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Smart Energy Retrofitting of China's Existing Building Stock: Digital Monitoring, Building Energy Management Systems, and Green Finance

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تحديث المباني القائمة في الصين باستخدام تقنيات الطاقة الذكية: المراقبة الرقمية، وأنظمة إدارة الطاقة في المباني، والتمويل الأخضر

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Abstract:
China's existing building stock represents a major opportunity for reducing final energy consumption, electricity demand, operating costs, and carbon emissions. As construction growth slows and the proportion of older urban buildings increases, improving national building efficiency will depend progressively on retrofitting residential, public, and commercial buildings. This article examines an integrated smart-retrofit framework combining building-envelope renovation, efficient heating, ventilation, and air-conditioning systems, heat pumps, high-efficiency equipment, digital monitoring, Building Energy Management Systems, and innovative green-finance mechanisms. A policy and technical assessment are developed using data and retrofit scenarios reported by the International Energy Agency for China's building sector. The assessment indicates that upgrading heating efficiency may reduce energy consumption by approximately 39%, combined heating and cooling improvements may deliver savings of approximately 53–55%, advanced building automation may reduce consumption by approximately 18–19%, and comprehensive retrofit packages could reduce final energy consumption by about 65% in selected buildings constructed between 1995 and 2010. The article proposes technical performance indicators covering energy-use intensity, peak demand, carbon intensity, HVAC efficiency, thermal comfort, load flexibility, cost savings, and investment performance. It also discusses performance-based subsidies, energy-service-company contracts, green loans, insurance-backed finance, on-bill financing, and carbon-market integration. The findings show that the greatest value is obtained when physical renovation, intelligent operation, measurement and verification, and financial incentives are implemented as an integrated system rather than as isolated interventions.

Keywords: Building Energy Retrofit; Building Energy Management System; Digital Monitoring; Energy Efficiency; Green Finance; Smart Buildings; HVAC; Energy Performance; China.

الملخص:
يمثّل مخزون المباني القائم في الصين فرصة كبيرة لخفض الاستهلاك النهائي للطاقة، والطلب على الكهرباء، وتكاليف التشغيل، وانبعاثات الكربون. ومع تباطؤ نمو قطاع البناء وازدياد نسبة المباني الحضرية القديمة، سيعتمد تحسين كفاءة المباني على المستوى الوطني بصورة متزايدة على إعادة تأهيل المباني السكنية والعامة والتجارية. تبحث هذه المقالة إطارًا متكاملًا لإعادة التأهيل الذكي، يجمع بين تجديد أغلفة المباني، وأنظمة التدفئة والتهوية وتكييف الهواء عالية الكفاءة، والمضخات الحرارية، والمعدات ذات الكفاءة المرتفعة، والمراقبة الرقمية، وأنظمة إدارة الطاقة في المباني، وآليات التمويل الأخضر المبتكرة. وقد أُجري تقييم فني وسياساتي بالاعتماد على البيانات وسيناريوهات إعادة التأهيل التي أوردتها وكالة الطاقة الدولية بشأن قطاع المباني في الصين. ويشير التقييم إلى أن رفع كفاءة التدفئة قد يخفض استهلاك الطاقة بنحو 39%، وأن التحسينات المتكاملة لأنظمة التدفئة والتبريد قد تحقق وفورات تتراوح بين نحو 53% و55%، وأن أنظمة الأتمتة المتقدمة للمباني قد تخفض الاستهلاك بنحو 18–19%، في حين يمكن لحزم إعادة التأهيل الشاملة أن تقلل الاستهلاك النهائي للطاقة بنحو 65% في بعض المباني المختارة التي شُيّدت بين عامي 1995 و2010. وتقترح المقالة مؤشرات فنية للأداء تشمل كثافة استخدام الطاقة، والطلب الأقصى، وكثافة الانبعاثات الكربونية، وكفاءة أنظمة التدفئة والتهوية وتكييف الهواء، والراحة الحرارية، ومرونة الأحمال، ووفورات التكاليف، والأداء الاستثماري. كما تناقش الإعانات القائمة على الأداء، وعقود شركات خدمات الطاقة، والقروض الخضراء، والتمويل المدعوم بالتأمين، والتمويل من خلال فواتير الطاقة، والتكامل مع أسواق الكربون. وتُظهر النتائج أن أكبر قيمة تتحقق عندما يُنفَّذ التجديد المادي، والتشغيل الذكي، والقياس والتحقق، والحوافز المالية بوصفها منظومة متكاملة، بدلًا من تطبيقها كتدخلات منفصلة.

