1996–2019, explained obstacles, and provided recommendations based on the context of China. Some studies have focused on one specific type of policy. For example, Hou et al. [37] examined financial incentive policies with respect to commercial building retrofitting in four cities. Li [38] investigated fiscal and tax policy instruments of energy retrofitting in northern China. Other studies focused on the comparisons of retrofit policies between different countries. For example, Sebi et al. [22] compared retrofit policies in the USA, Germany, and France from five aspects: efforts, successes and challenges, future directions, and savings. Jahed et al. [29] provided a discussion of the retrofit policy incentives and constraints to identify existing policy gaps and potential problems in UK and Turkey. Kerr et al. [39] evaluated different retrofit policies in four countries, and revealed that retrofit rationales vary with the change times and audiences.

Retrofit policies vary significantly since political structures, social milieu, economic and environmental factors, and existing building stocks are heterogeneous in different countries. In addition, the benefits of retrofit policies, such as carbon emission reductions, are quite subjective, depending on policy implementation pathways [40]. Despite a number of studies on retrofit policies, there are still several research gaps, which can be summarized as following: (1) ambiguous relationship between different kinds of RPIs and stakeholders; (2) unclear common obstacles observed in multiple countries to the uptake of retrofit schemes; (3) a lack of a roadmap for the penetration of retrofit schemes in the residential sector. Given the research gaps, this article aims at assisting stakeholders in gaining a holistic view of RPIs and their practice and providing a solid basis for analysis and further improvement. This critical review will provide dispersed knowledge for policy makers and project planners in better planning of RPIs so that they can deliver more benefits.

The remaining part of the article proceeds as following: Section 2 describes the methodology used for performing this review. Section 3 presents the retrofit policy coverage in the surveyed countries and discusses the interplay between different kinds of RPIs and stakeholders. Section 4 provides a review on retrofit policy implementation approaches and identifies obstacles to the uptake of retrofit schemes. Section 5 proposes policy recommendations to overcome the obstacles and promote the penetration of retrofit schemes. Finally, Section 6 concludes the study with key findings.

2 Methodology

In this review, keyword searches in related databases were used to collect required data. The data collection method is described in Section 2.1. Furthermore, a classification framework of retrofit policy instruments is explained in Section 2.2.

2.1 Data collection

This study aims at providing a systematic review of the state-of-practice of retrofit policy instruments for residential buildings and offering valuable references for governments to develop future RPIs. In order to achieve the objectives, a systematic review utilizing the document analysis technique was performed [41]. North America, Europe, and Asia are the primary continents of fossil fuel consumptions [42],. Thus, the enhancement of building energy efficiency in these regions will significantly contribute to non-renewable energy savings [43]. The representative countries selected in this research were the United States of America (USA), Canada (CA), Germany (DE), France (FR), the United Kingdom (UK), Spain (ES), China (CN), Singapore (SG), Japan (JP), Australia (AU), and New Zealand (NZ), where the retrofit policies are implemented successfully.

The systematic review of RPIs in the paper was conducted in accordance with PRRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [44]. The selection process of the literature is presented in Figure 1.

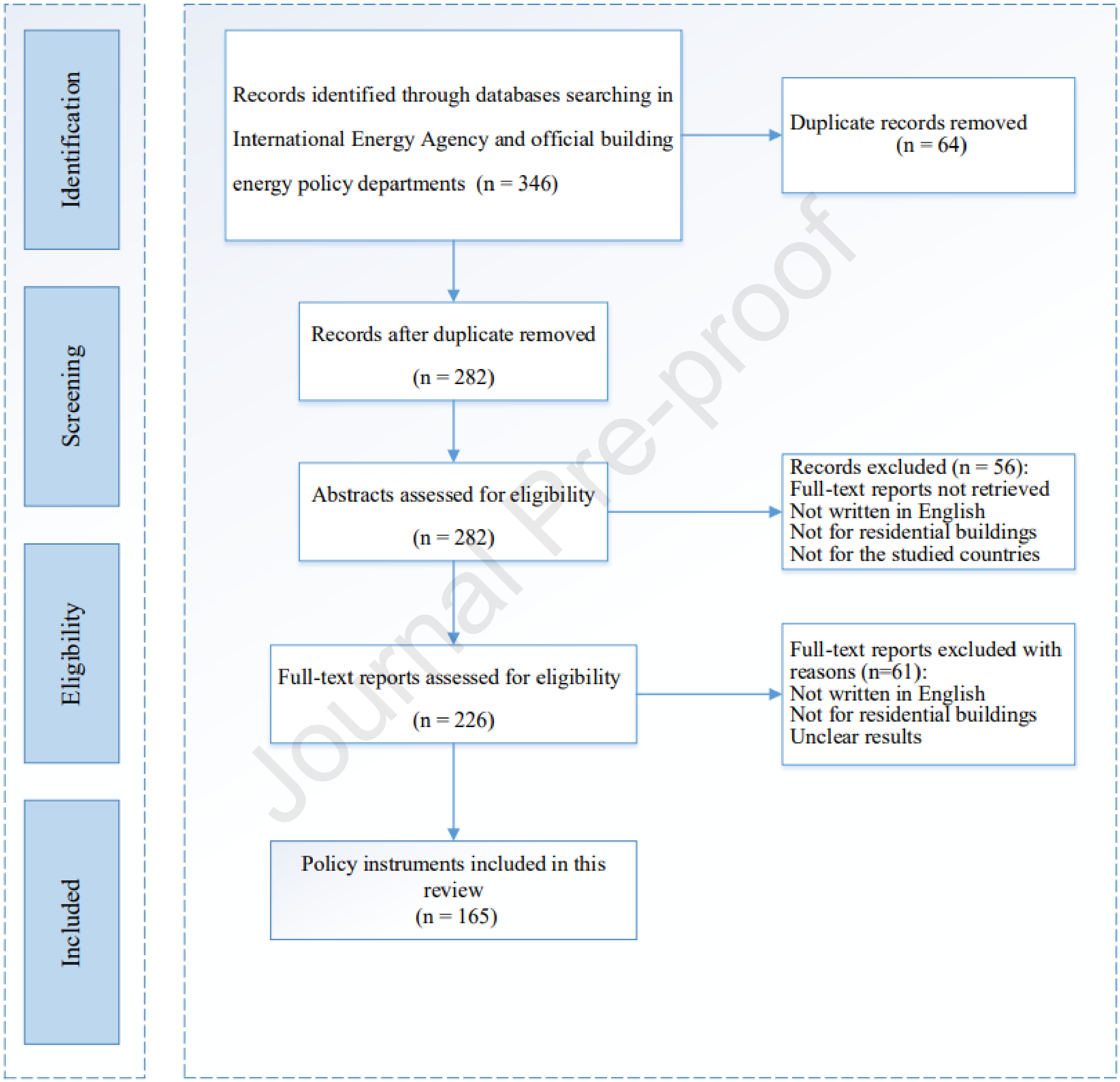


Figure 1: Visualization of the reviewing procedure using PRISMA flowchart

Retrofit policy documents published by various governmental organizations were utilized as essential references in this research. As shown in Figure 1, a total of 346 publications were identified through searching the International Energy Agency (IEA) and official building energy policy databases. Of those, 64 policies were duplicate, leaving 282 publications for primary screening of the abstract. The screening leads to the exclusion of 56 publications, leaving 226 publications for full-text assessment. Out of these, 61 publications were excluded because of the assessment criteria presented in Figure 1. Finally, 165 retrofit policy publications were included in this review.

In addition, previous studies associated with retrofit policies were reviewed to identify research gaps and develop a classification framework for the collected RPIs. "Science Direct", "Web of Science", and "Compendex Engineering Village" databases were searched utilizing the collections of keywords. Similar review methods had been utilized in previous studies [45–47]. Peer-reviewed articles after year 2015 were highlighted to ensure the data compliance with the latest building energy retrofit policies. Twenty-eight articles specific to retrofit policy research were reviewed, which indicated that there was a significant gap in the current studies.

2.2 Classification framework for retrofit policy instruments

According to [42], policy instruments focus on stakeholders' main concerns and can be important nexus between policy objectives and application market. These instruments have been recognized as primary channels for administrations to develop social and economic guidelines. Retrofit policy instruments represent a set of policy measures, such as requirements, ordinance, certifications, and financial supports, to achieve desired targets (e.g. increase of retrofit rate) set by governments [42]. It has been proved that RPIs have great potential to be studied [22,29,38,39].

