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Review

Building Energy Retrofit Measures in Hot-Summer–Cold-Winter Climates: A Case Study in Shanghai

Yuanda Hong [1,2,4], Collins I. Ezeh [3,4], Wu Deng [1,*], Sung-Hugh Hong [1] and Zhen Peng [1]

1 Department of Architecture and Built Environment, University of Nottingham Ningbo China, University Park, Ningbo 315100, China
2 Laboratory for Manufacturing and Productivity, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA
3 Department of Chemical and Environmental Engineering, University of Nottingham Ningbo, University Park, Ningbo 315100, China
4 Shanghai Daren Construction Engineering Co. Ltd., Floor 1, Building 60, No. 1818, Lianhang Road, Minhang District, Shanghai 201112, China
* Correspondence: wu.deng@nottingham.edu.cn; Tel.: +86-574-8818-0000 (ext. 8543)

Received: 16 May 2019; Accepted: 29 August 2019; Published: 3 September 2019

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Abstract: Building retrofit measures provide a significant means of mitigating the effect of climate change on buildings by enhancing building energy performance at a beneficial cost-effectiveness. An insight into the applicable building retrofit measures within a climate zone will guide the optimisation framework to attaining sustainability in architecture and the built environment. This article presents a brief overview of recent studies on retrofit measures and its application on a variety of buildings in hot-summer–cold-winter climates, with emphasis on Shanghai. Findings show that the major retrofit measures include improvement in the building envelope, heating, ventilation and cooling (HVAC) and lighting, supported by photovoltaic (PV) systems, accordingly. Furthermore, the study identifies key elements and plausible challenges for the evaluation of building retrofit measures in this region. In this regard, financial barriers and lack of standards and regulatory support are the main challenges identified. These insights provide a systematic approach to guide building researchers, practitioners and decision-makers in the design and development of existing and new retrofit measures for the future of rapidly growing cities with a broad climate variation scope.

Keywords: building retrofit measures; building energy consumption; climate change; hot-summer–cold-winter; Shanghai

1. Introduction

Generally, buildings account for 20–40% of energy consumption in most countries [1,2], and consume a significant share of global electricity [3]. The rise in energy consumption necessitates the development of smart buildings with optimal economic benefits to circumvent this trend. Accordingly, buildings are retrofitted with recent energy conservative measures (ECMs), which include technological advances such as usage of thermal energy storage (TES) [4], building fabrics upgrade [2] and installation of policies to overcome key retrofit barriers [5]. Moreover, the adoption of these measures is speculated to be driven by regional climate variation and population density, particularly in China [6]. Besides this, existing buildings are historical and are energy inefficient.

In order to promote energy-efficient buildings, the Chinese government has established comprehensive policies within the 11th (2006–2010) and 12th (2011–2015) Five Year Plans. These plans have necessitated the upgrade of parts of existing buildings or whole ("deep") building retrofits in order to improve the energy-saving potential across all building types within the country [7–9]. In northern China, the upgrades in building fabrics and heating systems has led to an estimated 18.5% of energy savings of residential buildings [8]. The reduction in internal loads, improvements in heating, ventilation and cooling (HVAC) and water heating systems resulted in an estimated 77.3% of energy savings in Tianjin [9]. Deep building retrofits entail the use of a whole-building approach to reduce the total building energy usage by more than 50% [7].

Even with the stipulated retrofit technologies, building energy consumption still contributes to about one-fourth of the total energy consumed and steadily increases annually, particularly for highly urbanising cities like Shanghai [10–12]. The reason being that the high urbanisation of the city is associated with the introduction of varying microclimates influenced by topographic features such as lakes and tall buildings. Subsequently, the city is rebuilt to accommodate increasing population density. As such, the density and height of buildings, green, water and floor area ratio, pavement area, etc. are affected, which affects solar reflectivity, urban heat capacity, the sky view factor and land surface roughness [13]. For example, streets and buildings will trap solar radiation, resulting in an increase in the average city temperature and building energy consumption beyond that of more open cities. To this effect, the 13th Five Year Plan in China (2016–2020) was formed to promote more sustainable buildings [14]. Shanghai is the largest industrial and populous city in the hot summer and cold winter (HSCW) climate zone in China [15]. Hence, a suitable framework is required to retrofit buildings amidst high population density to attain sustainability.

This article reviews the current literature on building retrofit measures adopted in highly dense cities with an emphasis on Shanghai. The article documents appropriate retrofit measures, their contribution, key concerns, evaluation methods and common challenges faced in this city. Figure 1 illustrates a graphical description of the aim of this study. This article also provides a good foundation for readers who aim at proposing policies on urban planning, energy consumption and climate change.

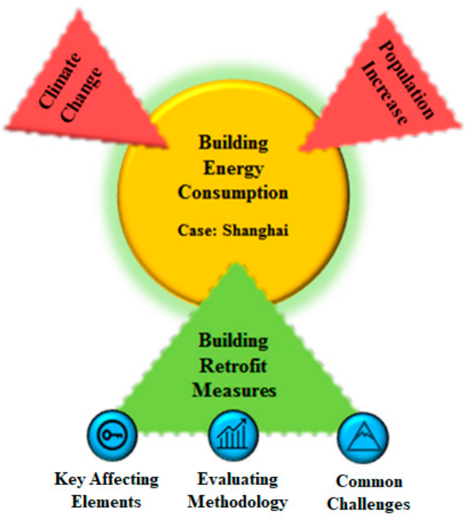

Figure 1. Graphical summary of the aim of this study.

Motivation for Review

This paper aims to document recent research studies and their findings on adopted building retrofit measures in a highly urbanising city with HSCW climate. Shanghai was considered as a case scenario while discussing suitable programs and notable concerns in implementing these measures. Like other highly expanding cities such as Beijing and Guangzhou (China), Sao Paulo (Brazil), Port Harcourt (Nigeria), the expansion of Shanghai has been associated with varying microclimates influenced by topographic features like lakes and buildings. Hence the information on building retrofit packages with a focus on the impact of population and climate variation was deemed necessary. Generally, the diverse scope of information is presented in literature and may pose challenges for practitioners and policymakers to identify the key elements needed for advancements in architecture and built environment, particularly in areas within this study scope. Thus, an attempt has been made to collate documented studies, analysis and assessments within this study scope, as well as to identify the necessary factors for mobilising this region and other similar regions in the world towards a sustainable future of building energy demand.

This paper is organised according to the following contents. Section 2 presents the methodical approach adopted for literature selection and review. Section 3 presents an updated insight into building energy consumption and climate context, which serves as the foundation for the development of existing and new retrofit measures. Section 4 reviews the global energy-saving retrofit measures, their application in the Shanghai scenario and key elements to be considered in the retrofit selection. Section 5 discusses the methodical approach for evaluating these retrofit measures with the proposed assessment and simulation tools. Section 6 presents the common challenges encountered in the implementation of these retrofit measures. Finally, Section 7 summarises and concludes the paper.

2. Methodology

Several studies published in English until 2019 were collected and reviewed. These studies include peer-reviewed articles from journal databases (Science Direct, Taylor & Francis, Scientific, Emerald, Chinese National Knowledge Infrastructure), and emerging research databases (MDPI, JSTOR, JOSRE). Other additional studies consulted to expand the research coverage included academic books, governmental and environmental institution reports and conference proceedings. The search and selection of literature were adopted from [16] and was conducted in January 2019. Table 1 presents a breakdown of the pool of selected literature for this study. Initially, the pre-selection of literature was based on a combination of keywords including: "buildings", "energy", "retrofit", "climate change", "HSCW climate", "impact" and "sustainable". As a sequel to this, additional keywords were adopted to streamline the search for this study ("hot-summer–cold-winter", "energy consumption", "development" and "Shanghai"). Here, the pre-selected literature from this search provided the studies for assessing the performance of retrofit measures in Shanghai. Furthermore, studies reviewed for retrofit "challenges", selection "methodical approach" and "key elements" were screened using the noted keywords in addition to "policy" and "uncertainty". An on-site survey was used to rank the enumerated challenges and was further discussed using supporting literature [16]. In total, 104 studies were reviewed, including 74 journal papers, 10 conference proceedings, 4 books and 16 government and research institute reports.

Table 1. Pool of reviewed selected literature.

Publisher	Keywords			Total
	Climate Change, Buildings, HSCW Climate, Retrofit, Energy, Impact, Sustainable	Climate Change, Energy Consumption, Shanghai, Development, Hot-Summer–Cold-Winter,	Building, Retrofit, Challenges, Methodical Approach, Policy, Key Elements	
Science Direct	48	8	4	60
Taylor & Francis	3	1	2	6
Conferences	3	3	4	10
Government Agencies Report	2	1	3	6
*** Independent Publications**	2	1	3	6
World Scientific	3		1	4
Books	2	1	1	4
MDPI		1		1
Mendeley			1	1
Emerald			1	1

Table 1. *Cont.*

Publisher	Keywords			Total
	Climate Change, Buildings, HSCW Climate, Retrofit, Energy, Impact, Sustainable	Climate Change, Energy Consumption, Shanghai, Development, Hot-Summer–Cold-Winter,	Building, Retrofit, Challenges, Methodical Approach, Policy, Key Elements	
Scientific		1		1
CNKI	1	2		3
JOSRE			1	1
Total	64	19	21	104

Independent publishing: Research institutes (such as Chalmers, Chartered Institution of Building Services Engineers etc.), National Bureau of Statistics, World Business Council for Sustainable Development, JSTOR and Asia Pacific Economic Cooperation.

3. Background Study: Building Energy Consumption and the Climatic Context in Shanghai

In recent years, the design or restructuring of buildings has been to adapt to different climate changes and to minimise building energy consumption. Due to the rapidly increasing average global temperature, indicative of anthropogenic global warming [17–21], necessary retrofit measures are required for existing buildings to accommodate the high ambient temperature [22–24]. However, the pre-selection of suitable retrofit measures is dependent on the regional climate changes [25–27].