الكلمات المفتاحية: إعادة تأهيل المباني لتحسين كفاءة الطاقة؛ نظام إدارة الطاقة في المباني؛ المراقبة الرقمية؛ كفاءة الطاقة؛ التمويل الأخضر؛ المباني الذكية؛ أنظمة التدفئة والتهوية وتكييف الهواء؛ أداء الطاقة؛ الصين.

1. Introduction

The building sector is central to China's energy transition because it combines rapidly growing demand for electricity services with substantial opportunities for energy efficiency, electrification, renewable-energy integration, and demand-side flexibility [1,2]. According to the International Energy Agency, buildings account for approximately 20% of China's total final energy consumption, corresponding to almost 23,000 PJ. Building energy demand increased at an average annual rate of nearly 3% between 2010 and 2023, influenced by urbanization, increasing floor area, improved household living standards, wider appliance ownership, and growing heating and cooling requirements [3,4].

China's urbanisation rate increased from 37.7% in 2001 to 66.2% in 2023, while urban residential floor space expanded rapidly during the construction boom that followed 2000. However, the annual growth of total building floor area slowed from approximately 3.5% during 2010–2015 to around 2% by 2024 [5,6]. This transition means that the contribution of new high-performance construction to national efficiency improvements will gradually decline relative to the importance of renovating existing buildings. Energy-intensity reductions will therefore depend increasingly on upgrades to buildings that were designed and constructed under older codes [7-9].

Climate change and increasing cooling demand make the retrofit challenge more urgent. Between 2015 and 2023, China achieved a sustained but relatively modest improvement in building energy intensity of slightly above 0.5% annually [10-12]. In 2024, however, building energy consumption increased by more than 4%, partly because of cooling requirements associated with record temperatures. Electrified heating and electric-vehicle charging connected to buildings also contributed to higher measured electricity demand [13-19].

At the same time, China has made significant progress in building electrification. Electricity accounted for approximately 47% of building energy consumption in 2024, compared with 22% in 2010, while the share of solid fuels declined from 52% to 13% [20-22]. This transition creates an opportunity to replace direct fossil-fuel consumption with efficient heat pumps, advanced HVAC equipment, renewable electricity, and digitally controlled end-use systems [23-30]. Nevertheless, electrification without demand management could increase peak loads and grid-investment requirements [31-37]. Smart retrofitting must therefore improve both energy efficiency and the capability of buildings to respond dynamically to grid conditions [38,42].

Ren et al. [43] reported that the Chinese government has committed to achieving carbon neutrality by 2060, making the transition toward green building development in the construction sector increasingly essential. Their study aimed to examine the historical evolution of green buildings in China and identify their future development directions. Using content analysis, the authors reviewed 69 research articles published between 2001 and 2022 and analysed their associated keywords and thematic trends.

Liu et al. [44] systematically reviewed the evolution of research on building stock energy conservation and emission reduction (BSECER) from 1992 to 2025 through a comprehensive bibliometric analysis of 2,643 publications. Their study examined the contributions of leading countries, institutions, and researchers, mapped major patterns of scientific collaboration, and traced the development and changing emphasis of research themes within the BSECER field over time.

In [45], the authors investigated advanced building-retrofit strategies designed to minimise energy consumption and carbon emissions while extending the operational lifespan of existing structures. The proposed approaches included high-performance insulation materials, dynamic glazing systems, energy-efficient HVAC technologies, and the integration of renewable-energy sources, particularly solar photovoltaic systems and geothermal heating.

Pang et al. [46] emphasized that energy-conservation management in public institutions is a key component of administrative governance and plays a demonstrative role in implementing China's green-development strategy and accelerating the transition toward a low-carbon economy. The authors explained that this field has evolved through three principal stages: behaviour-based conservation, policy-driven conservation, and digital and intelligent energy management. Each stage reflects distinct theoretical concepts, management tools, operational priorities, and value orientations. They further argued that the digital-intelligence transformation of energy management in China is primarily driven by practical problem-solving needs, changing environmental conditions, and continuing technological advancement.

This article develops an integrated framework for smart energy retrofitting of China's existing building stock. It focuses on four mutually dependent elements: physical retrofit technologies, digital monitoring, Building Energy Management Systems, and green-finance mechanisms. Particular attention is given to technical performance assessment, so that retrofit success can be evaluated using measured energy savings, carbon reductions, peak-demand impacts, indoor environmental quality, and financial returns.