In previous studies, RPIs have been characterized by using different classification methods. For example, Huang et al. [48] mapped the energy saving policy instruments in Japan and China into four clusters: control and regulatory tools, economic tools, fiscal tools, and information and voluntary actions. In the same vein, Liu et al. [36] developed a classification framework that groups China's RPIs into six types based on the retrofit policy implementation context. The similar classification framework was also adopted by Tan et al. [28] for examining RPIs in Hong Kong. Meijer et al. [49] grouped the RPIs in eight European countries into four clusters, while Markanda et al. [27] categorized the same in six European countries into three groups. The details are shown in Table 1.

Table 1 Literature review of retrofit policy instrument classification

Works	Retrofit policy instrument clusters	Studied regions
Jahed et al. [29]	Regulatory schemes, market-based/financial schemes, and informative approaches.	UK and Turkey
Kern et al. [50]	Economic tools, regulatory tools, and soft tools.	Finland and UK
Sebi et al. [22]	Regulatory instruments, and financial instruments.	France, Germany and USA
Liu et al. [36]	Command and control, economic instruments, information, certification, technology, organization, and professional.	China
Huang et al. [48]	Control and regulatory instruments, economic/market-based instruments, fiscal instruments and information, and voluntary actions.	Japan and China
Markanda et al. [27]	Command and control, economic policies, and information policies.	Germany, France, the UK, Spain, Ireland, Norway and Italy
Tan et al. [28]	Direction instruments, regulation instruments, evaluation instruments, financial instruments,	Hong Kong

	organization & professional training instruments, and knowledge & information instruments.	
Meijer et al. [49]	Regulatory, economic, communicative, and organizational instruments.	Australia, Finland, France, Germany, Netherlands, Sweden, UK and Switzerland
Baek and Park [51]	Compulsory control, inducement control, market mechanism, information, and home ownership.	France, Germany, Denmark and Sweden
Pombo et al.[34]	Regulations, information, and financial incentives	Spain

The literature suggests that the regulatory instruments and economic instruments are the most common instruments employed in the surveyed regions. Other groups, such technology, information, organization and operation instruments might be discussed separately to shed light on their importance in western countries. The command and control instruments are especially emphasized in China. Although previous studies categorized various retrofit policies into dedicated clusters, none of them developed a classification framework specific for residential buildings. The developed retrofit clusters for other building types may not be appropriate for residential buildings due to the involvement of different stakeholders in a retrofit project and the differences in building characteristics. Therefore, to reflect the general characteristics of the RPIs, especially for residential buildings, and streamline the analysis process, this article presents an enhanced classification framework for the collected RPIs. By using this framework, the collected RPIs provided by governments, utility companies, and other relevant institutions are distributed into four categories: direction and command (DC), assessment and disclosure (AD), research and service (RS), and financial incentives (FI). The descriptions of the DC, AD, RS, and FI instruments are shown in Table 2.

Table 2 Clusters of retrofit policy instruments

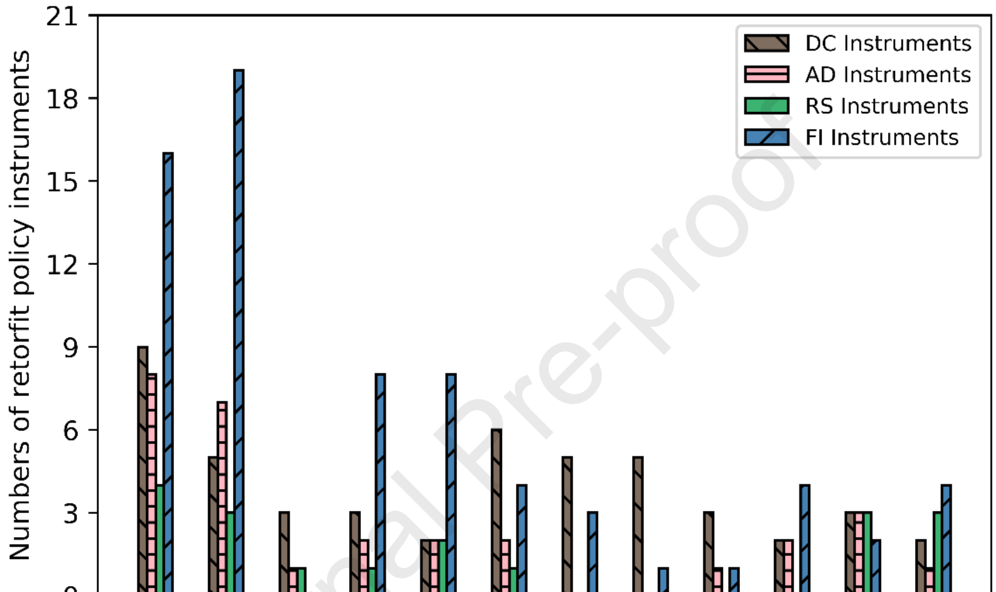
Instruments	Descriptions	References
DC	Overall direction: overall strategy, action plan; retrofit directives: environmental requirements, standards, regulations, and retrofit guidelines for existing residential buildings.	[18,27,28,36,48]
AD	Building energy performance assessment: energy auditing, rating, labeling, benchmarking, post-retrofit evaluation; disclosure of building energy consumption.	[27,34,51–53]
RS	Innovative researches: well-designed retrofit programs, new retrofit technologies, auxiliary tools; government public service: technical supports, increase of retrofit related institutions and departments, education and training programs.	[27,34,48,51,54]
FI	Economic supports for retrofit activities including grants: direct subsidies from governments; rebates: partial amount returned on applied retrofit measures; tax credits: deduction on the tax required to be paid; loans: purchase of retrofit materials or equipment at a low-interest rate.	[55–64]

3 International retrofit policy instruments for residential buildings

Based on the classification framework, an international survey of RPIs for ERB across 11 countries is presented in section 3.1. Following this, a detailed analysis of these RPIs under each cluster is performed in section 3.2.

3.1 Identification of retrofit policy instruments

In this section, an examination on RPIs for residential buildings under each category is conducted. As the examined RPIs are English-centered policies, the collected policies are partial. Therefore, instead of presenting the entire portfolio of RPIs enforced by each country, this section aims to show how some of the RPIs applied and the corresponding results, thereby summarizing retrofit policy implementation practice and identifying barriers to the penetration of retrofit schemes. In total, 165 RPIs enforced during 1998-2020 for ERB are summarized in Appendix, which are also depicted in Figure 2.



	USA	CA	EU	DE	FR	UK	ES	CN	SG	JP	AU	NZ
DC	9	5	3	3	2	6	5	5	3	2	3	2
AD	8	7	1	2	2	2	0	0	1	2	3	1
RS	4	3	1	1	2	1	0	0	0	0	3	3
FI	16	19	0	8	8	4	3	1	1	4	2	4

Figure 2: The numbers of the collected retrofit policy instruments in the surveyed countries

3.2 Analysis of retrofit policy instruments

The official energy efficiency departments in the surveyed nations have made great efforts to enforce a mix of different RPIs. These instruments can assist in improving stakeholders' retrofit awareness, knowledge, and skills and provide retrofit guidelines and supports for them [22,40]. Overall, the interplay between different RPIs and stakeholders are depicted in Figure 3. The details of the four kinds of RPIs in the selected countries are discussed in the following sections.