3.1. Climate Context

The climate system in China is complex given that insignificant changes have been observed in the average annual surface temperature despite the significant fluctuations in the average annual temperature of the eight major regions, as shown in Figure 2. According to the China Meteorological Administration, the average annual surface temperature in China has shown a significant upward trend from 1901–2017. From 1951 to 2017, the average annual surface temperature in China increased by 0.24 °C/decade, and the heating rate was higher than the global average. The difference between the regions is evident. The temperature increase rate in the north is larger than that in the south, and the western region is larger than the east. The Tibet Plateau region has the highest temperature increase rate [24]. In general, the variation between minimum and maximum temperatures in China decreased by 0.24, 0.21 and 0.09 °C for annual average, January and July, respectively [28]. Consequently, this has affected the design of buildings, particularly the fabric type, in China.

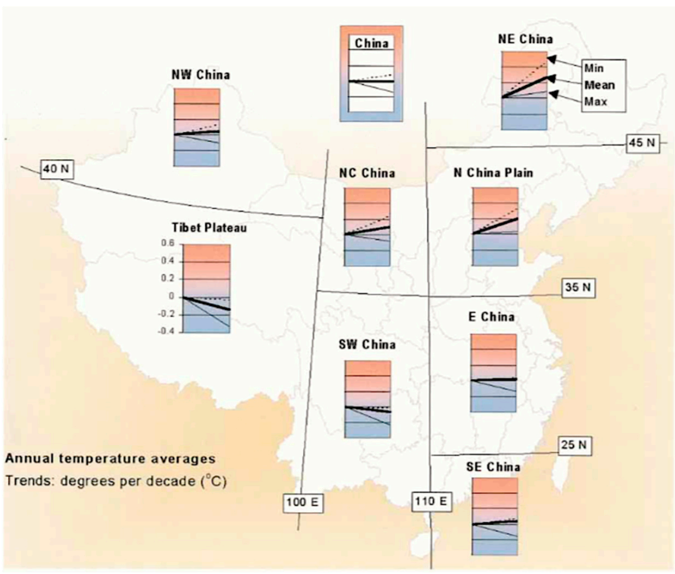

Figure 2. Annual temperature averages [28].

According to the Ministry of Housing and Urban and Rural Development of China, there are five major climate zones in China, with each zone having different building design guidelines [29]. Table 2 and Figure 3 show the climatic classification and characteristics, as well as building design requirements for each region in China. The north of China (north-east (NE), north-west (NW) and part of north-central (NC)) and most parts of Tibet Plateau are classed under a severe cold climate zone. The rest of NC, Tibet Plateau and North China plain are categorized as cold climate zones. East China, south-west (SW) China and south-east (SE) China are in the Hot-Summer–Cold-Winter (HSCW), temperate and Hot-Summer–Warm-Winter (HSWW) climate zones, respectively. In this study, the emphasis is on buildings located in the HSCW climate zone, with two extreme weather conditions within a year. This climate zone was noted to have the most widely ranged climate features which have posed significant technical challenges to building design.

Table 2. Climate zones, characteristics and building design requirements in China [30].

	Climate Zones	Average Temperatures	Requirements for Building Design
I	Severe cold zones	January: ≤−10 °C; July: ≤25 °C	– Anti-freezing requirement, – Heat preservation and other requirements.
II	Cold zones	January: −10 to 0 °C; July: 18–28 °C	– Anti-freezing requirement, – Heat preservation and other requirements.
III	Hot summer and cold winter zones	January: 0–10 °C; July: 25–30 °C	– Anti-overheating, – Shading, – Ventilation and cooling requirements in summer, – Anti-cold requirements in winter.
IV	Hot summer and warm winter zones	January: >10 °C; July: 25–29 °C	– Anti-overheating, – Ventilation cooling, – Shading, – and Anti-rain requirements in summer.
V	Temperate zones	January: 0–13 °C; July: 18–25 °C	– Ventilation, and – Anti-rain requirements in summer.

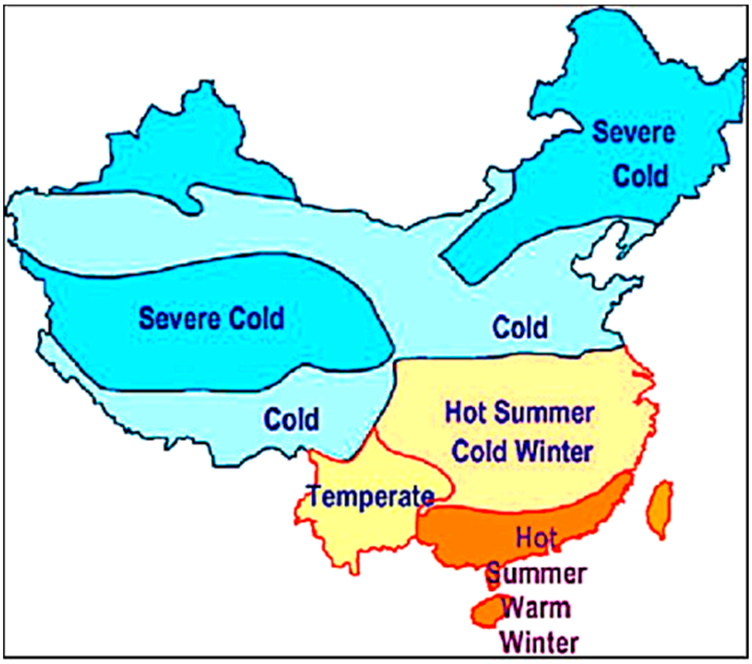

Figure 3. Climate zones of China.

A notable city situated in the HSCW climate zone is Shanghai. Shanghai's population was estimated to be 26.32 million in 2018, according to UN world urbanisation prospects. Extending 120 km from south to north, and 100 km from east to west, it covers an area of 6340.5 km^2 and contains 17 local government districts. Shanghai has a humid subtropical climate and experiences four distinct seasons [31]. Building energy consumption in this zone is considerably high due to the fluctuating seasonal climatic conditions. As a result, buildings must meet with anti-overheating, ventilation, shading, and cooling requirements in summer, while anti-cold requirements are also expected in winter [30]. Consequently, this leads to enormous energy consumption for heating and cooling during these extreme conditions. Also, this region is surrounded by several developing provinces such as Jiangsu and Zhejiang, which contributes to high building energy consumption with rapid economic demand. Hence, it is crucial to have an insight into the impact of climate conditions on building energy consumption in this climate zone if appropriate retrofit solutions are to be determined.

Documented climate data of Shanghai for the past 40 years (from 1970 to 2010) are summarised in Figure 4 [32]. Figure 4a shows an ascending trend for the annual average temperature of Shanghai within the stipulated period. Before 1990, the rate of temperature increase was slow before it rapidly increased until 2010. Specifically, the annual average temperature increased from ~15.4 °C to ~16.4 °C after two decades from 1970. Post-1990, the temperature continuously increased to above 18 °C in 2007 [33]. Figure 4b shows a more vivid clarification of the temperature rise within a day for different periods. Within the recent decades, it was observed that the hourly temperature variation in Shanghai increased at a greater magnitude than in the past decades. Accordingly, building energy consumption was channelled towards a cooling load in this region of China, and vice versa [34]. Recent observation and simulation research show that climate change in this region was significantly affected by both external climate variability and internal oscillation [35]. While climate variability has been attributable to the climate features of the city, the internal oscillation was associated with the additive effect of climate variation and urban densification. Owing to the rise in urban residents from 58% in 1978 to about 90% recently [36], an increase in building density was expected. Consequently, this was stipulated to induce an urban heat island (UHI) effect, resulting in micro-(local) climate variation. An extensive study in Nanjing, a similar neighbouring city, speculated that the distance between the buildings rather than the building typology was the critical factor of urban micro-climates [13].

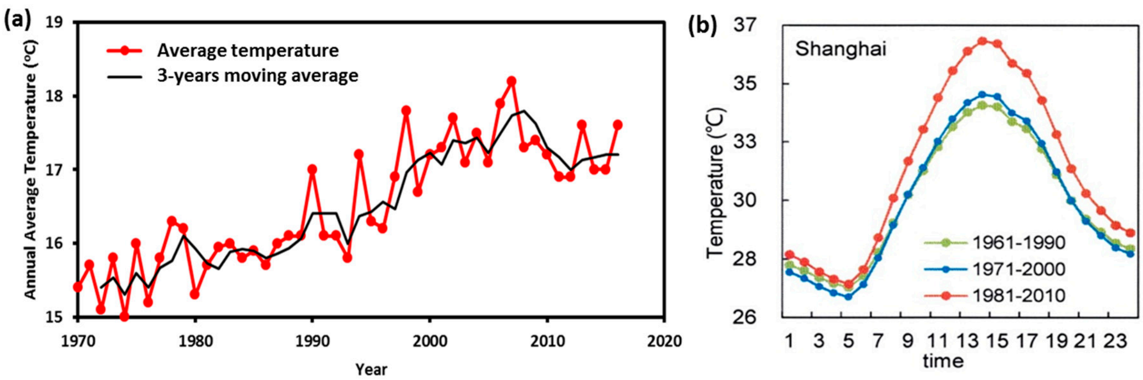

Figure 4. Impact of climate change in the city of Shanghai (**a**) annual average temperature change [32] (Presented temperatures are the annual average temperatures for the entire year) and (**b**) hourly temperature variation in summer for different periods [34].

3.2. Building Energy Consumption in Shanghai and Beyond

By way of their function, buildings consume much energy, particularly for occupant activities, facilities, comfort and lighting. Building energy consumption primarily depends on building typology among other factors [37]. According to the US Energy Information, residential buildings are more dominant in terms of energy use [38]. However, commercial buildings have a significant share and will probably increase their energy use tremendously in coming decades when compared with the

2003 baseline. A comparison of building energy usage with building typology in a different urbanising country is presented in Figure 5. In the US, commercial buildings consumed about one-third of the country's primary energy consumption in 2003 [39,40] and were estimated to rise to about 45% by 2030. In China, energy consumed by commercial buildings is expected to increase from 400 TWh (in 2003) to about 1000 TWh (in 2030).