2. Methodology

This article adopts a policy–technical review and scenario-analysis methodology. The principal dataset and policy evidence are derived from the International Energy Agency report on energy efficiency opportunities in China's building sector. The analysis concentrates on buildings constructed between 1995 and 2010 because this group represents a substantial retrofit opportunity and was explicitly assessed using the IEA Building Energy Efficiency Performance Tool [47]. The methodology contains four analytical stages. First, the current energy and policy context of China's building stock is examined, including energy-consumption trends, electrification, retrofit targets, building codes, energy labels, and financial programmes. Second, the technical functions of envelope upgrades, heating and cooling improvements, efficient appliances, digital sensors, automation, and BEMS are evaluated. Third, a technical performance framework is formulated using energy, carbon, comfort, load, operational, and financial indicators. Fourth, financing and implementation mechanisms are assessed according to their ability to link capital disbursement with verified performance outcomes.

3. Existing Building Stock and National Retrofit Potential

China's construction of new buildings reached a high level in 2014, when approximately 3.6 billion m² of residential, public, and commercial floor space was completed. New construction declined to approximately 3.4 billion m² in 2022 [48,49]. Because newer buildings are generally regulated by more stringent energy codes, the greatest marginal efficiency opportunities increasingly exist in older buildings constructed before modern standards were fully implemented.

China has already implemented large-scale retrofit programmes. By the end of 2015, approximately 990 million m² of existing residential buildings in northern heating regions had undergone heat-metering and energy-efficiency renovation. These interventions reportedly saved around 0.2 EJ annually. During the 13th Five-Year Plan period, approximately 514 million m² of residential buildings and 185 million m² of public and commercial buildings were retrofitted. The 14th Five-Year Plan subsequently established a target of more than 350 million m² of additional energy-saving retrofits by 2025 [50-52].

The national targets for the 2021–2025 period also included 50 million m² of ultra-low-energy and near-zero-energy buildings, 50 million kW of additional building-mounted solar photovoltaic capacity, 100 million m² of geothermal-energy applications, an 8% renewable-energy substitution rate in urban buildings, and a 55% electricity share in total building energy use [53,54]. These targets demonstrate that building efficiency is increasingly connected with electrification and distributed-energy deployment.

The IEA's preliminary technical assessment indicates that implementation of best-available retrofit measures in urban residential, public, and commercial buildings constructed between 1995 and 2010 could reduce final energy consumption by up to approximately 65%, equivalent to around 8,000 PJ.

The baseline final energy demand of the assessed stock was close to 13,000 PJ, whereas comprehensive implementation of efficient solutions reduced the modelled consumption to approximately 4,500 PJ. These estimates include electricity, other fuels, and district-heating consumption [55-62].

This large technical potential does not imply that every building should receive an identical retrofit package. Building age, construction type, climatic zone, occupancy pattern, heating system, cooling technology, electricity tariff, ownership structure, and remaining equipment life must be considered. A successful programme should classify buildings according to technical need and select cost-effective measures through energy audits and lifecycle assessment.

4. Integrated Smart-Retrofit Architecture

4.1 Building-Envelope Upgrades

The building envelope determines conductive and infiltration-related heating and cooling loads. Retrofit measures include external-wall insulation, roof insulation, basement insulation, improved glazing, window-frame replacement, air-sealing, shading, cool roofs, and reduction of thermal bridges. The required solution must be adapted to China's five principal climatic zones [63,64].

In severe-cold and cold regions, insulation, airtightness, high-performance windows, heat recovery, and heating-system renovation should receive priority. In hot-summer and cold-winter regions, the retrofit must address both seasonal heating and cooling loads. In hot-summer and warm-winter regions, solar shading, reflective surfaces, efficient glazing, ventilation, dehumidification, and high-efficiency cooling are especially important [65,66]. The annual transmission heat loss through an envelope component may be approximated as:

$$Q_{tr} = U \times A \times HDD \times 24 / 1000$$

where Q_{tr} is annual transmission heat loss in kWh, U is thermal transmittance in $W/m^2 \cdot K$, A is the component area in m^2, and HDD represents annual heating-degree days in K·day. The corresponding cooling calculation may use cooling-degree days. Reducing the wall or glazing U-value therefore produces an approximately proportional reduction in conductive load, although whole-building savings also depend on ventilation, internal gains, solar gains, and HVAC efficiency.