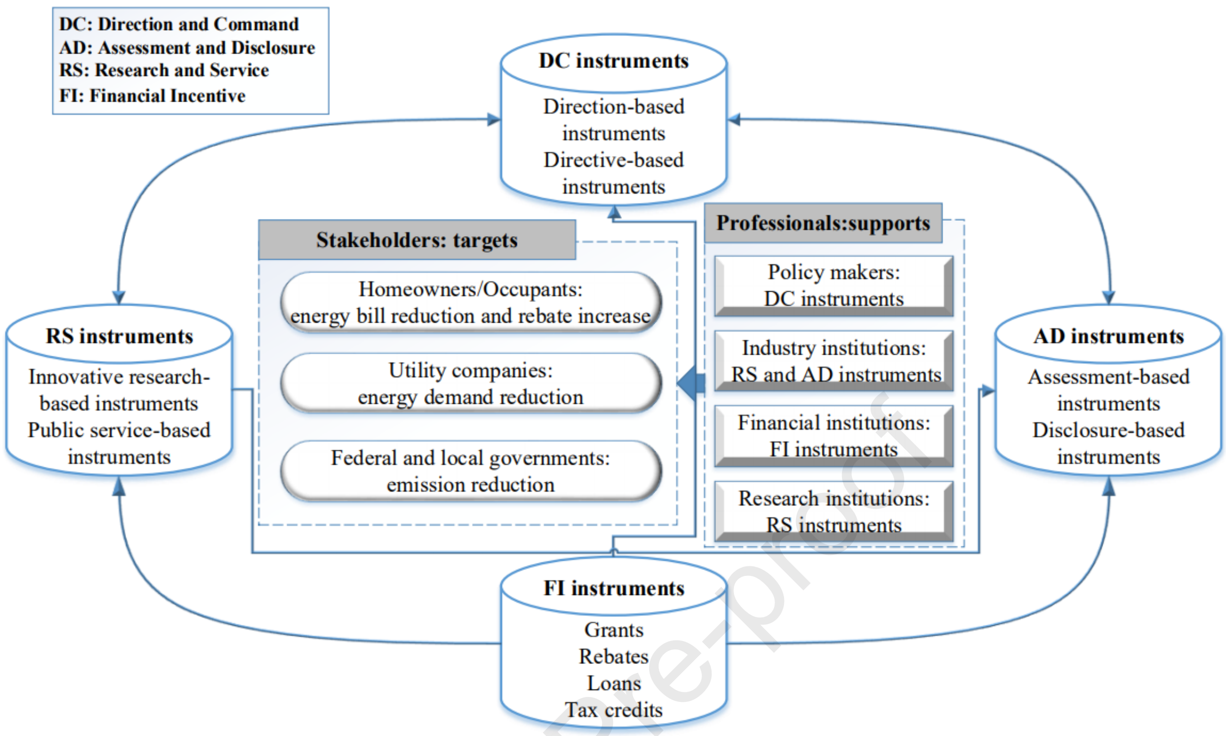


Figure 3: The interplay between different instruments and stakeholders

3.2.1 Direction and command (DC) instruments

When governments initiate RPIs, DC instruments, including direction and directive-based instruments, are their main choice, since the instruments have regarded as important interventions for retrofits at the initial stage [22]. It can be seen from Figure 2 that all the studied countries have enforced DC instruments.

Many efforts have been made to developing direction-based RPIs, including setting overall retrofit strategies, targets, and requirements without specifying guidelines. These efforts can assist stakeholders in better understanding basic knowledge, benefits, and the overall future direction for energy retrofits. To exemplify, USA has developed a retrofit plan to reduce 50% of building emissions by 2050 [33]. Similarly, European Union (EU) has enacted the "European Energy Performance of Buildings Directive (EPBD)", under which the EU countries have to establish strong long-term retrofit strategies aimed at decarbonising the building stock [13]. Under the EPBD guideline, Germany implemented a retrofit plan to increase the rate of building thermal retrofits from 0.8% to 2% per year [65]. These instruments present governments' strong determinations and act as key drivers to promote energy retrofits. However, a lack of effective auxiliary instruments, such as effective home auditing activities and technical supports, has undermined the uptake of retrofits [36,66]. The enforced directives shed light on mandatory tasks for retrofits, resulting in negative impacts on the effectiveness [67]. For example, in China, the "Energy Retrofit of Residential Buildings" plan was issued in 2008 to improve the living environment of old residential buildings, but the local administrations merely focused on the retrofitting areas to meet the requirements rather than prioritizing the retrofitting quality [68] [69].

Authorities have also enforced directive-based instruments while considering stakeholders' interests and providing them with detailed retrofit guidelines. The instruments can provide a clear framework for retrofit implementation, thereby overcoming retrofit implementation barriers and increasing market acceptance. For example, the Singaporean government implemented the "HDB Greenprint" program for ERB. This program assisted in investigating the homeowners' perceptions of retrofit schemes, exploring their willingness to conducting retrofit measures, and providing practical recommendations to the implementation of retrofit programs [70]. In the USA, the "Large Scale Residential Retrofit Program (LSRP)" enacted in California investigated a set of key research questions associated with market drivers and homeowner attitudes towards retrofits. As a result, this instrument contributed to the design of effective strategies to furnish energy efficiency outcomes, and it provided important insight to administer future retrofit schemes to enhance the flexibility of residential retrofitting projects [71]. The Germany government issued detailed retrofit requirements and guidelines, highlighting the installation of high-efficiency equipment systems and renewable energy systems [72].

Globally, DC instruments can play an important role in promoting retrofits of ERB by providing an overall development direction, retrofit requirements, and recommendations at the early stage of a retrofit project. With this kind of instrument, the stakeholders can be aware of long-term retrofit strategies, retrofit benefits, minimal retrofit requirements, and applicable retrofit measures [22,28,73,74]. However, the compliance of DC instruments requires sufficient technological and financial support from well-trained retrofit practitioners, such as retrofit training courses, energy auditing data, and rebates for retrofit activities. In this regard, DC instruments should be combined with AD, RS, and FI instruments to improve the effectiveness of policy implementation [18,36,73,75].

3.2.2 Assessment and disclosure (AD) instruments

AD instruments serve as an important tool for benchmarking building energy consumption, recognizing operational issues of systems, and identifying retrofit opportunities [16], [76]. This kind of instrument can help homeowners to understand the operational energy use conditions and encourage energy retrofits. The related institutes provide energy audits for owners, including an examination of utility bills and comprehensive checks of targeted homes to identify energy-waste locations, and householders can solicit expert advice on retrofit options based on the auditing results. Furthermore, assessors can assist in ensuring that the energy saving goals are achieved after retrofitting. [71,77,78]. For example, early in 2002, the "Home Performance with Energy Star" program was launched by the US Department of Energy to provide homeowners with advice, tools, resources and inspiration, and thus, improve BEE in residential sector [79]. This program assisted in evaluating entire houses, including different energy systems and their interactivity, to identify retrofit solutions that satisfy homeowners. Similarly, the "Energy Saver" program was conducted in Chicago in 2005 [80]. In general, this program has prompted owners to increase their cash flow and save on average approximately 30% annually on home appliance bills.

Countries have also launched special labeling or certification programs for homes, energy equipment, and materials to help the public understand the energy-efficiency property of these items [81]. With these programs, landlords can more easily choose suitable homes or products with energy-efficiency labels, as shown in Table 3. For example, the USA initiated the "Energy Star Verified HVAC Installation (ESVI)" program, which offered labeling service for existing residential buildings and helped households check whether they had code compliance HVAC systems installed [82]. In Europe, the "Energy Performance Certificate" scheme was introduced in France and UK, which assigned each building a rating (using an A-G scale). Germany enforced the "Efficiency Label with Heating System" program intended to equip aging low-efficiency heaters or boilers older than 15 years with efficiency labels, which prompted households to replace their inefficient heaters sooner [83]. Japan implemented the "Residential Environmental Points Systems" program. It made those homeowners with high energy bills realize the significance of envelope insulation upgrades as well as energy-efficient system replacements [84].

Table 3 Labeling and disclosure policy

Countries	Building elements with labeled energy properties	Disclosure content
USA	Labeled homes; labeled products: envelope insulation products, heating equipment, cooling and ventilating equipment, water heaters, windows, doors, skylights, lighting, and home appliances	Utility bills, energy benchmark scores, asset ratings
Canada	Labeled homes; labeled products: heating equipment, cooling and ventilating equipment, water heaters, windows, doors, skylights, lighting, and home appliances	None
Germany	Labeled products: heating equipment	Energy performance certificate
France	Labeled homes	Energy performance certificate
UK	Labeled homes	None
Singapore	Labeled homes	None
Japan	Labeled products: envelope insulation products, heating equipment, windows, PV facilities	None
Australia	Labeled homes	None
New Zealand	Labeled homes	None

However, previous studies have indicated that the energy-efficiency labels might not be an essential consideration for landlords when they decide to rent or buy a property. Furthermore, the decisions are highly dependent on the disclosure of energy use data [85]. Therefore, disclosure policies have been introduced with the objectives of making occupants understand their energy use, arousing their environmental awareness, and encouraging them to upgrade the buildings with low energy efficiency through transparent information sharing [86]. Homeowners are required to report their energy uses periodically or when the buildings are put on the market [87]. As shown in Table 3, in the USA, the information that needs to be disclosed includes utility bills, energy benchmark scores, and asset ratings. For example, the "Chicago Building Energy Benchmarking Ordinance" program was introduced; subsequently, the buildings with three consecutive years of reporting since 2013 showed a reduction of 4% in energy cost, leading to an estimated savings of $11.6 million per year. These buildings also showed an enhancement of 6.6% in their ENERGY STAR scores [80]. In Europe, the policies in Germany and France are under the guidelines of "EPBD". These instruments have stipulated that the BEE certificate (an EU BEE rating scheme) and an inspection scheme for HVAC systems must be issued, when a building was sold or rented since 2010 [99]. It has been proven that the policies can help appraisers to assess the energy performance of buildings and the building valuation in the sale process, and therefore, incentivize sellers to upgrade their houses to stand out in the market [89].