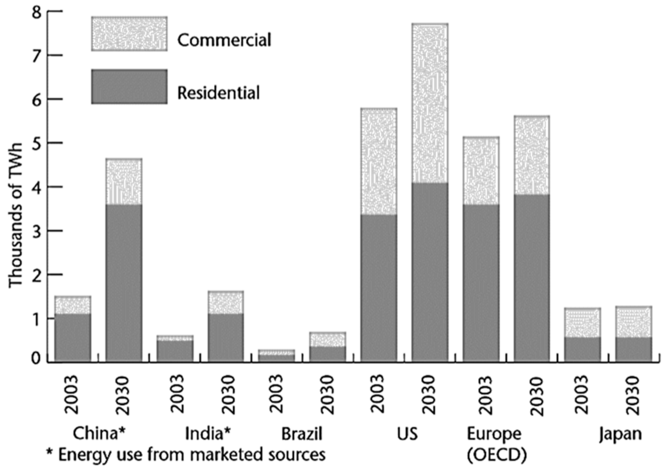

Figure 5. Building energy projection by region 2003–2030 [38].

Major reported consumers of building energy are HVAC systems—lighting and heat exchange systems. In the US, HVAC systems account for about 35% of building energy consumption [41]. In Canada, 54% of whole-building energy consumption is for heating and 6% for cooling; while equipment, lighting and hot water systems account for 20%, 13% and 7%, respectively [42]. In Europe, Vorsatz et al. presented that 52% and 4% of building energy usage was accounted for by heating and cooling, respectively [42]. In Greece, Asimakopoulos, Bougiatioti discerned that building energy consumption depends primarily on the immediate climate condition. Due to increasing global temperature, building heating load was found to have decreased by approximately 50%, while the cooling load increased by approximately 248% [43]. Therefore, HVAC and lighting systems are considered essential parameters in designing energy and emissions savings measures for existing buildings [41,44].

In China, annual energy consumption similarly peaked from 571 million to 4.64 billion tons of coal equivalent (TCE) from 1978 to 2018. Carbon emissions increased from 400 million to 7.95 billion tons representing an increase from 6% to 20.3% of the world's total, making China the world's largest emitter [45]. Buildings are critical consumers of energy accounting for 30% of total national energy consumption, which is projected to rise to 35% by 2020 [46,47]. Energy consumed by heating and cooling contributes a significant share (approximately 65%) to the total building energy consumption [47]. As a result, China has devised various policies to economically transform and sustain environment development by reducing the energy demand across all sectors, particularly architecture and built environment [48]. Hence, the proposal on energy-efficient buildings as a means of carbon mitigation poses not only a challenge to China's economic development, but also creates crucial economic transformation opportunities for achieving sustainable environment development.

As the economic centre of China, carbon emissions associated with high energy consumption has posed immense pressure on Shanghai. Data from Shanghai Municipal Statistics Bureau [36,49] shows that electricity, coal gas, liquefied petroleum gas (LPG) and natural gas, which are significant generators of CO_2, are the primary sources of building energy in Shanghai. Electricity is considered the primary source of energy with 3253.6 kWh/household [50]. Figure 6a shows the total energy consumption over the past 46 years. Figure 6a depicts a slow growth rate in annual energy consumption from 1970 to 2000. After this year, energy consumption grew faster than ever until 2013 when it gradually slowed down.

The rise in energy consumption can be attributed to the significant net increase in the population of Shanghai due to migration.

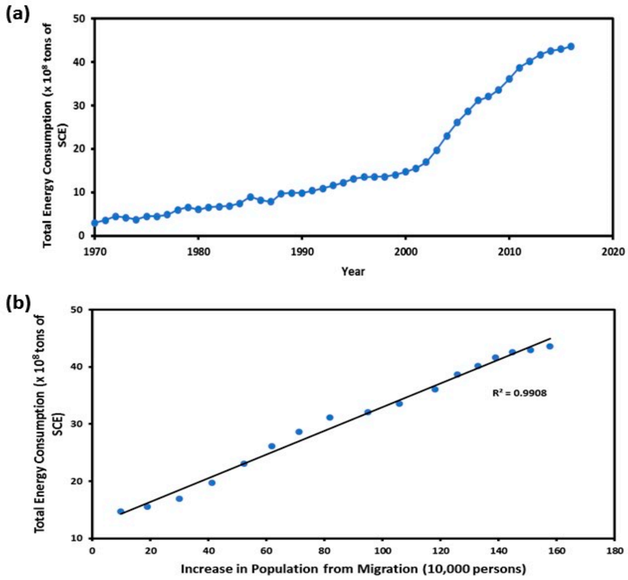

Figure 6. (**a**) The annual energy consumption in Shanghai from 1970 to 2016, (**b**) Relationship between annual energy consumption and net population increase from migration using the 2000 baseline. Data extracted from China Statistical Yearbook 2017 [49].

After 2000, the net migration influx in Shanghai witnessed an eight-fold increase compared to that of the 1990 baseline [36]. However, from 2011, net migration reduced to about 50% of the 2010 baseline and has remained so till date. The variation in net migration could explain the reason for the exponential growth in energy consumption before 2010 and the slow energy consumption rate beyond 2013. For further elucidation, Figure 6b presents the relationship between energy consumption and net population increase resulting from migration from 2000 to 2016. Figure 6b shows that a 99.1% correlation exist between these factors. Further insight into the statistical relationship is shown in a supporting document (Section S1). The statistical analysis confirms that the worsening effect of climate change was not the only factor contributing to the increase in building energy consumption in Shanghai. It is demonstrated that the rise in energy consumption is highly correlated to the increase in population density. Therefore, the appropriate sustainable built environment should account for climate variations, as well as for an increase in population density.

From a broader perspective, building energy consumption is affected by a complicated network of factors [51]. Figure 7 conveys the complexity of the relationship by categorizing the variables into five sections: (a) Causes of climate change, (b) indicators of climate change and its (c) environmental impact, effects on (d) buildings and (e) its occupants, with a feedback loop connecting potential activities of occupants that can increase the causative potentials of climate change. In summary, it can be deduced that the increasing energy consumption in Shanghai is associated with a network of factors, including the effect of climate change and population rise. Therefore, the most suitable building retrofit package for Shanghai would be measures that can mitigate the combinative effect of the major contributing factors to the rise in building energy consumption.

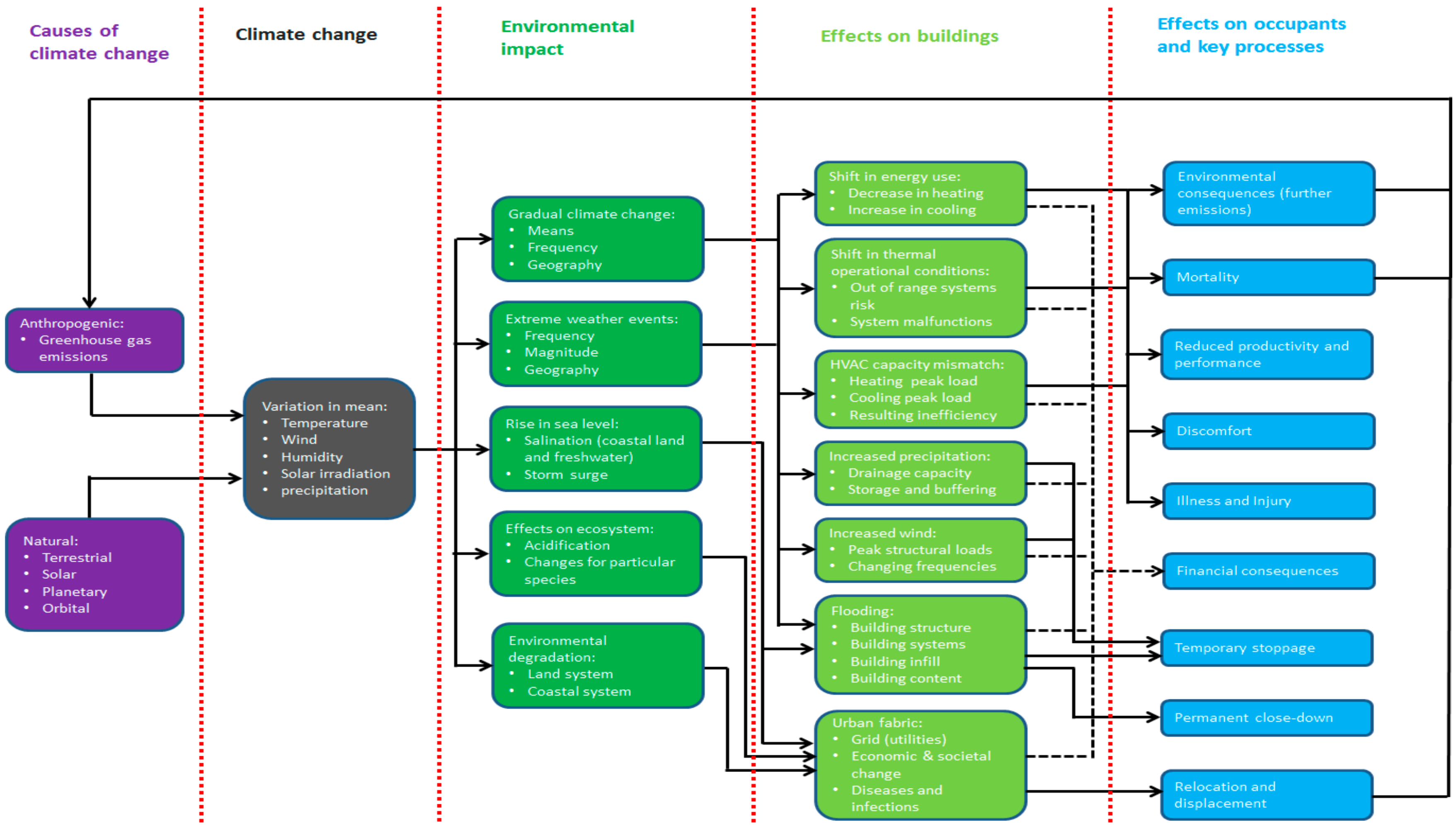

Figure 7. Interactions between buildings, climate change and subsequent potential effects on building occupants and the environment. The figure is based on a schematic overview by de Wilde and Coley [51]), but expanded to elaborate on the cyclic interactive nature.