The IEA scenario assessment suggests that upgrading building fabric to modern standards could reduce final energy consumption by approximately 25–28% in the assessed building stock. The percentage differs between urban residential and public or commercial buildings because of differences in internal loads, operating hours, surface-to-volume ratios, and HVAC operation [67-70].

4.2 Heating, Cooling, and HVAC Modernization

Heating and cooling systems represent the greatest single technical retrofit opportunity. Interventions may include heat pumps, variable-refrigerant-flow systems, efficient chillers, condensing boilers where temporary fuel-based systems remain necessary, variable-speed pumps and fans, hydraulic balancing, heat recovery, efficient district-heating interfaces, solar-assisted systems, and thermal-energy storage [71-73]. The instantaneous coefficient of performance for a heat pump is:

$$COP_h = \frac{Q_{heat}}{W_{el}}$$

where Q_{heat} is the useful heat delivered and W_{el} is the electrical input. Seasonal evaluation is more relevant for annual performance:

$$SCOP = \frac{\sum_{t=1}^{N} Q_{heat,t}}{\sum_{t=1}^{N} W_{el,t}}$$

For cooling systems, the seasonal energy-efficiency ratio or seasonal cooling COP should be calculated over representative weather and load conditions. Equipment should not be evaluated only at rated capacity because many buildings operate for long periods under partial load. The IEA assessment identifies heating and combined HVAC retrofits as the measures with the highest technical savings [74,75].

Improving heating efficiency could reduce consumption by approximately 39%, while improving both heating and cooling systems could deliver approximately 53–55% savings. Cooling-only improvements were estimated to provide around 14–16%, reflecting variations among building categories and climatic conditions. Heat-pump deployment is particularly important because it combines electrification with end-use efficiency. China's policy framework established a 55% electricity-share target for building energy use by 2025 and a 65% target by 2030 [76,78].

4.3 Lighting, Appliances, and Plug Loads

Lighting and appliance retrofits include LED lighting, occupancy sensors, daylight-responsive dimming, efficient air conditioners, refrigerators, water heaters, cooking equipment, motors, pumps, and office equipment. China's minimum energy-performance standards and China Energy Label cover more than 40 appliances and industrial components. The appliance-labelling programme has been estimated to save approximately 180 TWh annually, equivalent to around 20% of appliance electricity consumption in 2020 [79,80].

Lighting-only upgrades contribute relatively small whole-building savings in the IEA scenario, approximately 1–2%, because heating and cooling dominate the assessed stock. However, lighting replacement is usually inexpensive, technically simple, and suitable for early implementation. In commercial buildings, reduced lighting heat gains can also lower cooling demand, creating an indirect benefit [81-83].

4.4 Distributed Renewable Energy and Storage

Smart retrofits should prepare buildings for rooftop photovoltaic systems, solar thermal systems, battery storage, thermal storage, electric-vehicle charging, and two-way grid communication [84-89]. Renewable energy should be integrated after reducing demand because efficiency lowers the generation and storage capacity required to serve the building [90-95]. A building's photovoltaic self-consumption ratio can be calculated as:

$$SCR = \frac{E_{PV,load}}{E_{PV,total}} * 100$$

where $E_{PV,load}$ is the PV energy directly consumed within the building and $E_{PV,total}$ is total PV generation. BEMS scheduling of heat pumps, batteries, water heating, and vehicle charging can increase self-consumption and reduce grid exports during low-value periods.

5. Digital Monitoring and Energy Data Infrastructure

Digital monitoring converts retrofitting from a one-time construction activity into a continuous performance-management process. A typical architecture contains five layers: sensing, communication, data management, analytics, and control. The sensing layer includes electricity meters, heat meters, temperature sensors, humidity sensors, occupancy detectors, indoor-air-quality sensors, equipment status points, flow meters, pressure sensors, and weather stations. The communication layer connects devices through wired or wireless protocols. The data layer stores and validates time-series information. The analytics layer performs benchmarking, forecasting, anomaly detection, and optimization. The control layer sends commands to HVAC equipment, lighting, storage, and flexible loads [96,97].