In addition, AD instruments can be used as effective tools to evaluate the differences between estimated and actual energy savings achieved from retrofits. Previous studies have proved that the discrepancy between expected energy use evaluated by energy modelling software and actual energy use is significant due to occupant behavior influences and inaccurate energy modelling, leading to unreliable paybacks for energy retrofit projects [90–92]. Developing simple occupant-based energy models that better address different occupant types and their impacts on energy use has been proven essential for improving modelling accuracy [93]. As such, AD instruments can help retrofit professionals understand why estimated and actual energy use are inconsistent and tune pre-retrofit energy modelling. After completing retrofits, energy savings can be recorded to test the accuracy of the developed energy model. However, the effective enforcement of AD instruments relies on financial supports and specialized retrofit professionals [28]. Therefore, FI and DS instruments should be developed to support the implementation of AD instruments. Furthermore, previous research has shown that it is not cost-effective to monitor energy data in a great level of detail [22]. Thus, striking a balance between building energy monitoring and modelling is essential.

3.2.3 Research and service (RS) instruments

RS instruments, including research-related instruments and public service-related instruments, are used to increase occupants' awareness of energy retrofits and provided technological supports for retrofit practitioners.

Many efforts have been devoted to developing innovative research-related instruments, such as state-of-the-art retrofit technologies and innovative retrofit plans. The effectiveness of new technologies is mainly dependent on technological means, costs, climate conditions, and social contexts [16,18,74,94,95]. In this regard, governments have launched research and development (R&D) programs to apply renewable energy systems to transfer the existing buildings to be a net-zero ready state, for example, "Better Building Neighborhood Program" (USA), "Power Smart Geothermal Heat Pump Systems" (Canada), "New Energy Technology Development Plan" (Germany), and "Energy-Efficient R&D Program" (Australia). In addition, some developed countries have also developed innovative and high-end retrofit programs. However, the applied retrofit measures are not cost-effective in the energy savings market, where the marginal expenditures are high, but the profits are low [96]. In other words, the participants do not aim at saving money; rather, they focus on improving the living environment [97]. For example, a market-led and local community-based extended scheme was adopted to solve the problems unique to every community. The "Neighbor to Neighbor" program, which was implemented in the USA, clearly illustrates the benefits of this community-based mode [98].

Governments have provided many public services for stakeholders, such as establishing retrofit professional associations and developing training programs and retrofit support tools (see Table 4). Diverse institutions, departments, organizations, and workgroups, which can assist with coordinating among stakeholders and organizing retrofit activities, contribute to the adequate promotion, supervision, and service of home retrofit markets [99–101]. A lack of practitioners with rich retrofit knowledge and skills is a big challenge that hinders the implementation of energy retrofits [102,103]. Training programs and support tools can strengthen practitioners' knowledge and skills associated with energy retrofits and provide convenience for them to initiate retrofitting and avoid troubles [24], [94]–[99]. Targeted training audiences generally involve occupants and professionals. Hargreaves et al. [110] suggested that occupants' energy-saving behaviors depend considerably on their inclination towards reducing energy consumption, information exchange, and skills to handle energy-efficient technical systems. The training programs for occupants are conductive to improve their awareness of upgrading their homes and increase their knowledge and skills on manipulating home appliances through an energy-efficient way [111]. In addition, retrofit practitioners' skills can also be enhanced through trainings. Previous practice has indicated that energy assessors trained in building science are more easily to gain homeowners' commitments to conduct retrofits than contractors and clients trained in sales [18]. In the USA, a comprehensive multifamily toolbox was developed. This toolbox includes retrofit support tools for client and tenant education, retrofit incentives, training, program management and installation in the USA [112–117]. In Australia, the "Smart Block" program was enacted in Melbourne by using a web-based tool to prompt the energy performance of multi-residential buildings to be tracked and managed [118].

Table 4 Examples of training program and tools

Training programs and tools	Country examples
Retrofit training programs for local government agents	USA, Canada, Germany, France, Singapore
Retrofit training and certificate programs for owners, assessors, energy modelers, clients and contractors	USA, Canada, Germany, France
Retrofit support tools	USA, Canada, Germany, Australia

RS instruments mainly rely on supports from local governments. These instruments also help stakeholders to explore new retrofit technologies and more easily access retrofit information and technical supports to address practical retrofit problems. In this sense, this type of policy can provide reliable supports for DC and AD instruments and disseminate the benefits brought by FI instruments, and thus, arouse stakeholders' awareness and improve their work efficiency.

3.2.4 Financial incentive (FI) instruments

Financial incentives have been recognized as essential instruments for implementing retrofits in the residential buildings [14]. From the examinations of the practice of the surveyed countries in this article, a multitude of financial incentives can be distributed into four groups: grants, rebates, loans, and tax credits [39,119,120].

In the USA, FI instruments mainly come from the federal government, state governments, and financing institutions. In recent years, rebates and loans from utility companies have garnered more attention. Efforts have been devoted to developing financial incentives for perspective energy retrofit measures, energy performance labeling and rating, and the development of training programs and tools [121]. The rebates and incentives for heterogenous retrofit options, such as envelope insulation and HVAC systems from Mass Save, were provided for renters and landlords living in Massachusetts [122]. Tax credit programs, such as the "Federal Tax Credits", were also developed to prompt the public to conduct BEE related work. The attention of the federal funding programs focuses on innovative research and development for BEE improvement, such as the "Better Building Neighborhood" program [123]. In addition, full funding supports for low-income targeted households were also provided by this program. Energy Star research shows that the average investment totals $3500 per home, with 57% of this attributed to homeowner incentives, 14% to contractor costs, and 29% to administrative fees [79].

In Canada, FI instruments are mainly provided by utility providers and local governments. A number of rebate and loan programs have been launched to encourage homeowners to purchase energy-efficient HVAC equipment and replace old ones, such as the “Efficient Boiler Rebates Program” and the “Home Heating Rebates” program in British Columbia, the “Home Improvement Rebates” program in Alberta, the “Power Smart Residential Loan” program in Manitoba, and the “Home Energy Retrofit Loan” program in Toronto [124–130]. These programs can alleviate homeowners’ concerns about high upfront costs of retrofits and reduce economic burdens on them [103,125]. In addition, the Canadian governments have also implemented special programs to help low-income householders and senior citizens to live more comfortable, such as the “Healthy Homes Renovation Tax Credit” program and the “Energy Efficiency Retrofit Program for Low-Income Households” program.

In Europe, the “EPBD” program was enacted to provide financial supports for cost-effective enhancement retrofit measures [13]. In addition, countries have enforced extra FI instruments for energy retrofits besides the program. The most common FI is direct capital grants for retrofit works, such as “Carbon Dioxide Building Renovation Grants” in Germany and “New Barracks Estate retrofit fund” in the UK. Germany and France have also provided rebates for energy-efficient equipment and tax credits for retrofit work other than grants. For instance, the “KfW Bank Refurbishment Fund” program provided pre-defined financial bundles (up to €75,000) for a maximum of 30 years for each household in Germany. It also offered debt relief to homeowners who achieve a level of energy efficiency greater than that required for a new building under German regulation [131]. Furthermore, the “Energy Transition Tax Credit” program provided 30% of tax credits to encourage French homeowners to utilize energy efficient construction materials and equipment. The “Zero-Interest Rate Eco-loan” program provided landlords with up to €30,000 loans at a zero interest when they conduct BEE works. In Spain, retrofit investments from the “National Energy Efficiency Action Plan (NEEAP)” were managed by the national construction authorities, who in turn assign the capitals to local community authorities through signed synergic agreements. This process was achieved through direct grants or low-interest loans [34,132].