4. Building Retrofit Measures and Major Affecting Elements in Shanghai

Building retrofitting is defined as the modification of existing building with facilities or equipment for ease of operation, improvement of efficiency and reduction of environmental disturbance [52]. It includes specific methods such as an upgrade of the building envelope, improvement of mechanical systems, operating and management practices while sustaining a comfortable indoor environment for the occupants [53]. The selective implementation of specific retrofit measures also enhances the environmental impact, economics, as well as the energy efficiency of buildings. These measures are designed to suit the building characteristics and reduce the adverse effect of climate variation on the comfort level of the building. By enhancing building energy savings, greenhouse gas (GHG) emissions are also reduced.

Generally, building retrofit measures are categorised into five major aspects: Building envelope, equipment system, new technology updates (renewable energy sources), energy-conserving behaviours and energy management and control systems. However, based on the management structure, building retrofit measures are classified into three major groups: Demand-side, supply-side and energy conservation (also known as the human factor) [16]. Details of general retrofitting technologies and their classifications can be found in the following studies [9,54–56] and are summarised in Table 3. The application and effectiveness of these measures depend primarily on the building typology and its characteristics. Other notable factors include geographical location and its associated climatic variations.

Table 3. General building retrofit measures and classification (Adopted from [16]).

Building Retrofit Classification		Building Retrofit Measures
Demand-side Management	Building Envelope	– Building fabric insulation (i.e., ceiling, wall, etc.) – Windows retrofits (i.e., multiple glazing, low-E coatings, shading systems, etc.) – Airtightness – Cool roofs and coatings – Floor retrofits, etc.
	Equipment System	– Natural ventilation – Control upgrade – Lighting upgrade – Energy-efficient equipment (HVAC, water heating, lift, etc.) – Thermal storage and heat recovery, etc.
Energy Conserving Management	Energy Conserving Behaviors	– Occupancy regimes, schedules and activities – Comfort requirements – Staff training – New management scheme – Monitoring strategies, etc.
	Energy Management and Control System	– Management and maintenance (i.e., review service systems, energy sourcing, utility rate structure, etc.) – Access to control (i.e., automatic control systems, optimization control strategies, etc.)
Supply-Side Management	New/Renewable Technology	– Solar PV/PVT systems – Solar thermal systems – Biomass systems – Electric system retrofits – Geothermal systems – Wind power systems, etc.

4.1. Building Retrofit Measures in Shanghai

Based on the sensitivity of retrofit measures to geographical location, adopted retrofit measures tend to differ with location. Among other conditional factors, climate trend can be considered to be the primary cause of such variation. Hence, design meteorological parameters are considered in the development of adequate retrofit measures. For a city like Shanghai, characterised by hot summers and cold winters, specific retrofit measures should address this rapid climate variation based on building types.

Besides that, adopted retrofit measures should also mitigate the impact of population increase on building energy consumption, as witnessed. Nonetheless, there is little or no research that portrays a definitive relationship between building retrofit measures and the population of the city. Building retrofit measures are most likely defined based on the elements that constitute energy consumption, including climate variation and building characteristics. Hence, this research will confine its assessment of retrofit measures to studies based in Shanghai, which is characterised by high and still increasing population density. Table 4 presents a summary of retrofit measures for different building types in Shanghai and their outcome. The summary was based on a total of 19 reviewed papers with the keywords: Climate change, energy consumption, Shanghai, development, and hot-summer–cold-winter. A breakdown of these papers is shown in Table 1.

Table 4. Summary of various studies on building retrofit measures in Shanghai.

S/N	Building Type	Major Retrofit Measures	Performance Assessment Method	Major Results	Ref
			Commercial (Office)		
1	Green E-Park with 13127 m^2 total floor area (12344 m^2 ground floor area and 803 m^2 basement), Yangpu District	Improve natural ventilation, roof garden and vertical plants, runoff control measures, movable envelope, rainwater collection system, installation of wastewater membrane treatment system and intelligent management system, solar water heater and PV-system	Multiple simulations using BIM models	Annual CO_2 emission savings: 5716.3 kg, 140.2 kg of dust reduction, runoff coefficient was reduced to 0.62 from 0.78. Indoor environmental quality (IEQ) was within 90% acceptability range of ASHRAE 55-2010 comfort standard.	[57]
2	Office buildings built before 1980 and new constructions in Shanghai	Deep retrofit: Envelope system (upgrades in wall, windows, doors and roof), retrofitting lighting, HVAC, plug, power, domestic hot water system, behaviour management, and adaptable subsidy policy	Metered data from real-time energy use monitoring system	Achieved energy savings > 20% (5–10% due to management schemes, cumulatively 20–30% to lighting, air-conditioning, plug, power and water heating, and 30–50% to envelope system cumulatively). Suitable subsidy plan is vital for building retrofit measures.	[58]
3	Four high-rise buildings with 108, 250, 32 and 127 x 10^3 m^2 gross floor area, Shanghai	Upgrade in lighting systems (use of T5 lamps, high electronic discharge lamps and LEDs), HVAC upgrade (use of outside-air economisers, replacement of heat pumps, motors and exhaust fans)	EnergyPlus Simulation tool and actual measurement tools	Energy savings: 4%, 7%, 10% and 15% from an investment of 1.8, 5.0, 1.3 and 14.8 million RMB, respectively. Although huge variations were obtained between actual and simulated results (−43%, 1.6%, 47.3% and −37.7% respectively).	[59]
4	High-rise building with 300,000 m^2 total building area in Pudong New Area.	Changing to variable speed chilled and hot water pumps from fixed speed pumps, free winter cooling and upgrade of lighting systems	Collected data from on-site surveys and measurements and modelling using visualDOE4.0	Primary energy savings was less than 4%. Using free cooling in the winter season provided the least energy saving because of the high humidity of Shanghai air.	[60]
5	8-floors multi-function commercial building (with two floors underground)	Varying building cooling load by varying building thermal mass (furniture, walls and slabs) and radiation absorptivity	Genetic algorithm (GA) is employed to solve the multi-objective optimisation problem	Simulation of building's cooling load based on thermal masses receiving radiation best describes real practical cases with mean relative error (MRE) of 12.15%, whereas simulated model based on thermal mass best describes physical model simulation, with an MRE of 9.50%.	[61]
6	Two office buildings (26 and 36-storey with a total floor area of 49,650 and 87,765 m^2 respectively)	Insulations (walls, roof and floors, upgrade in windows and shading, upgrade of chiller units, HVAC, lightings, use of gas-fired boilers and centrifugal chillers for heating and cooling respectively	EnergyPlus Simulation tool, support vector regression (SVR) and actual measurement tools	Best simulation of practical cases is obtainable with physics-based simulation, supported by sensitivity analysis, optimisation algorithm and non-linear regression tools.	[62]

Table 4. *Cont.*

S/N	Building Type	Major Retrofit Measures	Performance Assessment Method	Major Results	Ref
			Residential		
1	Residential buildings in 26 cities in China including Shanghai	Insulation (wall, roof and window), solar gains (glazing and shading), better air-tightness, improved ventilation, heat and moisture recovery system, PV systems	Modelling with TRNSYS simulation program	Integrated PV-systems contributes effectively to attaining sustainability. Occupant activities dominate CO_2 emission after the retrofit.	[63]
2	A typical household in Shanghai with 150 m^2 total floor area	Installation with micro-CHP systems (Ecowill gas engine and Enefarm fuel cell)	Mathematical optimisation model to minimise annualised investment and operation cost	Compared with conventional systems, Ecowill and Enefarm are 105.2% and 115.7% more expensive, respectively. However, adequate promotional measures (involving subsidies and adaptable electricity and gas packages) can make this measure more economical.	[64]
3	An apartment with 110 m^2 total floor area in Xuhui district	Upgrade of doors and windows (double glazed), installation of mechanical ventilation fan, air purifiers and control systems.	In-situ measurements	Each measure is not adequate to improve IAQ to the set standard. However, a mix of the measures attained this, reducing PM2.5 I/O ratio from 0.41 to 0.01.	[65]
4	Residential community, Chongming Eco-Island, Shanghai	Installation of PV panels and solar water heaters	SketchUp 14.0, EnergyPlus 8 and Ecotect Analysis 2011	PV development scheme or zero non-renewable energy buildings can be attained under given building envelopes and energy trade-offs	[66]
5	Nine neighbourhoods in Shanghai, of which five are residential	Urban geometry plan, HVAC, building envelope and users behaviour	ArcGIS, Urban Modeling Interface (UMI) and Urban Weather Generator (UWG) toolkits	Density–energy relationship of each building depends on the geometry and intricate factors including materials, HVAC system and occupant behaviour	[67]
6	One residential household	External insulation, double glazed windows, heating measures: HVAC, oil heaters, electric heaters and electric blankets.	Data collation and analysis: survey, surrogate and real-life measurements	To attain an ultra-low thermal comfort, winter heating condition needs to be improved. Measures should include upgrading insulation and installing heat recovery systems	[50]