The minimum monitoring interval depends on the application. Monthly data may be adequate for policy reporting, but 15-minute or hourly data are preferable for load profiling, peak-demand assessment, demand response, and fault detection. Critical HVAC equipment may require one-minute or five-minute measurements for diagnostics and supervisory control. In this context, China could strengthen performance assessment through a national building-stock database combining energy-performance certificates, audit results, building characteristics, retrofit measures, measured energy consumption, carbon intensity, and indoor environmental data. Such a database would support regional benchmarking and identification of poor-performing buildings. The IEA recommends standardized audit software, a national building-stock database, real-time analytics, and expanded BEMS deployment [98-101]. Data-quality procedures should address missing values, sensor drift, communication failure, incorrect meter scaling, inconsistent time stamps, and changes in occupancy. Automated quality-control routines should flag implausible values and compare submeter totals with the building's main meter. Data governance must also define ownership, privacy, cybersecurity, retention periods, and authorized access.

6. Building Energy Management Systems

6.1 Functions and Control Structure

A BEMS coordinates energy-consuming and energy-producing devices according to operational objectives. Its core functions include data acquisition, equipment scheduling, temperature control, ventilation control, load forecasting, fault detection, alarm management, demand response, renewable-energy coordination, and performance reporting. The control objective may be expressed as a multi-objective optimization problem:

$$Mini\ J = w_1\ C_{energy} + w_2\ E_{CO2} + w_3\ P_{peak} + w_4\ D_{comfort} + w_5\ C_{maintenance}$$

Subject to thermal-comfort, equipment-capacity, indoor-air-quality, storage, and operational constraints. C_{energy} is the energy cost, E_{CO2} is operational emissions, P_{peak} is peak demand, $D_{comfort}$ represents discomfort, and $C_{maintenance}$ represents maintenance-related cost.

Rule-based control is simple and appropriate for small buildings, but it may not respond efficiently to weather, occupancy, or electricity-price uncertainty. Model Predictive Control can use building thermal models and forecasts to determine optimal equipment operation over a moving time horizon. Machine-learning models can improve load forecasting, occupancy estimation, anomaly detection, and predictive maintenance. Hybrid systems may combine physical models with data-driven learning to preserve interpretability while improving prediction accuracy.

6.2 Fault Detection and Predictive Maintenance

HVAC systems frequently operate inefficiently because of faulty sensors, simultaneous heating and cooling, stuck dampers, incorrect setpoints, fouled heat exchangers, refrigerant loss, leaking valves, and degraded filters. Fault Detection and Diagnostics compare actual measurements with expected operating patterns and identify abnormal deviations.

For a monitored variable y_t, a residual may be calculated as:

$$r_t = y_t - \hat{y}_t$$

where $\hat{y}_t$ is the predicted normal value. A fault alarm may be generated when $| r_t |$ exceeds a statistically or physically defined threshold for a specified duration. Persistent residuals should be prioritised according to their energy, comfort, and equipment-risk consequences.

6.3 Demand Response and Grid Interaction

A smart building can reduce or shift electricity demand according to grid conditions. Flexible loads include heat pumps, water heating, chilled-water storage, batteries, vehicle charging, ventilation, and temperature pre-conditioning. Demand response should not compromise health or comfort, particularly in vulnerable households. Peak-demand reduction is calculated as:

$$R_{Peak} = \frac{P_{base,max} - P_{retrofit,max}}{P_{base,max}} \times 100$$

Load-shifting effectiveness may be assessed by comparing the amount of energy moved from peak to off-peak periods. Dynamic tariffs and automated control can improve flexibility, but the financial benefits depend on tariff design and participation rules. China has introduced performance-based smart-building criteria linking automation with real-time energy performance and occupant comfort. Monitoring is already required for certain large public buildings with centralised HVAC systems. Extending BEMS requirements first to large public and commercial buildings and subsequently to appropriate residential buildings could improve operational efficiency across the stock.

7. Technical Performance Assessment

7.1 Energy Performance Indicators

The principal indicator is annual Energy Use Intensity:

$$EUI = \frac{\mathrm{E}_{\mathrm{annual}}}{\mathrm{A}_{\mathrm{floor}}}$$

Where $\mathrm{E}_{\mathrm{annual}}$ is annual delivered energy in kWh and $\mathrm{A}_{\mathrm{floor}}$ is conditioned floor area in m². EUI should be reported separately for electricity, district heat, gas, and other fuels before conversion into total final or primary energy.

The percentage energy saving is:

$$S_E = \frac{E_{base} - E_{post}}{E_{base}} \times 100$$

The baseline must be adjusted for weather, occupancy, floor-area changes, and operating schedules. Without normalisation, a warmer winter or higher building occupancy could obscure genuine retrofit savings. A weather-normalised regression may be expressed as:

$$E_m = \beta_0 + \beta_1 HDD_m + \beta 2\ CDD_m + \beta 3\ O_m + \varepsilon_m$$

Where E_m is monthly energy consumption, HDD_m and CDD_m are monthly heating- and cooling-degree days, O_m represents occupancy or operational intensity, and ε_m is the residual.