The FI instruments are still basic in Asian and Oceanian countries. China, Japan and Singapore have provided grants for specific retrofit measures, although the grant coverage in China and Japan is more limited than that in Singapore. For example, the “Low-carbon Development Plan in Jinan” program in China and the “MLIT Energy Efficiency Retrofits” scheme provided basic grants for building envelope and heating equipment upgrades [133]. The Singaporean government launched the “HDB green print” program, which provided special capital for communities where homeowners upgrade elevator energy regeneration systems, PV systems, outdoor street lighting, rainwater harvesting systems, and pneumatic waste conveyance systems [70]. In addition, the “Victorian Energy Efficiency Target” program implemented in Australia allows landlords to receive rebates for energy-efficient home appliances and offered grants to help them create energy-efficiency certificates for their homes [134].

As most of retrofit activities require economic supports, FI instruments have garnered much attention in the surveyed countries. These economic supports mainly come from government capitals, bank loans, utility provider rebates, and commercial institution grants. These instruments can address stakeholders’ main concerns on economic issues related to retrofit projects, such as high initial cost, long payback period, and uncertainty of return on investment, and thus, improve their willingness and aspiration to upgrade buildings [18,28,36,120,135]. In this regard, it is important to provide FI instruments to support the enforcement of DC, AD, and RS instruments.

However, FI instruments might impose a heavy financial burden on governments, especially for local governments in a long run. Therefore, the level of investment depends on each country's economic situation [136]. For example, the more developed countries have launched more kinds of FI instruments to support retrofits, whereas the financial supports in developing nations are relatively limited. In addition, the confusing mix of FI instruments provided by different governments and utility companies as well as a lack of monitoring departments for financing retrofit projects also pose challenges to the effectiveness of FI instruments [137].

4 Implementation of retrofit policy instruments

Although the investigated RPIs are categorized and characterized above, these instruments can only deliver expected benefits when they are implemented approximately. Additionally, a good RPI might fail because of poor implementation [138]. Therefore, it is essential to identify the policy implementation approaches and obstacles and learn experience from them.

4.1 Retrofit policy implementation approaches

The identification of policy implementation approaches is important for both understanding the structure and design principals of RPIs and further ensuring that expected instruments can be implemented effectively [81]. Based on the aforementioned analysis, the details of policy implementation approaches in the surveyed countries are summarized in Table 5.

Table 5 Retrofit policy implementation approaches

Country	Type	Compliance path	Level	Geographic scope
USA	Voluntary	Perspective and performance-based	Deep and conventional	An entire country and part of regions
Canada	Voluntary	Perspective	Conventional	Part of regions
Germany	Voluntary and mandatory	Perspective and performance-based	Deep and conventional	An entire country and part of regions
France	Voluntary	Perspective	Deep and conventional	An entire country
UK	Voluntary	Perspective	Conventional	Part of regions
Spain	Voluntary	Perspective	Conventional	Part of regions
China	Mandatory	Perspective	Conventional	Part of regions
Singapore	Voluntary	Perspective	Conventional	Part of regions
Japan	Voluntary	Perspective	Conventional	Part of regions
Australia	Voluntary	Perspective	Conventional	Part of regions
New Zealand	Voluntary	Perspective	Conventional	An entire country

In terms of enforcement types, nearly all the surveyed countries have enforced voluntary RPIs except China, whose RPIs are mandatory. Germany, whose RPIs are both mandatory and voluntary in nature, is different from other countries. In Germany, there is a basic requirement for energy upgrades for ERB and additional bonuses for extra promotion. In general, voluntary schemes are more flexibly implemented compared to mandatory requirements, since there will be more effective responses from stakeholders who have many interests in retrofitting. Subsequently, governments can easily make adjustments consistent with current enforcement issues [81]. In addition, depending on the country, RPIs might be imposed on municipalities or an entire country.

RPI compliance paths generally include the perspective path and the performance-based path [156]. The former path offers direct instructions that inform homeowners about which retrofit measures they should use, while the latter path sets performance targets and gives more freedom for retrofit implementation. All the surveyed countries have adopted the perspective path, which can help stakeholders to understand where they should start retrofit projects [39]. In addition, governments in the USA and Germany have also adopted the performance-based path, allowing stakeholders to adopt more flexible retrofit measures to ensure ambitious environmental targets are achieved [18].

The implementation levels of RPIs can be grouped into two categories: deep and conventional levels. Deep RPIs, which can solve multiple energy performance problems at once, generally improve the energy efficiency of buildings more effectively than conventional ones [139]. This is because deep RPIs employ a system-thinking approach, which takes into account all the energy uses in homes and the occupants' proactive role in energy conservation [140], while conventional ones might only involve one aspect. Furthermore, compared to conventional programs, deep instruments are also recognized as more cost-effective ways to upgrade buildings with poor energy performance caused by the deterioration of energy systems [141]. However, adopting deep RPIs usually requires stakeholders with extensive retrofit knowledge and skills to decide which retrofit measures are appropriate for specific homes [142]. A shortage of retrofit professionals can be a major challenge in the implementation of deep RPIs. Therefore, only the USA, Germany, and France have initiated deep retrofit RPIs.

Although the RPI development varies noticeably in different countries, some general trends can be observed. First, the main driver to develop RPIs is explicit environmental targets, for example, specific energy savings or carbon emission abatement targets set by governments. With these clear targets, there is a noticeable increase of retrofit schemes [143]. Furthermore, governments keep revising retrofit policies to meet the changes of practices in carrying out retrofit programs, including expanding policy coverage, improving retrofit requirements, and transferring the perspective compliance path to the performance-based compliance path. In addition, the implementation of RPIs generally undergoes a "small to large" process. As an illustration, governments usually start with pilot programs to analyze the influences of economy, industry practice, and program design and implementation methods on the willingness of occupants to upgrade their homes. These pilot programs can also help other stakeholders, including government agencies, contractors, and marketing experts to understand the scalability of retrofits. The pilots can be spread to municipal or even national level if the outcomes are welcome [87].

4.2 Obstacles to the uptake of energy retrofit schemes

Although the obstacles to the uptake of energy retrofit schemes for residential buildings differ across the surveyed countries, the main ones which are observed in multiple countries can be recognized by examining the implementation practice of retrofit schemes. Based on literature [136,144–146], the obstacles can be mainly categorized into four clusters: awareness and information issues, technical issues, financial issues, and management and other issues. The identified obstacles are illustrated in Table 6.

Table 6 Obstacles to the uptake of energy retrofit schemes

Obstacle clusters	Descriptions
Awareness and information issues	**Unwillingness to start:** Occupants have limited knowledge about building energy efficiency and energy retrofits [87,147]. Complicated retrofit processes and unsuccessful retrofit projects in the past further discourage them from following retrofit programs. The negative perception increases their unwillingness to start retrofits.
	Lack of motivation: Occupants are not well educated about the benefits of retrofits, and they have limited motivation to implement retrofits. In addition, deep retrofits may require the entire building to be vacated, leading to extra housing and financial problems. Thus, occupants are reluctant to upgrade their residences unless building components will be break or a high level of vacancy will affect their rental income. [103,148].
	Implicit targets and steps: Occupants are confused by unclear information about retrofit implementation due to a lack of consolidated standards or guidelines [149].
	Lack of faith in contractors' commitments: Occupants lack faith in contractors due to conflicting proposals associated with retrofit measures [125].
Technical issues	**Limited workforce capacity:** A shortage of retrofit-qualified professionals, such as building energy auditors, modelers, and project advisors and managers, is a big challenge for private stakeholders to access technical assistance [18,67,137,150].
	Difficulty to access eligible professionals: Ascertaining if retrofit laborers are appropriately trained to address specific problems is difficult [22,151]. For example, homeowners might ask a heating system contractor to solve a thermal comfort problem, such as uneven home heating, even though an air sealing and insulation contractor are more qualified to address the problem in a more efficient way [103].
	Lack of collaboration: Energy retrofits require professionals with interdisciplinary expertise to collaborate. However, few of them can efficiently work together due to a lack of convenient communication channels [93].
	Inability to identify optimal retrofit measures: The characteristics of aging buildings vary significantly in terms of building types, construction years, and energy-efficiency properties, and therefore, optimal retrofit measures are distinct for different aging buildings [152].
	Difficulty in assessing energy performance: Building energy auditing activities are expensive and require sustaining financial supports. Most aged buildings with outdated metering equipment could not provide adequate information to assess energy performance and identify energy-saving opportunities.
	Various technical problems: Implementing retrofit measures might be technically challenging and expensive, including mechanical ventilation system installation [97], envelope insulation upgrades [87], and window replacements [153].
Financing issues	**Unaffordable upfront cost:** Dwellers have limited financial resources to invest in costly retrofit measures [108]. The upfront costs of retrofits are obviously higher than other sustainable options (e.g. green vehicles) in terms of per ton of greenhouse gas abatement [154,155]. In addition, people are reluctant to spend more money on deep retrofits with higher upfront costs [181].
	Split financial incentives: The energy cost savings per year from retrofit measures are quite small compared to upfront costs. As such, occupants are confused about where the energy retrofit benefits end up and discouraged by the limited savings [90,91].
	Uncertainty of return on retrofit investment: A lack of estimations of price elasticity of demand for energy resources might decrease the return on retrofit investment, extend the payback period, and force retrofit investors to incur cumulative financial losses [157,158].
	Confusing financing process: The mix of federal and local financial incentives present an essential barrier to market entry [71].
	Stepwise cost growth: Technical problems encountered during the retrofitting process might lead to stepwise cost growths [33].
	A lack of financial supports from third-party investors: Commercial activities associated with energy services and energy-efficient renovations are lacking and are, therefore, unattractive to private sector investors [22].
	Difficulty to identify targeted residences: A lack of energy audit databases of aging residences poses a considerable challenge to identifying targeted residences [159].