Table 4. *Cont.*

S/N	Building Type	Major Retrofit Measures	Performance Assessment Method	Major Results	Ref
		Hotel			
1	Two hotels with 55.8 and 26 (× 10^3) m^2 gross floor area, Shanghai	Upgrade: Building envelope (insulating walls, roofs and windows; replacement of single glass windows to low-E ones); lighting systems (LEDs); domestic hot water system (with heat recovery and card-operated) efficient cookers, HVAC upgrade (replacement of heat pumps, motors and exhaust fans), water-saving cooling towers and solar water heater.	EnergyPlus Simulation tool and actual measurement tools	Energy savings: 26% and 38%, respectively, with energy user intensity (EUI) savings of 66.68 and 54.06 kWh/m^2 respectively. Actual measurement was 10.4% more than simulated benefits.	[59]
2	Forty-five hotels (15 3-star, 15 4-star and 15 5-star) with an average gross floor area of 42749 m^2.	Upgrade of lighting systems, adopting variable frequency pumps and condenser heat recovery, solar water heater, upgrade of cooling tower and use of gas boilers and heat pumps rather than coal operated ones	Energy consumption monitoring system	Electricity is the primary energy source (75% of total energy consumption). Energy efficiency ranged from 3.3% to 50% depending on the number of retrofit options adopted.	[68]
		Public			
1	100 public buildings, Hongqiao	External wall and window retrofit, installation of sub-metering and control systems, heat recovery systems, lift regeneration systems, upgrade of HVAC and upgrade of oil-fired to gas boilers	Fuzzy Multiple attribute decision making-Monte Carlo Method and investment prediction model	49% and 60.5% probability that energy savings and value of an investment will be beyond the expected values, respectively. Building insulations and energy recovery systems were the most beneficial measures.	[69]
2	Multipurpose Commercial building with 284,651 m^2 total floor area and height of 136.3 m, Shanghai	Upgrade HVAC, lighting systems, oil boiler to natural gas boilers, installation of sub-metering and control systems, roof and wall insulation, window upgrade (shadow, films and double-layer glass) and solar power installation	Cost–benefit analysis and Monte-Carlo simulation	Energy savings: 1949 GJ with energy-saving investment; 895,000 USD depending on ERMs. Net present value (NPV) changed by 97% with the discount rate changing from 0–8%.	[70]

A summary of the reviewed retrofit studies in Table 4 is presented in Figure 8. Figure 8 shows a mix of suitable retrofit technologies for each building type in Shanghai. The classification of these technologies is based on the general retrofit technologies defined in [16] and presented in Table 3. The significance of each retrofit technology (henceforth, known as the degree of application) was computed from the normalised average impact of each retrofit technology on the building energy performance using collated data from the reviewed papers. The equation was presented in previous studies [52,71] and is shown as Equation (1).

$$D_e = \frac{\sum_{x=1}^{e}\left(\frac{n_i}{\sum_i^N n_i} \times 100\%\right)_x}{e} \tag{1}$$

where De is the degree of application of the retrofit measure (i), n_i is the impact on building energy saving of the retrofit technology measure in building type x, e is the number of a particular building type reviewed, and N is the number of retrofit measures adopted.

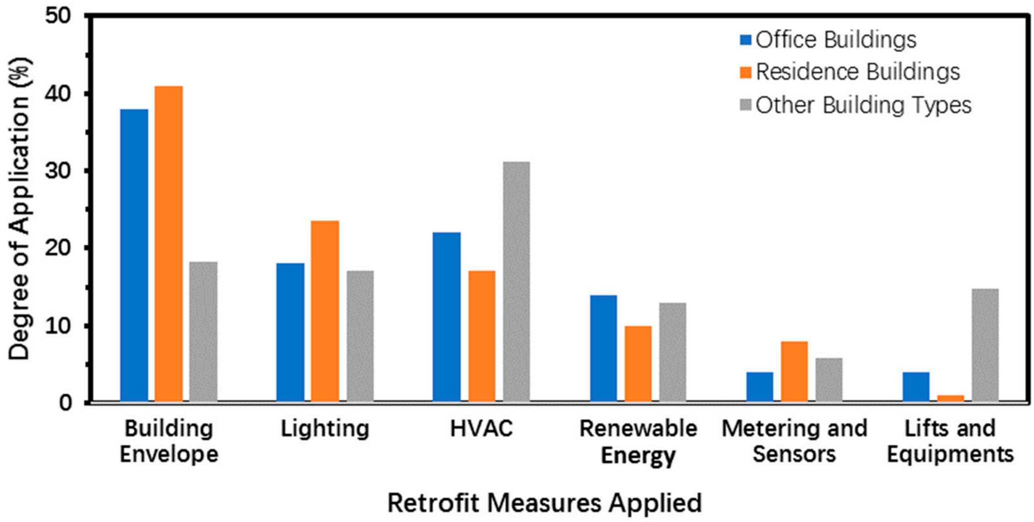

Figure 8. Degree of application of different retrofit measures on different building types (n-size = 19).

4.1.1. Building Envelope/Insulations

Upgrading building facades and envelopes such as roofs, floors, walls, shading, windows, and airtightness have shown tremendous contributions as energy conserving measures in building energy performance [59,62]. Although significantly unaffected by population variation, this measure was the most used retrofit measure for Shanghai buildings (as shown in Figure 8). Nevertheless, its retrofit economy is low, given that it is the most important measure based on geographical location. The building envelope should be designed to facilitate good indoor air quality for the occupants within. Green roofs and walls are highly recommended retrofit measures [57]. Aside from curbing emissions of greenhouse gases, it also reduces the urban heat effect and noise pollution [67]. Furthermore, high reflective double-glazed windows are also used for their soundproof, air-tight and safety qualities. Other alternatives include thermal window frames, which can prevent heat loss, thereby improving air conditioning efficiency. Generally, building envelopes should be supported by adequate HVAC measures for optimum IEQ [65]. Like HVAC systems, this measure is also expensive but can be subsidised by adequate governmental policies and promotions [58,64].

4.1.2. Lighting

Efficient lighting systems and their control mechanisms like motion and daylight sensors are the notable effective means of conserving energy in Shanghai. It includes energy-efficient fluorescent lamps, LED and electronic ballasts [59,60]. Most existing buildings in Shanghai are old and equipped with traditional lighting systems. Replacement of these traditional lighting systems with energy-efficient lighting systems should be the first step to green retrofit for this city [68]. This system is supported by adequate control lighting systems to check excess energy usage [70]. This building retrofit measure was estimated to be the second most applied measure for residential buildings in Shanghai with approximately 24% degree of application. However, it was the third most applied for office and other buildings (see Figure 8). The only impact of population increase on this measure would be increased space segmentation and subsequent increase in lighting facilities.

4.1.3. HVAC

Due to record peaking temperatures during summer, HVAC systems are considered to be the most energy demanding facilities in Shanghai [50,53]. Besides that, the associated increase in heat gain resulting from population increase necessitates an increase in space cooling demand. This finding explains the recent high growth rate in domestic air conditioning purchases by 21% of last year sales [72,73]. Installation of new and efficient air conditioning units, evaporative coolers and adequate ventilation measures will improve indoor air quality and temperature [57]. For this same reason, this technology is identified as the second and most influential building retrofit measure with 23% and 32% degree of application for office and other buildings (especially public buildings), respectively, as shown in Figure 8. Furthermore, the concept of free cooling from natural ventilation measures during cool weather was suggested to have an adverse effect on indoor air quality due to the humidity of Shanghai air [60]. Alternatively, it is suggested that the different building thermal mass and radiation absorptivity [61], as well as installation of micro combined heat and power (micro-CHP) systems, can also reduce building energy consumption in this city [64], although this measure is challenged by the high cost, poor quality and durability of the system [59,64].

4.1.4. Low-Carbon/Renewable Energies

Unlike the previously mentioned technologies, these retrofit technologies are classified under supply-side management (see Table 3). Solar/PV-assisted units and integrated wind turbines are the notable renewable energy systems retrofitted across all building types. They are speculated to account for about 10–15% of the retrofit measures across all buildings. Their energy-saving potential has been improved, especially when applied with given building insulations [57,63,66]. They have recently been adopted in Shanghai, but a great percentage of existing buildings are yet to implement these measures, the reason being that the associated costs are high costs with a long payback period. However, supporting policies and incentives can influence supply-side management in circumventing these setbacks [66]. Other notable low-carbon energy sources recommended for the city are gas boilers and heat pumps [68,70].

4.1.5. Sensors and Maintenance Measures

Sensors and control systems have been deemed resourceful for enhancing building energy performance [69,70]. They are classified under energy conservation management and include temperature and motion sensors. They aid in monitoring, detecting and regulating the operation of equipment to the desired set values, subsequently preventing excesses in energy consumption by the equipment [58]. Moreover, routine maintenance measures should be put in place to support these systems in order to reduce unnecessary risks resulting from their malfunction and/or failure [74]. This retrofit technology should be rated a top priority given the increasing population density in Shanghai. The rise in population density is expected to increase the frequency of usage of building facilities. Hence, if not properly monitored and maintained, can reduce the energy-saving potential of this measure significantly.

4.1.6. Energy Regeneration Systems for Lifts and Equipment

The use of energy regeneration systems can improve the energy efficiency of equipment by about 20–30% [69]. These systems include variable-frequency and variable-voltage drive systems. These systems can convert the mechanical energy of gravity-driven motors to electricity and can be applied to lift systems. Moreover, owing to the high population density and frequency of lift usage, a large amount of energy has been saved using this measure. Nonetheless, these systems should be adequately maintained for optimum performance. Figure 8 depicts that energy regeneration systems were mostly applied in office and other buildings.

Overall, the degree of impact of retrofit measures on energy-saving potential depends on the building-specific information [75,76] and, particularly, occupant behaviour [77]. Occupant behaviour and movement is a dominant element that affects the operation of all the retrofit measures mentioned above. Although occupant behaviour cannot be quantified like other retrofit measures, however, it has a significant impact on building energy consumption. Furthermore, this measure was suggested as the most significant element for defining the relationship between population variation and retrofit measures in dense cities like Shanghai.

In general, experts suggest that a "deep" or whole building retrofit, including all measures described in Table 3 would yield optimum energy-saving potential [78,79]. However, there are very few studies regarding "deep" or whole building retrofits in Shanghai. Hou et al. reported that 20% energy saving was achieved via deep building retrofit. 5–10% of the energy saved was due to management schemes. Cumulatively, 20–30% of the energy saved was due to lighting, air-conditioning, plugs, power and water heating, and 30–50% was attributed to the upgrade in envelope systems cumulatively [58]. Hence, cities with a high population should highly consider energy-conserving management a necessary retrofit measure.