7.2 Carbon Performance

Operational carbon intensity is:

$$\text{CI} = \frac{\sum_i E_i EF_i}{A_{floor}}$$

Where EF_i is the emission factor of energy carrier i. Annual avoided emissions are:

$$\Delta CO_2 = \sum_i \left(E_{i,base} - E_{i,post}\right) EF_i$$

Because China's electricity mix is expected to change over time, both location-based and time-dependent emission factors may be used. Heat-pump retrofits should be evaluated against the displaced coal, gas, or district-heating consumption rather than electricity use alone.

7.3 Thermal Comfort and Indoor Environmental Quality

Energy savings should not be achieved by reducing necessary heating, cooling, or ventilation. Indoor temperature, relative humidity, CO_2 concentration, particulate matter, and occupant satisfaction should therefore be monitored.

A temperature discomfort index can be defined as:

$$DI_T = \frac{1}{N}\sum_{t=1}^{N} \max\left(0, \left|T_{in,t} - T_{set,t}\right| - \Delta T_{allow}\right)$$

A lower value indicates fewer or smaller deviations beyond the acceptable comfort range. Relative humidity and ventilation must also be controlled because excessive airtightness without adequate ventilation can increase indoor pollutant concentrations. A large retrofit programme in Taiyuan illustrates the combined technical and social benefits of envelope upgrades. Reported outcomes included winter indoor-temperature increases of 3–5°C, summer indoor-temperature reductions of 2–3°C, a 50% reduction in energy consumption, avoidance of 193,600 tonnes of coal-equivalent emissions, and approximately RMB 100 million in cost savings.

7.4 Financial Performance

$$C_{save} = \sum_{t=1}^{T}\left[\Delta E_{tpt} + \Delta P_{Peak,t} dt\right] - C_{o\&M,add}$$

Where ΔE_t is energy saved, pt is the applicable energy price, $\Delta P_{Peak,t}$ is peak-demand reduction, dt is the demand charge where applicable, and $C_{o\&M,add}$ is additional monitoring or maintenance expenditure. Simple payback is:

$$SPB = \frac{C_0}{C_{save}}$$

Where C_0 is initial investment. Because simple payback ignores equipment life and discounting, Net Present Value should also be calculated:

$$NPV = C_0 + \sum_{t=1}^{n} \frac{C_{save,t}}{(1+r)^t} + \frac{V_n}{(1+r)^n}$$

Where r is the discount rate and V_n is residual value.

The Savings-to-Investment Ratio is

$$SIR = \frac{Present\ value\ of\ lifecycle\ savings}{present\ value\ of\ retrofit\ costs}$$

A project is generally financially attractive when NPV > 0 and SIR > 1, subject to financing conditions and risk.

7.5 Estimated Technical Savings by Retrofit Measure

Table 1 summarizes the approximate technical savings presented in the IEA scenario for urban buildings constructed between 1995 and 2010. The values are based on 2021 energy-consumption levels and should be treated as technical potential rather than guaranteed project outcomes.

Table 1. Estimated final-energy savings from selected retrofit measures.

Retrofit measure	Approximate energy saving	Principal technical effect
High-efficiency lighting	1–2%	Lower lighting electricity and internal heat gains
Envelope to modern standards	25–28%	Reduced transmission, infiltration, heating and cooling loads
Improved heating efficiency	Approximately 39%	Efficient heat generation, distribution and control
Improved cooling efficiency	14–16%	Efficient chillers, air conditioners, VRF and control
Combined heating and cooling upgrade	53–55%	Integrated HVAC modernization
Advanced building automation	18–19%	Scheduling, setpoint optimization, fault detection and load control
Comprehensive package	Approximately 65%	Combined envelope, HVAC, lighting and control improvements

The scenario demonstrates that comprehensive retrofits outperform isolated measures. However, the individual percentages should not be added arithmetically because interactions occur. For example, envelope improvements reduce HVAC load, while high-efficiency HVAC equipment then operates against the reduced demand. Similarly, automation savings depend on the efficiency and controllability of the installed equipment.

7.6 Measurement and Verification

Retrofit financing and policy evaluation require a formal Measurement and Verification process. A practical procedure should include at least 12 months of baseline data were available, documentation of operating conditions, installation verification, post-retrofit monitoring, weather and occupancy adjustment, uncertainty analysis, and independent review.

The verified saving is:

$$S_{verified} = E_{adjusted\ baseline} - E_{post-retrofit}$$

Confidence intervals should accompany the result when statistical baseline models are applied. Projects with uncertain baselines should use submetering, calibrated simulation, or component-level measurement.

8. Green Finance and Business Models

8.1 Performance-Based Subsidies

Traditional subsidies are commonly paid when equipment is purchased, or installation is completed. This approach does not guarantee that the building will achieve the expected savings. Performance-based subsidies provide an initial payment for eligible measures and release later payments after energy savings have been verified over a defined monitoring period. Smart meters and IoT sensors can support transparent verification. Older buildings with high heating or cooling demand should receive priority because they offer large energy, comfort, and social benefits.

8.2 Energy-Performance Contracting

Energy-service companies can design, finance, install, operate, and maintain retrofit measures under an Energy Performance Contract. Repayment is made from verified energy savings, reducing the building owner's initial capital requirement. China has the world's largest and fastest-growing ESCO market, but activity is concentrated mainly in industry and in commercial and public buildings. Expansion into the residential sector will require standardized contracts, credit guarantees, public ESCO registries, transparent benchmarks, trained energy managers, and effective dispute-resolution mechanisms [1,3]. A guaranteed-savings contract places technical performance risk primarily on the ESCO, whereas a shared-savings contract divides the realized savings between the ESCO and the building owner. Contract selection should reflect baseline quality, project complexity, ownership structure, and financing cost.

8.3 Green Loans and Insurance-Backed Finance

Green loans can offer lower interest rates or longer repayment periods when projects satisfy technical eligibility and verification requirements. Green insurance can reduce the lender's risk by compensating for defined technical underperformance. Qingdao's green-insurance mechanism demonstrates the potential of risk-sharing. In one case, an RMB 80 million loan was issued for a zero-carbon factory with an insurance product linked to performance outcomes. Overall, Qingdao's green-insurance initiatives reportedly supported RMB 13.2 billion in loans for green-building projects.

8.4 On-Bill and Property-Linked Financing

On-bill financing allows building owners or occupants to repay retrofit loans through utility bills. The repayment schedule can be designed so that the monthly charge remains below the expected energy-cost saving. Property-linked mechanisms attach repayment obligations to the property rather than the original borrower, which is valuable for projects with long payback periods. Adaptation to China requires consideration of its leasehold property system, under which residential leaseholds are generally 70 years and other building types commonly have terms of 40–50 years. Clear rules are required to protect retrofit investments when ownership changes or leasehold periods are renewed.

8.5 Carbon Finance

Verified retrofit emissions reductions could potentially generate additional revenue through carbon markets. China relaunched the Chinese Certified Emissions Reduction scheme in January 2024. Covered entities may use eligible CCER credits to offset up to 5% of verified emissions, although formal inclusion of building retrofits remains uncertain. Establishing approved building-retrofit methodologies could help monetize verified carbon savings and improve project economics.

9. Implementation Roadmap

9.1 Short-Term Actions to 2026

The short-term phase should establish national urban retrofit guidelines and launch pilot projects in major cities representing different climatic zones. Initial measures should include high-efficiency appliance replacement, envelope and HVAC audits, mandatory energy-performance disclosure for selected public buildings, BEMS installation in large buildings, standardised data formats, and accredited measurement and verification. Pilot programmes should report pre- and post-retrofit EUI, energy savings, peak-demand reduction, carbon intensity, thermal comfort, investment cost, operating savings, and payback. Data from unsuccessful or underperforming projects should also be disclosed so that implementation procedures can be improved.

9.2 Medium-Term Actions to 2030

By 2030, retrofit programmes should expand from pilots to large-scale deployment. The IEA roadmap proposes retrofitting approximately 30% of public buildings, combining envelope and system retrofits with appliance-upgrade and trade-in schemes, establishing digital monitoring platforms in major cities, and using accredited auditors to verify outcomes. BEMS should become standard in large public and commercial buildings, while simplified smart-control packages should be developed for multifamily residential buildings. National EPCs should incorporate measured EUI, carbon intensity, and demand-side flexibility rather than relying only on design calculations.

9.3 Medium- to Long-Term Actions to 2035

By 2035, retrofit guidelines should include minimum renewable-energy requirements, advanced demand-response capability, updated compliance protocols, and integration with decarbonization targets. Building automation, distributed resources, electric-vehicle charging, thermal storage, and grid communication should be coordinated through interoperable systems. The suggested IEA timeline combines continuous HVAC and envelope upgrades with urban retrofit guidelines, automation integration, public disclosure, digital monitoring, and independent compliance verification. Table 2 depicts proposed implementation roadmap for smart retrofitting.

Table 2. Proposed implementation roadmap for smart retrofitting.

Period	Priority technical actions	Information and verification	Financial and policy mechanisms
To 2026	National guidelines; climate-zone pilots; efficient appliances; initial BEMS deployment	Standard audits; baseline data; EPC disclosure; accredited verifiers	Performance-based grants; public-building EPC pilots; green-loan eligibility rules
2027–2030	Envelope–HVAC packages; 30% of public buildings retrofitted; citywide monitoring platforms	National building-stock database; real-time analytics; measured EUI and carbon ratings	ESCO model contracts; guarantee funds; on-bill pilots; transition-finance taxonomy
2031–2035	Renewables and storage requirements; demand response; interoperable building-to-grid systems	Updated compliance protocols; continuous commissioning; carbon and flexibility metrics	Scaled property-linked finance; carbon-credit methodologies; dynamic tariffs and utility obligations

10. Challenges and Future Research Directions

The first challenge is the diversity of China's building stock. Climate, building age, construction type, energy source, occupancy, and local economic conditions vary significantly. National requirements must therefore provide a common performance framework while allowing region-specific technical solutions.

The second challenge is the energy-performance gap between predicted and measured consumption. Design-stage simulations may not capture occupant behaviour, equipment schedules, construction quality, weather variability, and control-system faults. Future research should develop calibrated digital twins and standardized benchmarking models based on measured data.

The third challenge is interoperability. Sensors, meters, controllers, and equipment supplied by different manufacturers may use incompatible communication protocols. Open standards and cybersecurity requirements are necessary to avoid isolated systems and vendor lock-in.

The fourth challenge is data privacy and cybersecurity. Connected BEMS devices may reveal occupancy and operational patterns or provide access to critical building controls. Security-by-design, encrypted communication, authentication, access control, software-update procedures, and incident-response protocols should therefore be included in retrofit standards.

The fifth challenge is financing. Deep retrofits often have high upfront costs and long payback periods. Public funding alone is insufficient for nationwide renovation. Blended finance, green guarantees, ESCO contracts, on-bill finance, green insurance, and carbon revenue must be combined with transparent technical verification. Future research should also investigate climate-specific retrofit optimization, lifecycle embodied carbon, heat-pump performance under extreme temperatures, AI-based control, occupant-centred flexibility, low-cost residential sensing, building-to-grid integration, and the aggregation of flexible buildings as virtual power plants.

11. Conclusion

China's existing building stock offers one of the country's largest opportunities for improving energy efficiency while advancing electrification, carbon reduction, energy affordability, and urban resilience. As new construction growth slows, older residential, public, and commercial buildings will determine an increasing proportion of national building energy demand.

The technical assessment demonstrates that isolated measures provide useful but limited benefits. Envelope modernization may reduce consumption by approximately 25–28%, heating upgrades by around 39%, combined HVAC improvements by approximately 53–55%, and advanced automation by approximately 18–19%. When the best available envelope, equipment, HVAC, and control measures are implemented as an integrated package, final energy consumption could be reduced by approximately 65% in selected buildings constructed between 1995 and 2010. These values represent technical scenario potential and must be validated at project level through weather-normalized monitoring and independent measurement and verification.

Digital monitoring and BEMS are essential because they maintain savings after installation, detect faults, coordinate equipment, protect indoor comfort, reduce peak demand, and enable interaction with renewable energy and electricity grids. Their value is greatest when they are installed alongside physical envelope and HVAC improvements rather than treated as independent information technologies.

Green finance completes the retrofit framework. Performance-based subsidies, ESCO contracts, green loans, insurance-backed guarantees, on-bill finance, property-linked mechanisms, and carbon-market revenues can mobilise private capital while linking financial returns to measured energy and emissions performance. China's long-term retrofit strategy should therefore integrate technical standards, digital infrastructure, transparent data, independent verification, and performance-linked financing. Such an approach would transform existing buildings from passive energy consumers into efficient, low-carbon, flexible, and intelligently managed components of the national energy system.

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