Management and other issues	**Sophisticated implementation workflow:** Although retrofit professionals offer available retrofit channels, none of them can provide a set of retrofit services [87]. In this sense, building owners have to look for different professionals to implement distinct retrofit measures, which increases the difficulty of managing programs.
	Principal-agent problem: The retrofit interests of public and private stakeholders are different, which increases the difficulty of retrofit decision-making.
	Tenant-owner problem: This issue is especially noticeable in the countries with high home rental rates [166]. Landlords are responsible for making retrofit investments, while tenants enjoy the benefits of retrofits [167]. Therefore, the landlords are reluctant to implement retrofits for rental houses.
	Law of diminishing returns: Moderate retrofits can offer a sharp decrease in energy consumptions; however, much more efforts are needed to achieve more significant energy savings through retrofits [35].
	Pre-bound influence: Energy saving potential is not as much as estimated [160]. Dwellers tend to consume more heating fuels after promotions, and consequently, the actual post-retrofit energy use is higher than originally expected in the calculated energy rating [151,161].

5 Recommendations for the penetration of retrofit schemes

According to above-mentioned analysis, governments can play an essential role in promoting the success of retrofit schemes. Generally, the overall process of a successful retrofit scheme mainly consists of four key phases: preparation phase, design phase, pilot and commissioning phase, and utility-scale implementation phase [16,162]. In this section, policy recommendations corresponding to the key phases are proposed. These recommendations could be valuable for informing better planning of RPIs to overcome aforementioned obstacles and improve the penetration of retrofit schemes. The overall retrofit process and recommended policy instruments are depicted in Figure 4.

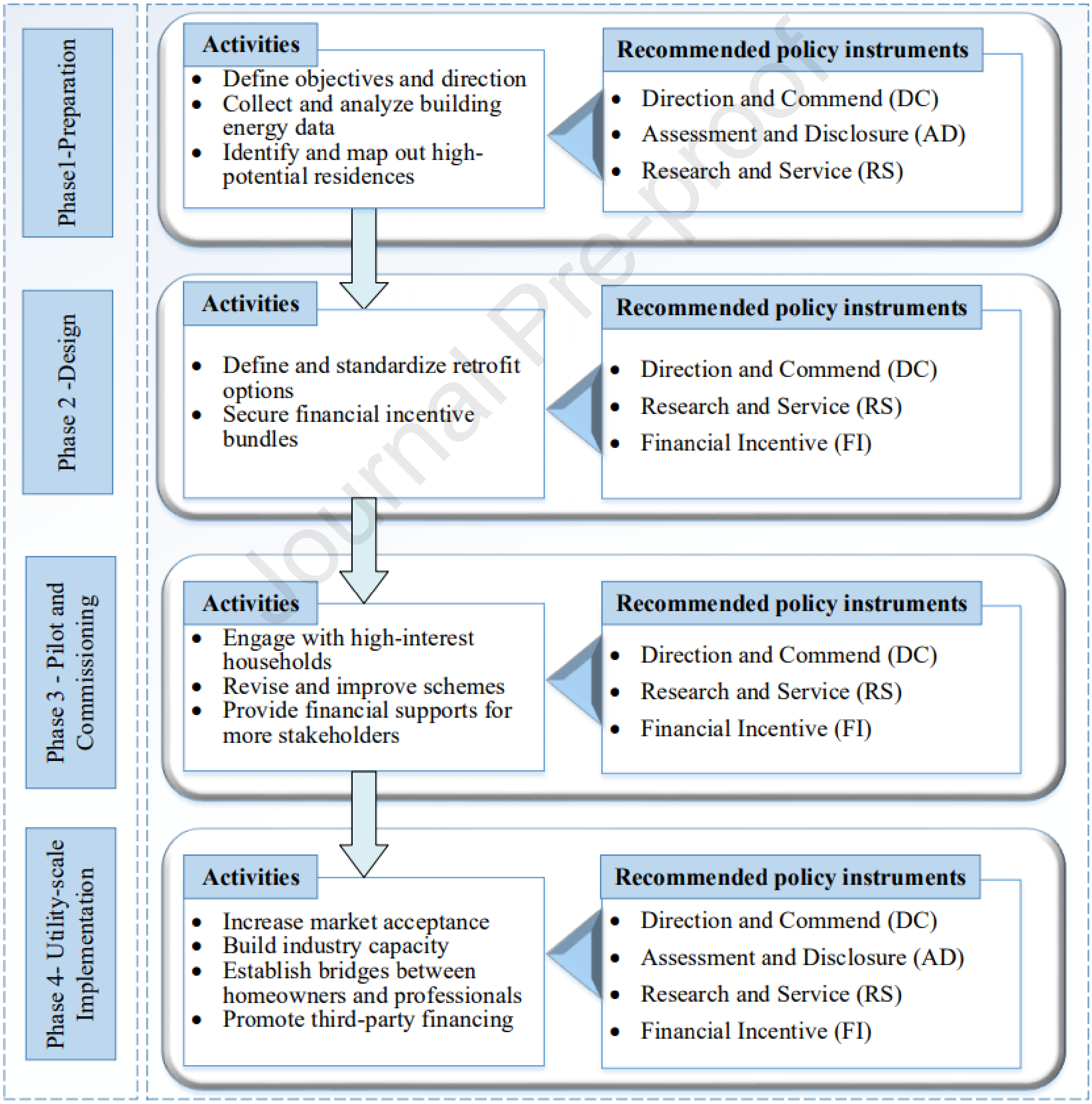


Figure 4: Recommendations for the penetration of retrofit schemes

5.1 Preparation phase

The preparation phase focuses on objectives definition, data collection, and high-potential household identification. It is recommended that DC instruments be implemented to devise retrofit objectives. DC instruments can assist retrofit stakeholders in understanding an overall direction and strategy of a retrofit scheme and learning about related retrofit technologies and activities.

Collecting building energy performance data is essential to understand building energy consumptions and identify residences with high energy saving potential [18]. Implementing energy retrofits for high-potential residences can improve the effectiveness of retrofit schemes (e.g., reduce more energy consumptions at a relatively low retrofit cost) [16]. AD and RS instruments can be employed to identify high-potential residences. Developing an assessment and rating system for ERB helps in investigating building energy consumptions and identifying low energy-efficient materials or equipment in old homes. This instrument can assist program administrators in collecting energy use data, exploring energy saving potential, and further identifying high-potential residences and appropriate retrofit strategies. In addition, applying advanced technologies, such as Geographic Information System (GIS), can provide technical supports to map out targeted residences. With the aid of this tool, spatial data can be investigated to locate high-potential building clusters, communities, and blocks. The identified building clusters can help retrofit planners perform long-term energy retrofit planning at an urban level [163]. As such, AD instruments should be launched to collect and analyze energy performance data to identify high-potential households, while RS instruments can be employed to provide technical supports and thereby increase retrofit work efficiency.

5.2 Design phase

The second phase focuses on defining and standardizing retrofit options as well as securing financial incentives. It is recommended that governments provide retrofit regulations and guidelines (DC instruments) for stakeholders. The guidelines should consist of standardized energy retrofit options with reasonable costs to appeal to homeowners with different interests and income levels. Those retrofit options, from simple envelope upgrade to renewable energy supply, should be packaged into different tiers (e.g., silver, gold, and platinum) that represent increasing levels of retrofit impact. RS instruments can provide convenience for developing retrofit guidelines. For example, a building archetype approach can be adopted to identify reference buildings, which reflect the main features of targeted houses. It has been proved that this approach can significantly increase work efficiency when developing retrofit strategies [152]. One essential strategy to overcome the tenant-owner dilemma is to impose restrictions on renting and selling a low-efficient home without retrofitting. For example, tenants can choose to pay less rental fees if homeowners do not take necessary home renovations. In contrast, expenditures allocation rules, for example, a higher share of the investment to the rent, between tenants and owners can be proposed when owners succeed in completing energy-efficient retrofits [164].