4.2. Key Elements Affecting Building Retrofit Measures in Shanghai

There are key factors that are considered for a successful building retrofit package (see Figure 9). These factors have significant impact on building retrofit measures and include policies and regulations, retrofit technologies, client resources and expectations, human factors, building specific information and other uncertainty factors.

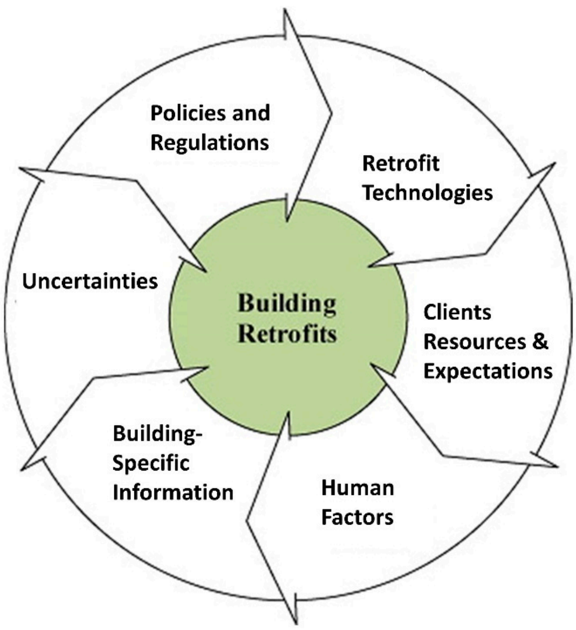

Figure 9. Key factors affecting building retrofit packages (adapted with permission from Ma et al. [16]).

4.2.1. Policies and Regulations

These are standards and principles set by the government to guide and manage decisions about building retrofit measures in order to achieve rational outcomes in building energy and environmental performance. In most jurisdictions, these policies and regulations are centred around energy efficiency obtainable by the retrofit package. Energy performance targets are set and monitored by the government. In some cases, the government may facilitate these policies by providing financial support to aid developers or building owners in realising the set outcome. The Ministry of Housing and Urban-Rural Development of China (MOHURD) summarised the standards for different buildings typologies in China [80]. Standards and regulations on building energy efficiency applied to buildings have aided in developing environment-friendly and more energy-saving buildings.

4.2.2. Retrofit Technologies

These are energy-conserving strategies adopted to stimulate the sustainability and energy efficiency of buildings [16]. They vary from the use of energy-efficient equipment, smart management and control systems and the integration of renewable energy sources to energy consumption changes. Based on their features, it is recommended that retrofit technologies are applied in the following trend: Payback period, efficiency, effectiveness and ease of implementation [81]. However, in line with their applicability, some concerns need to be considered, as an appropriate decision towards the selection of retrofit technologies is subjected to these concerns:

- *Specific retrofit technology.* Building characteristics were estimated to determine a buildings energy usage by 42% [82]. However, every building is unique and has specific characteristics depending on the building type. Consequently, building retrofit technologies used in one building may not have the same contributive impact on another building.
- *Integration of retrofit technologies.* Second to the definition of building type and the associated energy consumption, it is paramount to define the necessary measures required to conserve energy in these buildings. In most cases, the recommended optimum building retrofit measures are multiple ECMs. However, the benefits obtained from this is not equal to the sum of the individualistic measures [83], the reason being that the performance of multiple ECMs is subject to the integrative nature and interactions between ECMs and the building subsystem [84].
- *Selection of retrofit technologies.* This issue is a multi-objective optimisation problem, which tends to define the synergetic performance of various combinations of ECMs. In the selection process, a variety of proposed measures are assessed based on energy, environmental, social and financial targets to ensure retrofit maximisation [85,86]. The weighting factor assignments and criteria selection are essential determinants in devising the optimum retrofit package for each building type [16].
- *Intricacies of optimisation problems.* To best define a suitable retrofit package for a building or type of buildings, optimisation of the synergy of various ECMs is necessary. The optimisation of ECMs can be achieved either via a model-free (expert system) or model-based (requiring energy simulation tools) approach. In both approaches, the knowledge database and access to it are essential. Absence of this is likely to introduce significant errors in optimisation estimations [87]. Moreover, the integration of both approaches will promote an adaptive and well-suited model for any given building type [88,89]. Notable optimisation packages include generic algorithm (GA), simulated annealing (SA) and branch and bound (B&B) [16,61].

4.2.3. Client Resources and Expectations

This factor is another critical element for a successful building retrofit measure. However, it is subject to the client's exposure and knowledge of retrofit technologies. These technologies are quite sophisticated and are crucial in deciding the suitable technology to invest in. Also, it has been reported that the technology payback period was the most considered factor in determining clients' investment plan [90]. Moreover, the impact of technology on energy savings also influences client investment decisions. Clients are more likely to invest in technologies with higher energy savings potential as this is tantamount to saving costs and abiding to set standards and regulations. Nonetheless, high energy savings demands some level of cost invested in it. Alajmi [91] estimated that ECMs with little or no cost will save 6.5% of a building's annual energy consumption. The conservative opportunities include non-retrofitting measures like operational schedules. On the other hand, ECMs with high costs were able to save 49.3% of building annual energy consumption [91].

4.2.4. Human Factors

Human factors are added imperative components that should be considered for an adequate building retrofit measure. This includes schedules (occupancy, maintenance and management), comfort needs, activity and access to controls [81]. Changes in this factor will lead to changes in the energy use of buildings. Guerra et al. [82] estimated that occupant characteristics accounted for 4.2% of building energy use. Results from other studies have collaborated this finding, stating that changes in occupant behaviour, control and comfort range can significantly alter energy consumption [92,93]. The merit of this factor is that it involves little or no capital cost.

4.2.5. Building-Specific Information

In addition to the above factors, the availability and access to building information also affect the success of building retrofit measures. Building typologies, age, orientation, energy sources and building fabric and envelope structures are the vital information required for retrofit packages. A summary of building typology can be obtained from the National Standard of China Design Code for Buildings [80]. The office building has the largest share in terms of building area and energy consumption among building types. Regarding age, most of the buildings in Shanghai date back to before 1950 [47] and therefore require adequate retrofit measures. However, adequate records are required to identify such buildings. Other notable information required for a successful building retrofit package are scheduling (occupancy, maintenance and operation), the services system and utility rate structure [16]. Interaction of this information will aid in providing an optimal retrofit package for any building type.

4.2.6. Uncertainties

Apart from these elaborated determinants, some uncertain factors also affect the application of building retrofit measures. Such uncertainties include climate change, policy change and occupant behaviour change. Also, given the high interaction between building subsystems, individual retrofit measures may have a significant impact on each other. This interaction, indicative of the complexity of retrofit measures, tends to generate a degree of uncertainty in analysing the performance of the retrofit measures. Furthermore, different simulation tools have different prediction reliabilities and uncertainties due to inherent design assumptions. Consequently, the use of these tools for analysing retrofit performance also introduce some level of uncertainty [16]. Hence, a clear distinction and measurement of these uncertainties is appropriate when designing the best suitable retrofit for individual building types.

5. Methodical Approach for Evaluating Sustainable Retrofit Packages for Building Performance Enhancement

This section addresses the critical criteria to consider for identifying, evaluating and implementing the most suitable retrofit options for particular building types [16].

5.1. Methodical Approach for Building Retrofit Measures

Sustainable building retrofit measures are considered as an essential means of attaining green buildings for sustainable development of cities. Therefore, it is necessary to develop a systematic means of identifying retrofit options suitable for particular building types within a specific location.

Furthermore, evaluating and implementing these options are also crucial and should be included in the methodical approach. A general algorithm suggested for Shanghai is shown in Figure 10, and it incorporates all factors discussed earlier, as well as a cost-benefit analysis and risk assessment.

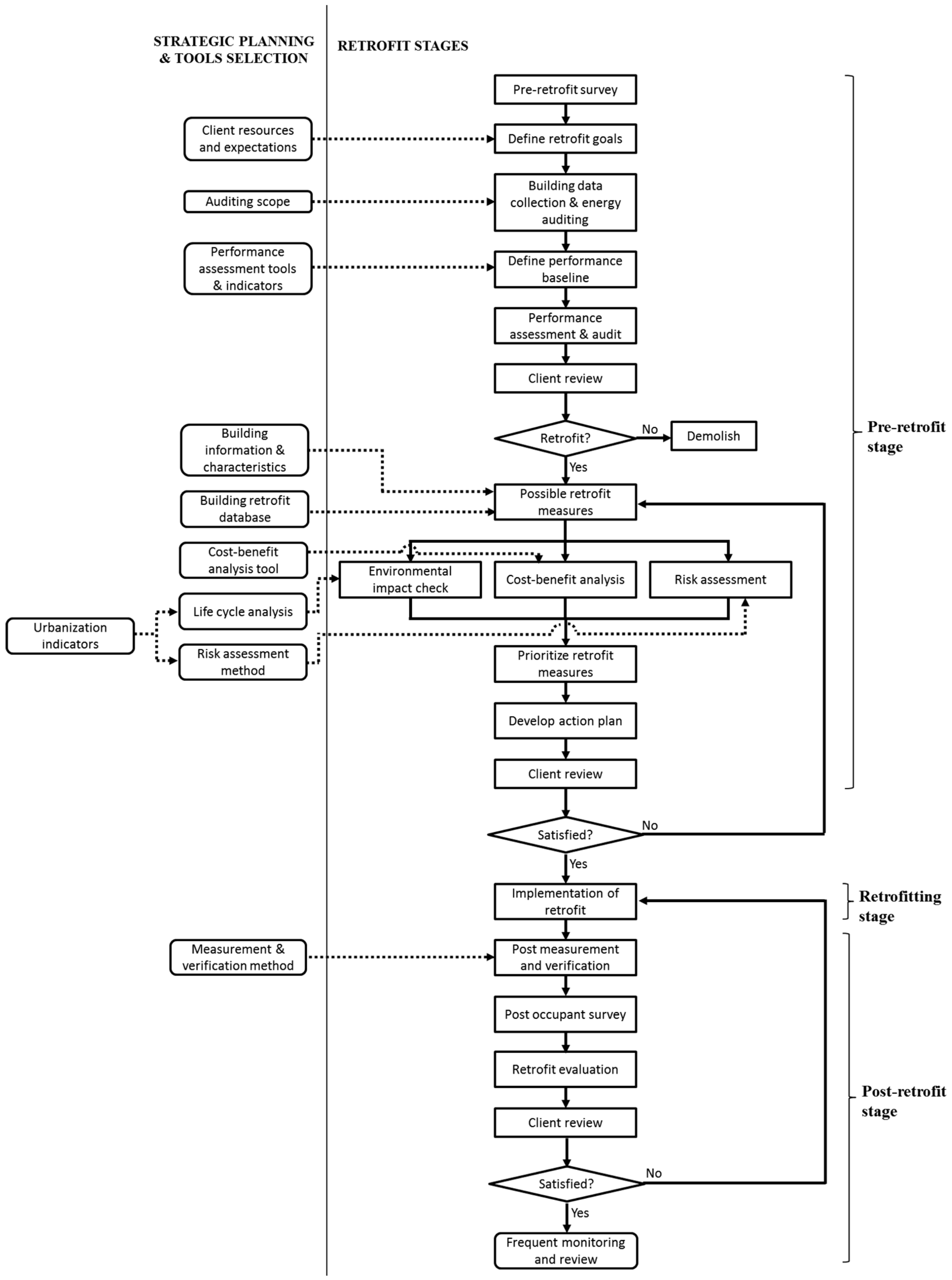

Figure 10. Methodical algorithm for green building retrofit measures [modified from Ma, Cooper [16]].

The algorithm presents two major stages. The first stage, known as the pre-retrofit stage involves the planning and selection of model tools to specify essential information and resources for retrofitting. Essential information can also be obtained from surrogate databases, surveys and measurements. The later stage is known as the post-retrofit stage. It includes the major retrofit processes, in addition to regular operation monitoring and management data review.

5.2. Energy Audit

An energy audit is the assessment of energy use within a defined area [16]. This facilitates the establishment of energy usage and costs, from which retrofit measures can be implemented and reviewed. Moreover, after the selection of suitable retrofit measures, an energy audit is required to filter the measures based on their energy demand and cost in a defined location. It helps in estimating energy saving potential and is a prerequisite for building performance assessment. There are several energy audits, depending on the location. In the US and Australia, the adopted energy standards are ASHRAE and AS/NZS 3598:2000, respectively. In China, the Ministry of Construction (MOC) instigated a building energy efficiency standard in 1993. However, this standard was not rigid enough and was revised in 2005 and 2015 by MOHURD [94]. The Chinese energy audit is still subject to improvement and requires updates to promote improvement in building energy performance. Subsequently, it will aid in a better comparison of potential retrofit options. To accurately predict the energy performance of retrofit measures, simulation model parameters need to be calibrated using energy audit data [95]. Energy data can be collected from automation systems, building energy management and control systems.

5.3. Certification of Building Performance

Buildings are known to degrade over time. Faults and malfunctions emanate during their life span, leading to performance degradations. The deterioration of buildings results in a reduction in energy efficiency. An estimated reduction of 2–11% in energy efficiency is likely for commercial buildings in the US as a result of deterioration [16]. In order to circumvent this, it is essential to assess building performance regularly and establish a means of preventing further deterioration. The purported prevention of deterioration justifies the relevance of this approach for sustainable building development. Basic tools for building assessment include Leadership in Energy and Environmental Design (LEED), E-top, Green Star and Building Research Establishment Environmental Assessment Method (BREEAM). They provide guidelines for building performance evaluation based on format, structure, criteria and scope. Set performance indicators (PIs) serve as benchmarks for the assessed buildings. Based on the differences between the assessed building PIs and the target PIs, building performances can be rated. A review of various assessment and diagnostic tools can be found in Reed et al. [96]. Basic criteria for selecting a suitable assessment method and the diagnostic tool include retrofit purpose, the experience of energy supply companies and occupancy requirements [16].

5.4. Evaluating Energy Conserving and Environmental Benefits

The energy benefits of each retrofit measure are quite valuable in pre-selecting a suitable measure of enhancing building performance. The pre-selection process is mostly conducted with the aid of suitable simulation or modelling tools, such as EnergyPlus [59,62], DOE [60] and TRNSYS [63]. EnergyPlus was adopted to simulate the energy performance of PV panels and solar water heaters in a residential building in Shanghai [66]. Similarly, Pan et al. [59] used the software to assess the energy-saving potentials of shopping malls and hotels in Shanghai. TRNSYS was used to investigate the energy savings of retrofit measures in residential buildings in 26 cities in China, including Shanghai [63]. Another alternative for simulating building energy performance is building information modelling (BIM), which was used by Li et al. [57] to simulate energy and environmental benefits of a green e-park in the Yangpu district of Shanghai. Ecotect Analysis 2011 used to assess both energy and environmental performance of residential buildings in Chongming eco-island, in Shanghai [66]. In general, there are numerous modelling tools for building energy evaluation; however, they have different uncertainties. Hence, prior knowledge of each tool's uncertainties is necessary for deciding the appropriate energy simulation tool. In most instances, these tools cannot inculcate the impact of population rise in the building energy assessment. As a result, the Urban Modelling interface (UMI) that can account for mutual shading, and the Urban Weather Generator (UWG) used for generating microclimate data based on geometric measures and urban planning, can be used to simulate the urbanisation effect on evaluating building energy and environmental benefits [67].

5.5. Economic Analysis

Another important systematic tool for evaluating building sustainability is cost analysis. The analysis usually involves a trade-off between cost investment and benefits [70]. Economic analysis is a means of financial evaluation to compare the various retrofit alternatives. A variety of tools can be used for this purpose. They include the internal rate of return (IRR), net present value (NPV), benefit-cost ratio (BCR) and simple/discounted payback period (SPP or DPP). Life cycle costing (LCC) is also another alternative for assessing the cost-effectiveness of a variety of retrofit measures. Economic analysis plays a major role as a decision-making tool for probable investments in proposed retrofit measures [64,70].

5.6. Risk Assessment

This approach provides necessary information about the inherent risks associated with each retrofit measure. As aforementioned, each retrofit measure has an element of uncertainty like system failures, measurement uncertainties, classification of behavioural patterns and weather forecasts. Each level of uncertainty is associated with a degree of risk, evocative of necessary assessment. This assessment will provide decision-makers with some confidence level in deciding suitable retrofit measures. Notable risk assessment methods include the Monte Carlo simulation, discount rate analysis [70], expected value analysis [69] and sensitivity analysis using support vector regression (SVR) [62]. Associated with urban sprawl is an increase in population density, as witnessed in cities like Shanghai. Consequently, the workload on most building facilities will increase, which is tantamount to increased risk probability. Hence, the effect of population rise must be accounted for in the risk assessment, as indicated in Figure 10.

6. Common Challenges for Building Retrofit Measures in Shanghai

Presently, many technological and economic obstacles affect the implementation of sustainable building retrofit measures in Shanghai and other major cities in China. Using descriptors from the literature [97–100] and a survey conducted within the city from 138 participants, there are five main challenges to building retrofit development in Shanghai. The survey involved an on-site data collection for green retrofitting packages for buildings in Shanghai and was conducted from November to December 2018. 30% of the feedback were from experts in building construction and retrofitting, while the rest are individuals that have had building retrofit experience.

Figure 11 presents the breakdown of the five major barriers identified by the survey respondents towards building retrofit measures. For this particular question, participants were made to choose from a list of selected and defined literature-based challenges (resistance to change, client's resources and expectations, availability of funds, policies and regulations, human factors, access to building specific information, lack of comprehensive building information, available technology and quality of technology). Also, space was provided for participants to describe other barriers not included in the listed ones, to which the number of buildings and home appliances, among others, were suggested. Based on the result, there was no significant distinction between the five challenges for the "very challenging" feedback (indicated by red lines). However, "extremely challenging" feedback displayed a notable distinction between the considered challenges. Here, the challenges are discussed using insights from the reviewed literature.

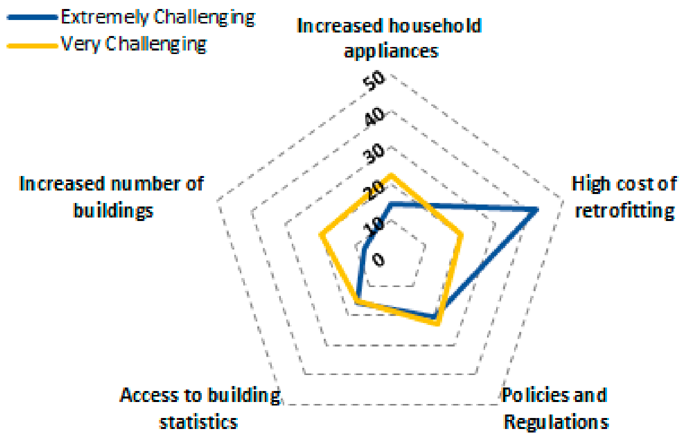

Figure 11. Common challenges (%) affecting building retrofit measures in Shanghai.

6.1. Financial Barriers

Most retrofit strategies imply that retrofit projects are cost-effective with high return rates. Nonetheless, numerous projects are unexecuted owing to a lack of funds given the high cost of retrofitting. An estimated 15 billion m^2 of urban existing buildings are deemed retrofittable for improved energy performance. Retrofitting these buildings costs approximately 2000 billion RMB at a rate of about 100–300 RMB/m^2 depending on the building type [98]. This challenge was ranked as the most challenging and accounted for about 42% of the survey. Besides this, the owners of the buildings may not have enough capital to finance retrofitting strategies [69]. Also, most owners are unwilling to invest in a short term retrofit project with long term benefit [101]. The savings from retrofit measures are quite small compared to the benefits of other economic investments [58]. Additionally, uncertainties over financial gain is also a significant deterrent for most building owners to invest in retrofit projects. The expected benefits from retrofits differ from the predicted due to uncertainties in parametric assumptions made during retrofit design, construction and operation [5,69,70]. However, if the government establishes policies that promote sustainability, this can produce a long-term positive impact on building owners' inclination towards retrofit projects.

6.2. Lack of Standards and Regulatory Support

The unavailability of standards and regulatory support is considered the second most challenging factor, with 20% of survey feedback agreeing. Standards and regulations on building energy efficiency have aided in the development of environment-friendly and energy-saving buildings, as documented from the 1980s and most updated in 2015 [102]. In 2016, the government published a more comprehensive document with new standards and regulations for different building types [80]. However, before this year, it was impossible to assess and validate building retrofit measures in existing building types in China. Furthermore, the uncoordinated/unavailable regulatory support has acerbated the application of building retrofit measures in this city.

As a policy decision-maker, adequate measures to optimise the effectiveness and efficiency of policies at low cost should be championed. Presently, energy-efficient retrofit initiatives are limited due to low government fiscal budget for this sector [58,94]. Also, the difficulty of controlling building retrofit quality is another major issue under standards and regulations. There is a lack of structured quality management system due to different policies from different governmental departments like Housing and Urban-Rural Development (MOHURD), Development and Reform Commission (DRC), Government Offices Administration (GOA) and Ministry of Construction (MOC) [94]. Consequently, the integration of policies from various tiers of government should be encouraged. By so doing, dependable policies would be designed to stimulate the most appropriate policy tool to attaining optimum building energy savings [103]. For example, "administrative policies for government-owned office buildings, fiscal subsidies for private-owned commercial buildings and a combination of these two for public buildings" [58].

Furthermore, policymakers should consider market-oriented mechanisms in addition to local fiscal capacity and economic conditions in crafting policies. The mechanism will aid promote sustainable market cultivation in the long run as well as maintaining a healthy retrofit market, operation and control. In terms of technical solutions, incentive policy should be directed and well defined for building envelopes/insulation in different climate zones in order to enhance its retrofit economy. On the other hand, the limited subsidy should be channelled towards measures involving the retrofit of lighting systems, improving the human factor, operation management and optimization [58].

Besides that, policies should be promulgated to promote sustainable business models for the Building Energy Efficiency Retrofit (BEER) market [58,69]. Plans should be put in place for futuristic subsidies to lessen payback periods and subsequently attract ECMs. Moreover, government-owned buildings need measures to reduce institutional obstacles to facilitate the implementation of sustainable business models. In order to overcome such obstacles, coordinated and refined standards and regulations across the different governmental departments should be promoted.

6.3. Lack of Comprehensive Building Statistics

The availability of existing building information provides the planning foundation for sustainable building retrofit measures. However, the Chinese National Bureau of Statistics does not possess either statistical classifications for buildings nor their fundamental data detailing the existing building types and their building energy consumption annually. Before 2016, this information was not easily accessible in China and posed a significant challenge towards building retrofit measures. Also, the lack of comprehensive data on implemented retrofit measures, their impact and the associated cost have deterred building owners towards investing in retrofit projects. Consequently, decision-makers are devoid of adequate information on most building types, adopted energy systems, implemented retrofit projects and associated energy consumption, environmental and economic implications and its trend. An estimated 16% of the survey highlighted this factor as posing an extreme challenge to implementing retrofit measures.

6.4. Increased Number of Buildings

As aforementioned, the rapid urbanisation in Shanghai has led to an exponential increase in urban buildings. Consequently, an estimated 70–80 million m^2 of inefficient buildings were erected each year in China before 2015 due to rapid urban development [46]. According to the Shanghai statistical yearbook, urban residents have increased from 58% in 1978 to about 90% in 2016 [35]. Similarly, the building construction area of the city has risen from 19 million m^2 in 2000 to more than 74 million m^2 in 2016 [104]. Without the availability of appropriate energy-saving measures and management, these buildings consume an enormous amount of energy annually.

Coupled with the increase in building density, the urban form and distance between the buildings are speculated to induce the UHI effect [13]. Hence, designing sustainable building retrofit measures should incorporate the UHI index and other urbanisation indicators. However, until this very day, there has been no detailed approach for determining these measures based on both external climate variation and urbanisation indices. Furthermore, the lack of accurate building statistics has made the potential identification of the most suitable retrofit package for this city more challenging. This factor was considered to pose the lowest challenge among the considered challenges.

6.5. Increased Household Appliances

In addition to the increase in the number of buildings, rapid urbanisation also resulted in a commensurated increase in the number of energy-consuming household devices. Also, the lack of available information to the general public regarding the efficiency of these devices can deter the performance evaluation of these devices. Moreover, the absence of statistical data regarding these appliances makes it difficult to quantify or monitor the incremental energy consumption resulting from their usage. For example, it was reported that the annual purchase of air-conditioning units increased by 20% [47]. This increase will significantly contribute to building energy consumption, but the extent of contribution is unquantified due to lack of available information.

Aside from those mentioned above, other notable challenges include behavioural trends like resistance to change, which is exacerbated by occupancy's unwillingness to learn and invest due to several respective barriers. Yohanis [93] reported that 65–80% of householders were unwilling to invest in energy savings measures, and the few householders willing to invest have identified cost to be a key barrier.

7. Conclusions

This article presents a brief overview of recent studies on building retrofit measures and their application on a variety of different building types in Shanghai. It identifies key elements needed for developing sustainable buildings in this region. Furthermore, the review elucidates a basic systematic approach for appraising sustainable retrofit packages in addition to plausible challenges facing these measures. Based on this study, the following conclusions are deduced:

1. Shanghai is characterised by rapid urban development. However, there are limited research studies on the building retrofit measures for the large proportion of existing buildings.
2. The limited previous studies have demonstrated that the most applied building retrofit measures are upgrades in the building envelope, HVAC and lighting systems. In some cases, these measures are supported by PV systems. The degree of application of each measure varied with the building typologies. Based on their degree of application, the measures followed the particular order: Building envelope > HVAC > lighting for office buildings; building envelope > lighting > HVAC for residential buildings; and HVAC > building envelope > lighting for other buildings.
3. Key elements identified to affect building retrofit measures include policies and regulations, retrofit technologies, client resources and expectations, human factors, building specific information and other uncertainty factors. Lack of most of these promoting factors contributed to key barriers facing the retrofit measures, among which financial barriers and lack of policies and regulatory support are considered as the most challenging.
4. Appropriate selection criteria and weighting factor assignments are necessary in determining the optimum retrofit solution for buildings. These criteria should include comprehensive energy simulation and audit, risk assessment, environmental and economic analysis.

Also, the following remarks and recommendations are suggested in the line of future studies:

1. Studies posit that appropriate retrofits for individual buildings can improve the energy and environmental performance of existing buildings. An optimum improvement of building energy-saving potential requires a whole ("deep") building retrofit. Nonetheless, extensive studies on economic evaluation and risk assessment in this regard are needed.
2. Based on limited publication, extensive studies on the evaluation of building retrofit measures that include the UHI index and other urbanisation indicators in Shanghai should be considered. These studies will be valuable for designing sustainable buildings in rapidly expanding cities like Shanghai.
3. This study also recommends that more practical experimentation should be included to augment and increase the confidence level of model-based results. Most retrofit studies adopted the model-based approach to determine and evaluate retrofit options. Estimated energy conservation/efficiency may differ from actual measurements. In addition, human factors have been shown to affect building energy usage due to the rise in population density. Hence, a comprehensive study to investigate the impact of this factor on building retrofit measures is needed.
4. The nascent nature of building retrofit measures in Shanghai demands an adaptive retrofit package, which can be achieved by designing a whole energy–cyber–physical system (eCPS)

promoted by fully-integrated hybridisation of the embedded building equipment, computational tools, sensing and control mechanisms and physical network with real-time communication via digital signals and information processing algorithms.

In summary, China, in particular Shanghai, still has a long way to go in building retrofit measures; promoting and implementing necessary policies and regulations in this regard; and establishing maintenance and management methods to ensure existing buildings are energy-efficient and environment-friendly. In the quest to attain this, this study will provide the essential guide of recent measures and approaches to achieving this feat. This study can also be applied to highly urbanising cities with similar climate complexity as Shanghai.

Author Contributions: W.D. conceived and designed the research analysis, contributed data and revised the paper. Y.H. contributed in the designing the research analysis and partook in data collation and processing, performed the analysis, and wrote the paper. C.I.E. partook in the data collation and processing, performed the analysis and wrote the paper. S.-H.H. contributed in the design of the research analysis and paper revision. Z.P. contributed data and revised the paper.

Funding: This research was funded by Shanghai Daren Construction Engineering Co. Ltd.

Acknowledgments: The authors will like to appreciate the support and data shared from the Research Department of the Shanghai Daren Construction Engineering Co. Ltd.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

B&B	Branch and Bound
BCR	Benefit-Cost Ratio
BEER	Building Energy Efficiency Retrofit
BREEAM	Building Research Establishment Environmental Assessment Method
CO2	Carbon dioxide
DPP	Discounted Payback Period
ECMs	Energy Conservative Measures
EUI	Energy User Intensity
GA	Genetic Algorithm
GHG	Greenhouse Gas
HSCW	Hot-Summer-Cold-Winter
HSWW	Hot-Summer-Warm-Winter
HVAC	Heating, ventilation and cooling
IEQ	Indoor Environmental Quality
IRR	Internal Rate of Return
LEED	Leadership in Energy and Environmental Design
LPG	Liquefied petroleum gas
MOC	Ministry of Construction China
MOHURD	Ministry of Housing and Urban-Rural Development of China
NC	North-Central
NE	North-East
NPV	Net Present Value
NW	North-West
PIs	Performance Indicators
SA	Simulated Annealing
SCE	Standard Coal Equivalent
SE	South-East
SPP	Simple Payback Period
SW	South West
TCE	Tons of Coal Equivalent
UHI	Urban Heat Island

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