FI instruments can effectively moderate owners' concerns on economic issues such as high upfront cost, payback period, and return on investment [61,129,165,166]. In this regard, it is necessary to provide financial support bundles for households. The bundles may comprise multiple forms of economic supports, such as subsidies, tax credits, and low-interest loans on conducting specific retrofit measures and rebates for purchasing energy-efficient equipment (e.g., heat pump). Furthermore, utility on-bill financing is also recommended, which can effectively address the concern of upfront cost [135]. It is important to keep low administrative burden and interest cost and ensure that administrative and compliance systems can readily adapt to the new billing requirements. In order to assist homeowners in understanding the total actual costs of retrofit options, all available financial choices should be involved in retrofit costs shown to homeowners.

5.3 Pilot and commissioning phase

The third phase consists of launching pilot programs and commissioning. This phase focuses on engaging with high-interest homeowners, collecting feedback, and tuning retrofit measures in the pilot experience, thereby improving future iterations.

First, engaging with high-interest homeowners is essential since the success of a pilot program mainly depends on sufficient initial participation [103]. Therefore, governments should conduct a pre-retrofit survey and target marketing or engagement efforts to identify homeowners most likely to implement energy retrofits before implementing pilot programs. As sophisticated retrofit steps discourage participation, the principle of simplicity is essential to reduce the inconvenience of participating in multiple retrofit measures. For example, bundling programs developed in the design phase are conductive to streamline the overall retrofit process. Furthermore, it is recommended to highlight technical assistance when a retrofit program involves low penetration of renovation techniques in the local industry.

A post-retrofit survey should be conducted to collect feedback from participants, followed by analyzing shortcomings in existing pilot programs and then revising retrofit schemes to allow the implementation system to operate optimally at a large scale. In addition, while financial supports for homeowners have been widely provided, upstream financing for manufacturers and midstream financing for contractors should garner more attention to establish critical relationships with industry, reduce supply chain risks, and prompt suppliers to recommend efficient energy equipment to homeowners [167–169]. Meanwhile, consideration should be given to streamlining the financing process. For example, contractors should assist homeowners in applying for rebates to reduce the complexity of the financing process.

5.4 Utility-scale implementation phase

The utility-scale implementation phase should focus on improving market acceptance, increasing building industry capacity, establishing a bridge between homeowners and professionals, and promoting third-party financing.

It is recommended that RPIs be implemented to increase market acceptance to implement a full-scale scheme successfully. As such, improving public awareness and knowledge is essential. Initiating retrofit directives (DC instruments) is beneficial for stakeholders to learn comprehensive information about full-scale utility energy retrofits. Meanwhile, enforcing disclosure policies (AD instruments) can assist homeowners in understanding the energy conditions of their homes and encourage them to upgrade buildings. Widely promoting the benefits of retrofit pilot programs through multiple pathways to engage with households can play an essential role in enhancing public awareness. For example, asking local volunteers who participated in pilot programs and experts to provide both written and verbal training resources for homeowners is a practical pathway to educate them about retrofitting benefits of energy savings [151]. In addition, economic benefits, which are homeowners' primary concern, should also be articulated in the training sessions. These benefits consist of decreasing energy bills, shortening payback periods, providing insurance against unexpected spikes in heating fuel prices, and enabling households to budget more effectively [16,87]. Other information that homeowners highly value can be disseminated through various media to attract more households. These benefits consist of increasing health and comfort, enhancing home durability and safety, and making buildings look more attractive [170–173].

As a lack of highly skilled retrofit professionals might undermine the effectiveness of retrofit schemes, increasing industry capacity is also essential [174]. For example, recruiting newly qualified renovators by examining contractors who have work experience with old house retrofit or new energy-efficient dwelling construction should garner more attention. Practitioners could be encouraged to document their work qualifications and corroborate their eligibility for participation [164]. Furthermore, there is a need to provide training programs for professionals to improve their skills and increase retrofit workforce capacity, which can play an essential role in addressing homeowners' concerns on technical problems.

Providing a bridge between homeowners and professionals can help in removing regulatory barriers and streamline the overall retrofitting process. For instance, establishing a central coordinator and consultant center can assist homeowners in evaluating retrofit opportunities, calculating retrofit costs, submitting rebate applications, verifying the retrofit quality, and conducting a post-retrofit survey [103]. Meanwhile, developing a user-friendly tool (e.g., mobile app) can provide convenience for homeowners to explore retrofit packages and financial incentives most applicable to their homes.

In addition, there is a need to promote third-party financing loans offered by commercial lending institutions for home retrofits. Financial institutions can adopt credit screening tools and regain capital investments through repayment utilizing a billing system separate from a utility [147]. For this financial incentive, it is crucial to develop an integrated information center to periodically inform borrowers of energy cost savings and loan payments to solve the disconnect problem between loan repayment costs and energy bill savings.

6 Conclusions

Many countries have recognized the importance of the built environment and have set clear environmental targets. RPIs can play an essential role in energy savings and GHG emission reductions in residential buildings. However, few studies have summarized and compared various RPIs for residential buildings across different countries. Moreover, the obstacles to the uptake of retrofit schemes are still not clear. By examining existing RPIs, policy makers can promote the penetration of retrofit schemes by acknowledging and learning from their implementation, success, and obstacles.

In this sense, this study investigated various RPIs and developed a classification framework to summarize and characterize the scattered information related to retrofit policies in 11 countries. In total, 165 RPIs were categorized into four groups: DC, AD, RS, and FI instruments. The interplay between the four kinds of RPIs was articulated to assist stakeholders in understanding the enactment mechanism of different RPIs, thereby providing a solid basis for policy analysis and further improvement. The results indicate that the RPIs employed in the USA, Canada, Germany, and France are more comprehensive than other surveyed countries in terms of policy coverage and enforcement levels.

However, many obstacles hinder the uptake of energy retrofit schemes. These obstacles can be mainly divided into four categories: awareness and information issues, technical issues, financial issues, and management and other issues. Finally, policy recommendations for the penetration of retrofit schemes are proposed according to the overall process of successful retrofit schemes, including the preparation phase, design phase, pilot and commissioning phase, and utility-scale implementation phase. These recommendations can be valuable for informing better planning of RPIs to overcome the obstacles and improve the penetration of retrofit schemes.

The authors appreciate the limitations that the focus lies on the residential buildings. Further studies need to be conducted to analyze other types of buildings and compare the effectiveness of different RPIs to advance retrofit policy research further.

Acknowledgments

The authors would like to gratefully acknowledge MITACS and FortisBC for funding and supporting this research.

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Appendix. List of retrofit policy instruments

Country		
US	**DC**	
	California Energy Efficiency Obligation (2004)	Large Scale Residential Retrofit Program (2011)
	Chicago Energy Savers Programme (2005)	Iowa State Energy Code (2012)
	Nevada Energy Efficiency Obligation (2005)	Residential Building Energy Standards (RBES) – Vermont (2015)
	Arizona government introduced an energy efficiency obligation (2010)	Mass Save Residential Renovations and Additions (2016)
	Nebraska Energy Code (2011)	
	AD	
	Labs21 (2001)	Building Labelling and Disclosure Policy (2007)
	Energy Star Verified HVAC Installation (2002)	Chicago Building Energy Benchmarking Ordinance (2013)
	Home Performance with ENERGY STAR (HPwES,2002)	Better Buildings for Michigan (2010)
	Nevada Energy Efficiency Obligation (2005)	New York City's Local Law 87 (2009)
	RS	
	Sustainable Communities Initiative (2001)	Big Bold Energy Efficiency Strategies (2008)
	Home Performance with ENERGY STAR (HPwES, 2002)	Better Building Neighborhood Program (2010)
	FI	
	Energy Policy of Act (2005)	Large Scale Residential Retrofit Program Fund (2011)
	Federal Tax Credits for Residential Building (2006)	Home Energy Affordability Loan (HEAL,2011)
	Property-Assessed Clean Energy finance (PACE, 2006)	Colorado Home Efficiency Loan (2015)
	Assisted Housing Stability and Energy and Green Retrofit Investments (2009)	Colorado Home Efficiency Rebates (2015)
	Energy Efficient Retrofits (2009)	Energize Connecticut Home Rebates (2017)
	Clean Energy Works Oregon Fund (CEWO,2010)	Mass Save Rebates and Incentive (2018)
	Oregon Clean Energy Works (2010)	Bay Area SunShares (2019)
	Bay Area Affordable Multifamily Fund (2010)	NHSaves Home Rebates (2019)
Canada	**DC**	
	ecoENERGY Retrofit – Home (2007)	Minor, Major and Deep Retrofit Suggestions for Homes (2019)
	BC Community Energy Leadership Program (2015)	Building Energy Technology Programme (2019)
	Alberta Home Energy Plan (2016)	
	AD	
	Rénoclimat (Quebec, 1999)	LiveSmart BC (2011)
	Northwest Territories Building Efficiency Programs (2007)	EcoSave Energy Retrofits Program (2012)

	ecoENERGY Efficiency for Housing-Assessment Program (2007)	EnerGuide Rating System (2019)
	Efficiency Nova Scotia's Building Optimization Program (2008)	
	RS	
	Power Smart Geothermal Heat Pump Systems (Manitoba,2002)	Nunavut Energy Management SAVE 10 Program (2010)
	Efficiency Nova Scotia's Building Optimization Program (2008)	
	FI	
	Rénoclimat (Quebec, 1999)	Low-Income Households (2016)
	EnerGuide for Houses Incentive (2001)	Vancouver Heritage Energy Retrofit Grant (2016)
	Power Smart Geothermal Heat Pump Systems (Manitoba, 2002)	Hydro-Quebec Energy Efficiency Retrofit Program for Low-Income Households (2016)
	ecoENERGY Efficiency for Housing-Financial Program (2007)	EcoSave Energy Retrofits Program (BEEP-Incentives,2016)
	Northwest Territories Building Efficiency Programs (2007)	HAT Smart Programs (2017)
	Manitoba Power Smart Residential Loan (2010)	Alberta Home Improvement Rebates (2017)
	LiveSmart BC (2011)	Home Reno Rebate Program (BEEP-Incentives), Provincial Utilities – Enbridge Gas (2018)
	Ontario Homes Renovation Tax Credit (2012)	Mass Save® rebates and incentives (2018)
	Fortis BC Efficient Boiler Rebates Program (2015)	Toronto Home Energy Retrofit Loan (2020)
	The Commercial Energy Incentive Program (Yukon, 2015)	
EU	**DC**	
	Energy Performance of Buildings Directive (EPBD,2010)	COM/2016/0765 (EU,2016)
	Holistic energy-efficient retrofitting of residential buildings program (2012)	
	AD	**RS**
	Energy Performance Certificates (2007)	POI Energia (2014)
Germany	**DC**	
	Energy Conservation Ordinance (2002)	Thermal Efficiency Retrofit of Residential Buildings (2011)
	Energy Conservation Regulations (EnEV, 2009)	
	AD	
	Energy Performance Certificates (2007)	Efficiency label for heating systems (2016)
	RS	
	New Energy Technology Development Plan (2008)	
	FI	
	Energy consulting for residential buildings (On-site Consultation, individual road map for renovation) (1998)	Incentive Scheme of EnEV (2009)

	Residential Building Tax Reform (1999)	IKK/IKU - energy-efficient construction and retrofitting (2009)
	Carbon Dioxide Building Renovation Grants (2001)	KfW Energy Efficiency Programme: Energy-efficient construction and retrofitting (2015)
	KfW Bank Refurbishment Grants (2007)	Home Tax Incentives (2020)
France	**DC**	
	Existing Buildings Programmes (1998)	Energy Transition Toward Green Growth Act (2015)
	AD	
	Energy Performance Certificates (2007)	Quality Label Certification Scheme (2009)
	RS	
	Existing Buildings Research Programs (1998)	Point Renovation Info Service (PRIS, 2016)
	FI	
	Existing Buildings Financial Programs (1998)	Zero Interest Rate Eco-loan Scheme (2009)
	Tax Credit for Energy-Efficient Appliance (1998)	Habiter Mieux Programme (2017)
	Energy Transition Tax Credit (1999)	Bourgogne Franche-Comt Energy Audit Grants (2018)
	French Government Retrofit Support Program (2005)	Energy Transition Grants (2018)
UK	**DC**	
	Community Energy Saving Programme (CESP, 2009)	CCC Projections (2013)
	Low Carbon Industrial Strategy (LCIS,2009)	Green Deal (2013) EN 16883:2017
	Birmingham Energy Savers (BES, 2011)	
	AD	
	Standard Assessment Procedure Scheme (SAP, 1999)	Kirklees Warm Zone Scheme (KWZ,2007)
	RS	
	Aberdeen Heat and Power scheme (AH&P,2002)	
	FI	
	Aberdeen Heat and Power scheme (AH&P,2002)	Low Carbon Industrial Strategy (LCIS,2009)
	Kirklees Warm Zone Scheme (KWZ,2007)	New Barracks Estate retrofit scheme (2010)
Spain	**DC**	
	Technical Building Code (2006)	RENOVE plans (2011)
	Implementation of the Energy Performance in Buildings Directive (2007)	National Energy Efficiency Action Plan (2014)
	Spanish Strategy on Climate Change and Clean Energy (2007)	
	FI	
	State Plan 2013-2016 for Rental Housing, Housing Rehabilitation, and Urban Regeneration and Renewal/Retrofit of Buildings (2013)	PAREER II/Aids Program for Energy Retrofit of Existing Buildings (2018)
	National Energy Efficiency Action Plan (NEEAP, 2014)	

China	**DC**	
	Energy Retrofit of Residential Buildings scheme in Jinan (2008)	13th FYP for the Development of Building Energy Efficiency and Green Building (2017)
	Technical regulations for energy-saving renovation of existing residential buildings (2012)	Green and High-Efficiency Cooling Action Plan (2019)
	GB/T51141-2015 Evaluation Standard for Green Retrofit of Existing Buildings (2016)	
	FI	
	Low-carbon Development Plan in Jinan (2018)	
Singapore	**DC**	
	BCA Green Mark Scheme (2011)	HDB Greenprint Scheme (2016)
	Code for Environmental Sustainability of Buildings 3rd Edition (2012)	
	AD	
	BCA Green Mark Scheme (2005)	
	FI	
	HDB Greenprint scheme (2016)	
Japan	**DC**	
	Energy-Saving Act (2013)	Building Energy Efficiency Act (2016)
	AD	
	Nationwide House Energy Rating Scheme (NatHERS,2003)	Victorian Energy Efficiency Target (VEET,2009)
	FI	
	Financial measures for houses (2002)	MLIT Energy Efficiency Retrofits scheme (2009)
	Low Interest Loans for Energy Efficient Retrofit/Construction for Buildings (2004)	Subsidies for commercial and residential building energy efficiency investments (2016)
Australia	**DC**	
	Austrian Institute of Construction Engineering (OIB) Guideline (2007)	Trajectory for Low Energy Buildings (2019)
	Smart Blocks (2018)	
	AD	
	Nationwide House Energy Rating Scheme (NatHERS,2003)	Trajectory for Low Energy Buildings-Information Program (2019)
	Victorian Energy Efficiency Target (VEET,2009)	
	RS	
	Energy-Efficient R&D program (2011)	Trajectory for Low Energy Buildings-Training Program (2019)
	Smart Blocks (2018)	
	FI	
	Victorian Energy Efficiency Target (VEET,2009)	Low-Interest Loan on Energy-Efficient Building (2011)
NZ	**DC**	

	Working with Local Government (1999)	Warm Up New Zealand Insulation Programme (2009)
	AD	
	New Zealand Green Star (2006)	
	RS	
	Energy-Wise Councils Partnership (1999)	Warm Up New Zealand (2009)
	Energywise Homes Package (2005)	
	FI	
	Energywise Home Grants Scheme (2004)	Warm Up NZ Scheme (WUNZ,2009)
	Energywise Homes Package (2005)	Insulation Programmes (2009)

Highlights

- Examine various retrofit policy instruments (RPIs) in different countries
- Develop a classification framework to characterize RPIs
- Recognize financial incentives as the most commonly used RPIs
- Summarize barriers to the uptake retrofit schemes
- Provide recommendations for the penetration of retrofit schemes

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: