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Review of low-carbon refurbishment solutions for residential buildings with particular reference to multi-story buildings in Hong Kong

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ABSTRACT

As the second largest GHG emitter in the world, the building sector needs to play an active role in reducing GHG emissions. Particular attention should be directed to existing buildings, not only because of the amount of emissions caused by inefficient buildings but also due to the existence of a variety of sustainable refurbishment solutions for different levels and stages of building refurbishment. The emission reduction performance of different sustainable refurbishment options, however, varies enormously as a result of different building design conditions. Cooling, for example, is a much more important consideration than heating in warmer climates. For high-rise multi-story existing buildings, due to the complexity of the occupant mix and their emission reduction goals, more attention should be paid to reducing the energy consumption of common areas and increasing the energy performance of the building envelope. This paper provides a comprehensive literature review of the nature and assessment of existing sustainable refurbishment options for residential buildings in sub-tropical high-density cities such as Hong Kong. The paper will also help policy and decision-makers delineate a set of sustainable refurbishment solutions that are suitable for multi-story buildings to maximize the opportunity for reducing their emissions.

Keywords: Low-carbon; Refurbishment options; Residential buildings; Multi-story

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1. Introduction

The commonly known definition of *sustainable development* was made by the World Commission of Environment and Development in 1987, calling for development "that meets the needs of the present without compromising the ability of future generations to meet their own needs". This statement brought about the need for integrated decision making that would be able to balance human economic and social demands with the regenerative capacity of the natural environment [1]. A broader terminology was put forward to encompass the economic, social and environmental principles of the "triple bottom line" [2].

Each of the three components is given equal attention in considering sustainable development. The *economic principle* is to increase people's income over time without threatening the regeneration of nature [3]. This approach calls for careful economic analysis of the costs and benefits of developmental and environmental policies that will strengthen environmental protection and improve the level of social welfare [4]. The *social principle* refers to the harmony of social and cultural systems. For instance, more benefits should be directed to the poor, including increases in the provision of food, real income, education, health care and water supply, none of which are entirely equivalent to economic growth [5]. In addition, it also requires businesses to contribute to economic development while enhancing the living standard of the workforce and the families involved, which is considered a corporate social responsibility [6]. The *environmental principle* aims at maintaining essential ecological processes and life support systems, preserving genetic diversity, and utilizing the species and ecosystems in a sustainable manner [7]. Examples of efforts to promote this principle include the Montreal Protocol, designed to enable a significant reduction in recognized ozone depletion substances [8], the Kyoto Protocol to mitigate carbon emissions [9], and the Harbor Effluent Export Scheme implemented by the Hong Kong government to control the impact of algal blooms. Sustainable development involves the mutual interaction of all three components.

The building sector is responsible for 40% of energy consumption and 30% of GHG emissions worldwide [10]. Taking into account the massive growth of new construction and the great number of inefficient existing buildings, carbon emissions from the building sector are expected to more than double in the next 15 years if the 'business-as-usual' scenario continues [10]. In developed countries and regions such as the UK and Hong Kong, the ratio of new buildings to old is lower than 4% each year [11,12]. The existence of a huge number of inefficient existing buildings compound the GHG emissions of a city, making efforts to mitigate the carbon intensity of existing buildings indispensable [13].

Considerable experience of sustainable refurbishment has been accumulated around the world as it is considered to be essential in reducing the amount of GHGs emitted by existing buildings [14,15,16], and a great number of sustainable refurbishment approaches have been developed for both residential buildings [17,18,19] and non-residential buildings [20,21,22].

The quantification of emission reductions resulting from these approaches remains an area of interest for research scientists [23,24,25] and provides support for studies of decision making for sustainable refurbishment (e.g. Jaggs & Palmer [26] and PRUPIM Developments [27]). However, as most research into sustainable refurbishment has been conducted in North American / European countries, the distinctive climatic features and building characteristics of those areas may render such approaches unsuitable or ineffective for application in such high-density subtropical cities as Hong Kong [28]. It is, therefore, important to understand the suitability and emission reduction performance of various sustainable refurbishment options in reference to the local situation.

Until now, many research projects in Hong Kong have been directed towards enhancing the energy efficiency of offices and commercial buildings. Examples of these include studies of the optimal control of building HVAC systems [29,30], fault detection and diagnosis strategy for HVAC systems [31,32], demand control ventilation strategies [33], summaries of energy saving measures [34,35] and the shading effects of buildings [36]. The better known explorations of suitable approaches to lower the energy consumption of residential building stocks remain relatively sparse, however, and mainly focus on the improvement of insulation [37], glazing systems [38,39] and air-conditioning [40,41].

In response, the objectives of this paper are (i) to provide a comprehensive review of the most suitable existing sustainable refurbishment options for residential buildings in subtropical regions; and (ii) to understand their suitability for high-rise multi-story buildings with multiple occupants such as occur in Hong Kong. A list of 88 sustainable refurbishment approaches is identified, of which 39 are considered relevant to Hong Kong's climate and building characteristics. The solutions are further classified according to three levels of scale of refurbishment together with the detailed practical implications for Hong Kong and other similar situated cities.

2. Building life cycle GHG emissions

The carbon footprint refers to the total GHG emission produced directly and indirectly by an individual, organization, event or product expressed in the form of carbon dioxide equivalent (CO_2e) [42]. CO_2e is calculated by multiplying the emissions of each of the six GHGs by their 100-year global warming potential, as defined by the IPCC [43]. According to Carbon Trust [42], the carbon footprint can be measured based on either organization or product. An organizational carbon footprint measures the GHG emissions caused by all the activities of an organization, including energy consumption in buildings, operational processes and transportation, while a product carbon footprint measures the GHG emissions across the life of a product, from raw material and manufacturing through consumption and demolition [42].

While numerous studies have explored the life cycle carbon emission and energy consumption of commercial buildings [44,45,46,47], few focus on the residential sector. Examples of such studies include the life cycle energy consumption of single dwellings in Sweden [48] and the embodied energy in building materials over the whole life of high-rise residential blocks in Hong Kong [45].

Despite the difference in building types, the life cycle carbon emissions of a building are commonly divided into four phases: initial emission, operational emission, renovation emission and demolition emission [44]. The sources of GHG emissions in each phase of a building's life cycle and their estimated proportion are shown in Table 1. As can be seen, the building's operational phase is the major source of life cycle GHG emissions (60-90%), followed by the initial phase (10-40%), which includes emissions from materials, transportation and the construction process itself. The GHGs emitted in the renovation and demolition stages are relatively minor.

Thus, energy performance during the operational stage plays the essential role in the life cycle emissions of a building. As the amounts of GHG emissions vary significantly (from 60% to 90%) and the degradation of energy efficiency tends to be inevitable in the operational stage of buildings, there is great potential for emission reduction through refurbishing existing buildings in a sustainable manner. However, although renovation accounts for a minor proportion of GHG emissions (10%), little is known of the relationship between the emission level in the renovation stage and that in the operation stage.

Table 1

Source and estimated proportion of GHG emissions in different phases of buildings' life cycle [44,45,48,49]

Phase of building life cycle	Source of emission	Estimated proportion of total GHG emission
Initial	Manufacturing Transportation Construction process	10-40%
Operation	Daily operation	60-90%
Renovation	Materials Process of renovation	0-10%
Demolition	Demolition activities Landfill	0-10%

3. Sustainable refurbishment

According to the Oxford Dictionary (1995), to “refurbish” is defined as to “renovate and redecorate (something, especially a building)”. Definitions that are more detailed have been given by professional groups for major and minor refurbishments. For instance, the Building Research Establishment [50] defines a major refurbishment project as an activity that results in the provision, extension or alteration of thermal components and/or building services and fittings, these components including: (1) thermal elements such as walls, roofs and floors; (2) fittings such as windows and entrance doors; and (3) building services like lighting [51], heating and cooling, and the operation of pumps. Similarly, the U.S. Green Building Council (2012) defines major refurbishment as consisting of the significant modification and internal rehabilitation of HVAC.

These descriptions indicate that the scope of the involved elements plays an important role in defining different refurbishment projects, as this dictates the type of assessment methodology to be used [11]. Moran et al. [52] have developed a four-level classification of refurbishment comprising

(1) *Light touch:* repair and upgrade minor elements of the building;
(2) *Medium intervention:* replace building services in part of the building;
(3) *Extensive intervention:* replace building services and make some fabric changes; and
(4) *Comprehensive refurbishment:* which covers the scope of Levels 1 to 3 and includes development opportunities outside the building.

In assessing the building’s condition and performance, Shah [11] has established four levels of refurbishment similar to those given above, adding demolition as a fifth level.

These studies reveal the scale of altered components to be a key concern in identifying different levels of refurbishment. However, other factors, such as intervention of the occupants, building age and financial benefits of refurbishment need to be considered [11,52]. It should be noted that these levels are accumulative, with the higher levels of refurbishment encompassing the scope of the lower ones.

With increasing attention on excessive GHG emissions from the building sector, considerable research has been conducted worldwide into sustainable refurbishment. The methodology of sustainable refurbishment has been intensively studied throughout the process of refurbishment projects. Examples of these include studies of building energy audits and surveys [26,53], building performance assessment and diagnostics [54,55], quantification of buildings’ energy conservation [18,56], as well as economic analyses [57,58], risk assessment [59], key performance indicators [60], and the measurement and verification of energy savings [61,62]. Many sustainable refurbishment techniques have been developed to provide options for the refurbishment of residential buildings [17,63], commercial buildings [20,21] and other types of buildings [53]. The establishment of a decision support model has also been considered, including the issues involved in assisting building owners and occupants select the best solutions for sustainable refurbishment by optimizing the outcomes of economic, environmental, human comfort and other benefits [64,65].

In Hong Kong, the Building Environmental Assessment Method (HK-BEAM) has been developed to assess the environmental performance of existing buildings as well as that of new buildings. Of the various environmental criteria defined in the HK-BEAM, building energy performance is one of the key concerns in the evaluation process, accounting for a significant portion of overall assessment results [66,67]. Several studies have been conducted to enhance the effectiveness of the building energy criteria in order to facilitate greater energy conservation [68,69]. These efforts can encourage the initiation of sustainable refurbishment by providing guidelines and incentives for improving the energy efficiency of existing buildings [70]. In addition, suitable approaches for lowering operational energy consumption have been explored, such as installing wall insulation [37], improving window glazing systems [38,39] and enhancing the performance of air-conditioners [40,41]. Other research in Hong Kong, including the energy audit of existing buildings [34,35], surveys of energy end-use and building characteristics [71] and building energy models [72,73], forms a solid basis for the assessment of energy savings as a result of sustainable refurbishment.

The differences between domestic and non-domestic buildings, such as occupancy characteristics, building service devices, ownership, etc., are frequently emphasized by researchers in distinguishing between refurbishment approaches. Many studies have focused on the refurbishment of domestic buildings, e.g. Thorpe [18], Burton [74] and Hakkinen et al. [23]; while the renovation of non-residential buildings has also been an area of interest to research scientists [20,21]. Hence, suitability for residential use plays an important role in identifying applicable refurbishment initiatives.

According to Bojic et al. [37,39] and Tso & Yau [75], the high demand for housing due to intensive population and the use of air-conditioners during the long summer periods are the two fundamental causes of high and increasing electricity consumption of residential buildings in Hong Kong. High population density and a limited habitable land area lead to high land values, thus promoting the development of high-rise residential buildings [76]. As a result, over 90% of the population lives in high-rise apartment buildings, usually of 10 to 30 storys [28,36]. This characteristic has become an essential consideration in research into the residential sector, and studies have been made on the use of daylight [77], remote sources of lighting [76], potential for applying thermal insulation [37,39] and especially on the simulation of overall building energy performance [71,73].

Previous research shows that space cooling is needed for seven months a year by Hong Kong's residential buildings, and this has become the dominant energy end-use in the residential building sector [78,79]. Moreover, according to a survey of local electricity end-use, approximately 90% of residential units have air-conditioners installed, with an average number of installations per unit being about two; while the use of space heating devices is quite rare in apartments [71]. To reflect actual building energy performance better, therefore, it is important that attention be paid to space cooling rather than to space heating in the study of local sustainable refurbishment.

Although many other factors that influence the energy end-use in local apartments, such as floor area, number of household members, housing type, etc. [75], have been considered, these have seldom been regarded as major characteristics in previous research into the renovation of residential buildings. However, three distinctive features are identified in the following as important bases for exploring suitable approaches for sustainable refurbishment, namely: suitability for residential usage, relevancy for high-rise building and pattern of energy consumption.

With increasing attention being paid to energy performance in the residential sector, some pilot studies have been conducted, e.g. EST [63], CPA [17], Thorpe [18], Burton [74] and Hakkinen et al. [23]. However, sustainable refurbishment solutions for non-residential buildings also remain an area of interest [20,21]. Others, such as Clark [80] and Xing et al. [81], have investigated sustainable refurbishment strategies for both residential and non-residential sectors. These, together with useful findings concerning sustainable refurbishment [11], relevant guidelines [13,82,83] and the tools / frameworks for sustainable decision-making [27,84], provide a solid basis for compiling a set of sustainable refurbishment methods. However, as these existing sustainable refurbishment approaches have been developed for specific contexts (e.g. EST [63] and CPA [17] focus on building in West European countries, Burton [74] was mainly based on single or multi-family dwellings, Baker [20] studies non-residential buildings, etc.), it is important to consider their relevance for the local scenario, including its climatic features and building characteristics.

4. Assessment of carbon emission reduction in sustainable refurbishment

Although the concept of a building's life cycle emissions has been widely recognized, it is not frequently applied in the study of sustainable refurbishment [85]. Even though life cycle assessment (LCA) may be adopted to determine the possibilities for emission reduction, the boundaries of assessment and the types of renovation approaches vary in different studies. Hence, previous studies are summarized and compared in order to explore the boundary of emission assessment.

Table 2 illustrates the scope of emission and energy assessment identified in the literature concerning sustainable building refurbishment. As can be seen, most studies have been merely investigations of emission reduction in the operational stage instead of throughout the building's whole life cycle, probably because this stage accounts for the majority of overall

GHG emission. The results also reveal that LCA has been mostly applied in studies of single refurbishment methods, such as of insulation, shading and photovoltaic panels [86]. Thus applying LCA to multiple refurbishment approaches is difficult due to the lack of detailed and accurate data required by this assessment method.

It is also worth noting that, for the refurbishment of lighting, air-conditioning and other building service equipment, the embodied emissions of building materials are often neglected. Two reasons are proposed to explain this phenomenon. On one hand, the components of electrical and mechanical devices are usually too complicated to be precisely quantified while, on the other hand, the carbon emissions in the manufacturing stage is insignificant when compared to its impact during the operational stage of such devices [87]. Although the levels of embodied emissions from building service equipment could be obtained from a database, the reliability of this data is considered much lower than that for the data concerning construction materials such as concrete, steel and wood [85].

As shown in Table 2, energy simulation, case study and combinations of the two have been the major methods used to assess the energy savings from refurbishment. Simulation tools are frequently used to estimate these savings, such as from the use of insulation layers [64,78], upgrading window glazing [37,38,39], improving sealing against air leakage [87,88], etc.

Table 2

Boundary of emission / energy assessment in sustainable refurbishment

Literature source	Scope of emission / energy assessment	Calculation method	Building type	Components included in refurbishment	Measurement criteria
Al-Ragom [64]	Operation	Simulation	Residential	Insulation	Energy
Ardente et al. [85]	Raw materials, operation, disposal	Case study	Residential, office, church	Building service, envelope, photovoltaic panels	Energy
Bojic et al. [37,39]	Operation	Simulation	High-rise residential	Windows	Energy
Bojic & Yik [78]	Operation	Simulation	High-rise residential	Insulation	Energy
Chatagnon et al. [89]	Operation	Simulation	Social housing	Space heating, photovoltaic panels, solar water heating	Energy
Dong et al. [87]	Construction material, operation	Simulation	Detached housing	Insulation, air leakage sealing	Energy
Häkkinen et al. [23]	Raw materials, replacement, operation	Simulation	Residential	Insulation	CO_2e
Hertzsch et al. [90]	Operation	Simulation	Office	Building service, envelope	Energy
Hong et al. [91]	Operation	Case study	Dwelling	Space heating	Energy
Huang et al. [92]	Raw material, transportation, installation, operation, disposal	Case study	Office	Overhang shading	CO_2e
Jaggs & Palmer [26]	Operation	Simulation	Apartment	Building service, envelope	CO_2e
Kannan et al. [93]	Manufacturing, construction, operation, disposal	Simple calculation	N.A.	Photovoltaic panels	CO_2e
Konstantinou & Knaack [84]	Operation	Simulation, case study	Residential	Envelope, building service, solar heating	Energy
Nemry et al. [88]	Operation	Simulation	Residential	Insulation, windows, air leakage sealing	CO_2e
Yik & Bojic [38]	Operation	Simulation	High-rise residential	Switchable glazing	Energy

In addition to such simulation, electricity consumption can be directly calculated for some building service devices, such as highly efficient fluorescent lighting [94], LED lighting [95] and photovoltaic panels [85,89].

The embodied emissions of materials include the GHGs emitted in the manufacturing, transportation, construction and demolition processes [96]. Previous research has shown that the amount of direct GHG emission is relatively proportional to the amount of energy consumption [44] involved in these processes. There is, however, no direct relationship between the amounts of embodied carbon and embodied energy due to GHG emitted in the inherent process of forming material [46]. For instance, cement generates a measurable amount of GHG from the chemical process inherent in forming concrete but without consuming any energy.

To support the study of embodied carbon emissions of materials, various databases have been developed around the world, such as Ecoinvent, the US Life Cycle Inventory (US LCI), Inventory of Carbon and Energy (ICE), etc. Unfortunately, there is no database to date for embodied GHG emissions in countries such as Hong Kong, which has prompted some local research in this area. Cole & Wong [97] (cited in [96]), for example, have investigated the life cycle energy consumption of a high-rise residential building in Hong Kong, including the consumption of embodied energy, operational energy and energy consumed in demolition. In their study, however, the determination of embodied energy was based on data from Canada instead of Hong Kong and it was assumed that transportation accounts for 5% of the energy consumed in manufacturing, which may not fully reflect the actual situation. To address these shortcomings, Chen et al. [96] adopt multiple data sources of energy consumption in the manufacturing phase and analyze the energy consumed in transportation by determining the proportion of materials imported from different countries and their corresponding distances from Hong Kong, hence providing more precise data of the embodied energy in construction materials.

Apart from methods for calculating embodied energy, two carbon audit toolkits have been developed to assess embodied GHG emissions for small and medium enterprises [98] and households [99] in Hong Kong. Using these toolkits, users are able to calculate the embodied carbon emissions from materials by multiplying the mass of material by the corresponding emission factor.

As the quantification of energy savings plays an essential role in decision making for sustainable building refurbishment [100], considerable research has been conducted in this area. Rysanek & Choudhary [101], for example, have established a new building physics and simulation engine for building energy supply systems for analyzing the effects of various carbon-reducing retrofit options. The strength of this model is in its applicability to realistic investment contexts through producing the necessary primary energy consumption profiles of each option. Murray et al. [18] carried out a case study to assess the emission reductions of refurbishment using two different modeling approaches and proposed a modeling technique that is sufficient to support decision-making. Based on Artificial Neural Networks (ANN), Yalcintas [102] estimated the difference in energy consumption between pre-retrofit and post-retrofit scenarios. Asadi et al. [56] developed a multi-objective mathematical model to optimize the energy benefits of building retrofits. With this model, all available combinations of alternative refurbishment solutions can be considered simultaneously. Raftery et al. [103] also describe an evidence-based methodology for calibrating whole building energy models that can be used to estimate the energy savings of different refurbishment approaches.

5. Sustainable refurbishment solutions for multi-story residential buildings in Hong Kong

Table 3 summarizes the 88 sustainable refurbishment solutions identified in the literature review. A brief introduction is presented for each solution together with the source of references. According to the building components involved, these solutions are classified into three broad categories, namely: building service, building envelope and renewable energy, under which sub-categories are proposed such as lighting, heating, insulation and windows. Building service refers to the equipment and devices that are installed in a building, e.g. lighting and lifts. Building envelope includes the external components of a building, e.g. external wall, roof and windows. Renewable energy means the approaches that generate or utilize renewable energy.

Table 3 (a)

Summary of sustainable refurbishment methods related to building services

Category		Sustainable refurbishment methods	Description	PRUPIM Developments [27]	Xing et al. [81]	Konstantinou & Knaack [84]	Clark [80]	Gelfand & Duncan [21]	HKGBC [82]	HKGBC [82]	EST [63]	CPA [17]	Thorpe [18]	Shah [11]	Burton [74]	Baker [20]	Hakkinen et al. [23]
Building service	*Lighting*	Low energy lamps (T5 fluorescent)	Replacing T8, T10, and T12 fluorescent with T5 fluorescent	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
		Light emitting diode (LED) lighting	Replacing fluorescent and light bulbs with LED lighting		✓			✓	✓	✓	✓		✓	✓	✓	✓	
		Daylight sensors	Switching off unnecessary lighting when there is adequate daylight	✓				✓		✓			✓	✓	✓	✓	
		Motion sensors	Switching off the lighting when there is no occupant					✓	✓	✓	✓		✓	✓	✓	✓	
		Daylight and task lighting backup	Combining daylight with task lighting													✓	
		Programmable lighting control system	Installing a control system to switch off unnecessary lighting										✓	✓		✓	
	Heating	Induction cooking	Cooking with induction cooker							✓			✓				
		Reduce hot-water storage temperature	Reducing hot-water storage temperature				✓										
		Power-factor correction	Improve the stability and efficiency of the transmission network											✓			

	Installing low-flow aerated showerheads	Reducing the use of hot water	✓			✓	✓	✓	✓		✓	✓	✓	✓		
	Radiant heating	Improving the efficiency of space heating				✓	✓			✓		✓	✓		✓	✓
	Combined heat and power, cogeneration	A heat engine to simultaneously generate electricity and useful heat	✓	✓	✓		✓			✓	✓	✓	✓	✓	✓	✓
	Under-floor heating	Installing a heating device under the floor					✓					✓			✓	
	District or block heating system	Central heating from a district	✓	✓	✓		✓					✓		✓		✓
Ventilation	Desk fan or locally controlled fan	Locally controlled fan to reduce thermal load				✓		✓		✓					✓	
	Mixed mode ventilation	Combining natural ventilation with mechanical ventilation	✓				✓						✓		✓	✓
	Displacement systems	Supply outdoor air at floor level and extracted above the ceiling	✓													
	Mechanical extract ventilation	Extracting air using a mechanical device			✓		✓	✓		✓	✓					✓
	Mechanical ventilation with heat recovery	Combining heat recovery with mechanical ventilation		✓	✓	✓	✓			✓	✓	✓		✓		✓
	Under-floor air distribution	Distributing outdoor air at floor level		✓			✓									
Cooling	Revising air conditioning set-points	Raising the air conditioning set-point to save energy				✓										
	Evaporative cooling	Space cooling with evaporation	✓	✓			✓									
	Upgrade heat rejection of cooling towers	Upgrading heat rejection to reduce cooling loads						✓								
	Chilled beams or under-floor supply	Cooling equipment with higher efficiency	✓										✓		✓	
	Heat-recovery chiller system	Chiller system with heat-recovery	✓			✓	✓	✓					✓		✓	
	Install thermal wheels to pre-cool fresh air	Using pre-cool fresh air to reduce cooling loads							✓							
	Air-cool oil-free magnetic AC chillers	High efficiency chillers					✓									

Lifts	Lifts with power regeneration system	Increasing the efficiency of lifts	✓				✓								
	Modernize lifts with a VVV-F control system	Higher efficiency equipment for lifts	✓					✓	✓						
Others	Time switches	Switching off the equipment during specific period	✓			✓		✓					✓		
	Multiple-level switching	Controlling devices in different levels				✓									
	Individual switching	Improving the flexibility of control	✓			✓	✓		✓	✓			✓	✓	
	Energy efficiency appliance selection	Selecting energy efficient appliances	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Thermostat for heating or cooling	Installing thermostats to control energy consumption				✓	✓	✓		✓					
	Installing meters for energy auditing	Exploring the direction of energy saving by auditing	✓			✓		✓	✓	✓		✓			
	Building management system	Overall control of building service devices	✓				✓	✓				✓	✓		✓
	Replacing pumps with higher energy efficiency	Using high energy efficient pumps	✓			✓	✓	✓	✓				✓		✓

Table 3 (b)

Summary of sustainable refurbishment methods related to the building envelope

Category		Sustainable refurbishment methods	Description	PRUPIM Developments [27]	Xing et al. [81]	Konstantinou & Knaack [84]	Clark [80]	Gelfand & Duncan [21]	HKGBC [82]	HKGBC [82]	EST [63]	CPA [17]	Thorpe [18]	Shah [11]	Burton [74]	Baker [20]	Hakkinen et al. [23]
Building envelope	*Roof & wall*	Reflective surface (cool roofs or walls)	Light color surface to reduce heat absorption				✓	✓		✓						✓	
		Green wall	Reducing thermal load with green wall						✓	✓			✓	✓	✓		
		Green roof	Reducing thermal load with green roof		✓	✓		✓	✓	✓			✓	✓		✓	
		Roof pond	Reducing thermal load with roof pond													✓	
	Windows	Simple coating	Sticking a film over the window to reduce emissivity			✓		✓	✓			✓		✓			
		Tinted glazing	Replacing clear windows with tinted glass					✓		✓		✓	✓			✓	✓
		Internal shutters	Installing a shutter behind the window					✓					✓				
		Inter-pane glazing	Reducing emissivity using inter-pane glass		✓			✓								✓	
		Reflective glazing	Reducing emissivity using reflective glass						✓							✓	✓
		Double / multiple glazing	Installing multiple glazing to reduce heat transfer and emissivity		✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

	Window frames with thermal brake	Installing a thermal brake to reduce heat transfer									✓	✓	✓		✓	
	Internal roller blinds	Installing internal blinds to block the sunlight	✓		✓	✓		✓					✓		✓	
	Louvres	Installing louvres to block the sunlight					✓								✓	
	External blinds	Installing external blinds to block the sunlight					✓								✓	
Shading	Automatic blinds	Installing automatic blinds to block the sunlight	✓													
	Vertical fins	Vertical shading on the external wall		✓			✓	✓							✓	
	Overhangs	Horizontal shading on the external wall	✓	✓	✓	✓	✓	✓	✓				✓	✓	✓	
	Light shelves	Horizontal shading with the reflect of sunlight	✓				✓					✓	✓		✓	
	Ductwork and pipework insulation	Insulating pipework to reduce heat loss				✓				✓	✓	✓		✓	✓	
	External wall insulation	Insulating external walls to reduce thermal transfer	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓
	Internal wall insulation	Insulating internal walls to reduce thermal transfer	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓
	Floor or ceiling insulation	Insulating floors or ceilings to reduce thermal transfer				✓	✓			✓	✓	✓	✓	✓	✓	
	Rafter insulation	Insulating rafters to reduce thermal transfer					✓				✓					
Insulation	Loft insulation	Insulating lofts to reduce thermal transfer		✓						✓	✓	✓	✓	✓	✓	
	Door insulation	Insulating doors to reduce thermal transfer								✓	✓	✓	✓	✓		✓
	Basement insulation	Insulating basements to reduce thermal transfer			✓											✓
	Roof insulation	Insulating roofs to reduce thermal transfer	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓
	Dynamic insulation	Using insulation fibers to reduce heat loss from outdoor air		✓												
	Integrated balconies in the thermal envelopes	Integrating the balcony in the thermal envelope to reduce heat loss			✓											

Air tightness	Check and repair duck work leakage	Repairing duct work to avoid leakage				✓	✓			✓		✓	✓			
	Joint sealing	Sealing joints to reduce air leakage					✓			✓	✓	✓	✓	✓	✓	✓
	Draught-proofing	Reducing gaps in the envelope to eliminate draughts	✓	✓		✓				✓	✓	✓	✓	✓		✓

Table 3 (c)

Summary of sustainable refurbishment methods related to building layouts

Category		Sustainable refurbishment methods	Description	PRUPIM Developments [27]	Xing et al. [81]	Konstantinou & Knaack [84]	Clark [80]	Gelfand & Duncan [21]	HKGBC [82]	HKGBC [82]	EST [63]	CPA [17]	Thorpe [18]	Shah [11]	Burton [74]	Baker [20]	Hakkinen et al. [23]
Building layouts	*Lighting*	Rearrangement of lighting circuits to fully utilize daylight corridors	Rearranging lighting circuits to reduce artificial lighting											✓		✓	
		Shallow plan	Reducing the distance from window to desk to utilize daylight	✓						✓						✓	
		Remote source solar lighting (light pipes)	Introducing daylight to corridors through light pipes							✓			✓	✓			
		Reducing the size of framing elements	Reducing the size of framing to increase daylight													✓	
		Create an atrium to improve daylight	Creating an atrium to improve daylight	✓				✓		✓				✓		✓	
	Ventilation	Night ventilation	Promoting natural ventilation at night	✓	✓								✓	✓		✓	
		Operable windows	Replacing with operable windows to promote ventilation	✓				✓	✓				✓	✓		✓	
		Passive stack ventilation	Installing stacks to enhance passive ventilation				✓	✓			✓	✓	✓	✓			

Others	Appropriate zoning	Appropriate zoning plan to reduce artificial lighting	✓			✓	✓	✓	✓						✓	
	Cut out and replace balcony with thermal break	Cut out and replace balconies to eliminate heat transfer			✓											
	Double skin façade	Double skin façade to improve insulation and ventilation	✓		✓		✓		✓						✓	

Table 3 (d)

Summary of sustainable refurbishment methods related to renewable energy

Category	Sustainable refurbishment methods	Description	PRUPIM Developments [27]	Xing et al. [81]	Konstantinou & Knaack [84]	Clark [80]	Gelfand & Duncan [21]	HKGBC [82]	HKGBC [82]	EST [63]	CPA [17]	Thorpe [18]	Shah [11]	Burton [74]	Baker [20]	Hakkinen et al. [23]
Renewable energy	Green energy procurement	Procuring energy with a low emission factor				✓	✓			✓	✓	✓	✓		✓	
	Phase change materials	Materials that absorb heat in the daytime and emit heat at night	✓	✓								✓				
	Biomass heating	Using biomass to generate heat	✓	✓			✓			✓	✓	✓	✓	✓	✓	
	Ground source or air source heat pumps	A central heating system that transfers heat from the ground	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓
	Solar heating intake air	Heating the intake air by solar energy		✓			✓									
	Solar water heating	Using solar energy to heat the water	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Photovoltaic (PV) panels	Transferring solar power into electricity	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	
	Wind turbine	Generating electricity using wind power	✓	✓			✓		✓	✓	✓	✓	✓		✓	

To understand the suitability of these solutions better, a desktop study is used to eliminate those that are not applicable to Hong Kong's high-rise residential buildings. The three criteria identified earlier are adopted in this screening, namely: the pattern of energy consumption, suitability to residential usage and relevance to high-rise buildings. The results are presented in Table 4 and explained below.

Pattern of energy consumption: Research into energy audits and field surveys has revealed that air-conditioning dominates electricity consumption in Hong Kong [71,73,75]. In contrast, the demand for space heating is extremely rare in this city and few households have equipment for heating interior spaces. Therefore, it is reasonable to eliminate the sustainable refurbishment solutions relevant to space heating, such as radiant heating, cogeneration, under-floor heating, district heating systems, mechanical ventilation with heat recovery, heat-recovery chiller systems, thermostats for heating, solar heat intake air, ground source or air source heat pumps, etc. Furthermore, as geothermal heat pumps and biomass heating are not common in Hong Kong, these solutions are also not considered applicable due to the city's high urban density.

Suitability for residential usage: Compared with commercial buildings, high-rise residential apartments have several distinctive characteristics. Except for luxurious or service apartments, very few residential buildings have centralized heating, ventilation or air-conditioning systems. This makes it impossible to introduce measures such as displacement systems, upgraded heat rejection of cooling towers, high efficiency air-cool oil-free magnetic chillers, thermal wheels to pre-cool fresh air, under-floor air distribution, evaporative cooling, chilled beams or under-floor supply of cool air, mixed mode ventilation, multiple-level switching, power-factor correction, etc. Other solutions proposed in the literature, such as individual switches, operable windows, mechanical extract ventilation, internal roller blinds, desk fans or locally controlled fans, louvers, etc., already exist in most apartments. Moreover, initiatives including absorption coolers, appropriate zoning, shallow plans and smaller size framing elements are difficult to apply in an existing multi-story building. In Hong Kong, most family members leave home in the daytime for work or school, making solutions such as light shelves, daylight and task lighting backup and automatic blinds impractical.

Relevance to high-rise buildings: Because of various statutory, design and practical considerations, it is difficult to introduce any new component to the external envelope of a building, such as a canopy, dynamic insulation, green walls, double skin façade external blinds, etc. Other initiatives such as rafter insulation, loft insulation, roof ponds, integration of balconies within the thermal envelope, passive stack ventilation and basement insulation are also not relevant for local multi-story buildings.

Applying these three criteria to the 88 solutions results in the 39 sustainable refurbishment initiatives considered relevant in the Hong Kong situation.

Table 4

Sustainable refurbishment solutions in Hong Kong

Sustainable refurbishment methods	Criteria			Result
	Pattern of energy consumption	Suitability for residential usage	Relevant to high-rise building	
Low energy lamps (T5 fluorescent)				✓
Light emitting diode (LED) lighting				✓
Daylight sensors				✓
Motion sensors				✓
Daylight and task lighting backup		×		×
Programmable lighting control systems		×	×	×
Induction cooking				✓
Reduce hot-water storage temperature				✓
Power-factor correction		×		×
Installing low-flow aerated showerheads				✓
Radiant heating	×			×
Combined heat and power, cogeneration	×			×
Under-floor heating	×			×
District or block heating systems	×			×
Desk fan or locally controlled fans		×		×
Mixed mode ventilation		×	×	×
Displacement systems		×		×
Mechanical extract ventilation		×		×
Mechanical ventilation with heat recovery	×			×
Under floor air distribution		×		×
Revising air conditioning set-points				✓
Evaporative cooling		×		×
Upgrade heat rejection of cooling towers		×		×
Chilled beams or under floors supply		×		×
Heat-recovery chiller systems	×			×
Install thermal wheels to pre-cool fresh air		×		×
Air-cool oil-free magnetic AC chillers		×		×
Time switches				✓
Multiple-level switching		×		×
Individual switching		×		×
Energy efficiency appliance selection				✓
Thermostats for heating or cooling	×			×
Installing meter for energy auditing				✓
Lifts with power regeneration system				✓
Modernize lifts with VVV-F control system				✓
Building management system		×		×
Replacing pumps with higher energy efficiency				✓
Simple coating				✓
Tinted glazing				✓

Internal shutters			×	×
Inter-pane glazing				✓
Reflective glazing				✓
Double / multiple glazing				✓
Window frames with thermal brake				✓
Reflective surface (cool roofs or walls)				✓
Green wall			×	×
Green roof				✓
Roof pond			×	×
Internal roller blinds		×		×
Louvres		×		×
External blinds			×	×
Automatic blinds		×		×
Vertical fins				✓
Overhangs				✓
Light shelves	×	×		×
Check and repair duck work leakage				✓
Joint sealing			×	×
Draught-proofing				✓
Ductwork and pipework insulation				✓
External wall insulation				✓
Internal wall insulation				✓
Floor or ceiling insulation				✓
Rafter insulation			×	×
Loft insulation			×	×
Door insulation				✓
Basement insulation			×	×
Roof insulation				✓
Dynamic insulation			×	×
Rearrangement of lighting circuits to fully utilize daylight corridors				✓
Integrated balconies in the thermal envelopes			×	×
Shallow plan		×		×
Remote source solar lighting (light pipes)				✓
Reducing the size of framing elements		×		×
Create an atrium to improve daylight		×	×	×
Night ventilation			×	×
Operable windows		×		×
Passive stack ventilation			×	×
Appropriate zoning		×		×
Cut out and replace balcony with thermal break			×	×
Double skin façade			×	×
Green energy procurement	×			×
Phase change materials				✓

Biomass heating	×	×
Ground source or air source heat pumps	×	×
Solar heating intake air	×	×
Solar water heating		✓
Photovoltaic (PV) panels		✓
Wind turbine		✓

6. Discussion

In this section, we consider in more detail the practical implications of the methods identified in Table 4 for application in Hong Kong.

6.1. Applicable sustainable refurbishment solutions

Lighting: Low energy lamps such as T5 fluorescent tubes are becoming increasingly popular in Hong Kong, and many refurbishment projects have applied these measures to increase energy efficiency. However, though LED lighting is another possible solution, its cost is still rather high and it is uncertain if the savings in energy bills can offset the initial cost involved. In addition, the performance of LED lighting is better in an indoor environment with a more stable temperature.

Sensors: Daylight sensors and motion sensors can be applied to reduce artificial lighting when there is sufficient light or no human activity. However, public buildings with open corridors provide more opportunities for installing daylight sensors, and motion sensors are also restricted by local fire safety codes, which stipulate that all staircases must be lit throughout the night [104]. Although the Hong Kong Housing Authority has developed and applied a two-level lighting system with motion sensors in staircases for new buildings, introducing this technology to existing buildings is yet to gain in popularity. Time switches could improve energy efficiency by cutting off the daily operational time of building services equipment. For instance, some of the lifts for high-rise residential buildings could be switched off after midnight to reduce energy consumption.

Lifts: Power regeneration systems and variable voltage frequency lift drives have almost become standard designs for new lifts. However, they are major approaches for existing buildings that would only be justified when an extensive refurbishment project is undertaken.

Insulation: Although insulation plays a key role in energy conservation, it is almost impossible to upgrade the insulation of buildings because the annual and daily temperature differences are less significant in subtropical climates and the possibility of substantially improving the thermal insulation of the roof system is also quite low.

Windows: Replacing clear windows with low-emissivity glass, tinted glazing, reflective glazing or multiple glazing can reduce the sunlight and heat from outside and thus cut down the thermal load on air-conditioners. However, the disruption resulting from window replacement can be very high, especially when the property is still occupied, and many residents prefer the better visual comfort of clear glass. As for inter-pane glazing, the cost is likely to be too high to gain popular usage in Hong Kong. Applying high efficiency lighting equipment such T5 fluorescent and LED lighting may be more acceptable than enhancing window glazing.

Roofs and shading: Although a green roof can be applied to some buildings, its effectiveness depends on how well it is maintained, which can be quite expensive. As for vertical fins and overhangs, these approaches are suitable for shading from sunlight provided they satisfy statutory requirements and do not influence the structural stability of the building.

Renewable energy: As with insulation, phase change materials are not recommended because they would cause a higher thermal load, thus adversely increasing energy consumption. Solar water heating and photovoltaic panels should generate a certain proportion of energy provided there is sufficient sunlight in subtropical regions, but the small roof area of high-rise buildings restricts their capacity. In addition, if solar power were used for water heating, the absence of a central hot water supply system for multi-story residential buildings would restrict its application and even though additional power can be generated by photovoltaic panels, it can hardly be fed back into the existing power grid under the existing regulations. As for wind turbines, none are feasible due to their high investment cost, limited space in the urban area and noise generation. Therefore, renewable energy is not yet a practical sustainable refurbishment initiative for Hong Kong.

User-habits: Six approaches to conserve energy inside the units are identified: reducing the storage temperature of electric water heaters, installing low-flow aerated showerheads, reconfiguring air conditioner temperature, selecting energy efficiency appliances, stopping draughts and using induction cookers. However, the application of these measures depends on the residents' awareness of sustainability, rather than on technical issues. To help overcome this, the Hong Kong government has established labeling schemes for both energy efficiency of appliances and water efficiency of showers in recent years [105,106]. The influence of local tradition is also important. For example, using induction cookers is not popular in Hong Kong, as many prefer cooking by deep-frying.

In addition to the solutions identified from this review, further refurbishment approaches that are applicable in practice are compacted fluorescent lighting (CFL), electronic ballast and permanent magnetic synchronous lift motors.

6.2. Refurbishment in private-occupied areas and common areas

Apart from the technical issues involved, whether a refurbishment approach can be applied depends greatly on the authority over the corresponding building components. For public buildings, the Hong Kong Housing Authority can only undertake refurbishment works in common areas, such as stairs, corridors and lobbies; leaving full authority for individual tenants to apply energy saving approaches within their units provided they satisfy the relevant statutory requirements. Similarly, in private buildings, the authority for refurbishing indoor units and common areas belongs to the individual owners and owners' corporations.

Sustainable refurbishment solutions can therefore be classified into two groups – those for private-occupied areas and those for common areas – In order to satisfy the needs of different stakeholders. The scope of these areas as well as the corresponding project initiators are identified in Table 5.

Table 5

Scope of privately occupied and common areas

Name	Scope	Example	Refurbishment initiator	
			Private buildings	***Public buildings***
Privately occupied area	The area inside a unit	Living room, bedroom, kitchen, bathroom	Owner	Tenant
Common area	The areas except outside the units	Stair cases, corridors, lift lobbies	Owners' corporations	Government

A list of sustainable refurbishment solutions suitable for both privately occupied and common areas of multi-story residential buildings in Hong Kong is also presented in Table 6.

6.3. Level of refurbishment

As illustrated earlier, four levels of sustainable refurbishment are identified based on the scope of the components involved, and the refurbishment approaches listed in Table 7 are classified according to these levels (no solution fits Level 4 refurbishment because there is no approach relevant to the components outside a building). Again, it should be noted that in the selection of a higher level of refurbishment, the solutions below this level are also included.

Table 6

Sustainable refurbishment solutions for high-rise residential buildings

Area	Category	Refurbishment solutions
Common area	Lighting	Low energy lamps (T5 fluorescent) LED lighting Compacted fluorescent lightings (CFL)

		Electronic ballast
	Sensors	Daylight sensors
		Motion sensors
	Lifts	Lift with power regeneration system
		Lifts with advanced VVV-F control system
		Permanent magnet synchronous lift motor
	Roof and walls	Reflective surface (cool roofs or walls)
		Green roof
	Shadings	Vertical fins
		Overhangs
	Layouts	Rearrangement of lighting circuits to fully utilize daylight
	Renewable energy	Photovoltaic panels
	Others	Time switches
		Replace water pumps with higher efficiency one
Privately occupied area	Lighting	Low energy lamps (T5 fluorescent)
		LED lighting
		Compacted fluorescent lightings (CFL)
		Electronic ballast
	Windows	Simple coating
		Tinted glazing
		Reflective glazing
		Double / multiple glazing
		Stopping draughts
	User-habits	Installing low-flow aerated showerhead
		Reducing storage temperature of electric water heater
		Reconfiguring air conditioner temperature
		Selecting energy efficient appliances
		Using induction cookers

Table 7

Levels of the sustainable refurbishment solutions

Level	**Refurbishment solutions**	
	Common area	*Private-occupied area*
1	T5 fluorescent	

	LED lighting	Reducing the storage temperature of electric water heaters
	Compact Fluorescent Lighting	Reconfiguring air conditioner temperature
	Electronic ballast	Selecting energy efficiency appliances
	Time switches	Using induction cookers
	Daylight sensors	
2	Motion sensors	Simple coating
	Lifts with advanced VVV-F control system	T5 fluorescent
	Lift with power regeneration system	LED lighting
	Permanent Magnet Synchronous Lift Motor	Compact fluorescent lighting
	Replace water pumps with higher efficiency ones	Electronic ballast
		Installing low-flow aerated showerhead
3	Reflective surface (cool roofs or walls)	
	Green roof	Stopping draughts
	Vertical fins	Tinted glazing
	Overhangs	Reflective glazing
	Rearrangement of lighting circuits to fully utilize daylight	Double / multiple glazing
	Photovoltaic panels	

7. Conclusion

The comprehensive literature review has identified 88 existing solutions for the sustainable refurbishment of residential buildings irrespective of their type and characteristics. Three distinctive features of buildings in Hong Kong – pattern of energy consumption, suitability for residential usage and relevance to high-rise buildings – are then used as criteria for identifying 39 most suitable for such subtropical high-rise / high-density cities as Hong Kong. In doing this, two differing patterns of refurbishment work are considered, those for common areas and areas occupied by owners / tenants. The developed solutions form a solid basis for research into sustainable refurbishment, with the consideration of various aspects such as cost, human behavior, policy and decision support.

The scope of the work is limited to high-rise residential buildings and hence the research outcomes may be mostly suited to this type of building. The study also focused on the energy savings and carbon emissions from sustainable refurbishment. Other relevant factors only briefly touched on here include cost, human intervention, environment and culture. For future research, while emission reduction is only one of the factors involved in considerations of sustainable refurbishment, these other factors also need be explored in order to obtain an overall perspective. This would not only improve our understanding of the options available in the sustainable refurbishment of high-rise subtropical residential buildings and their likely implications, but should enable the development of a decision support system to optimize outcomes by selecting the best solutions.

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Highlights

- This paper reviews the low-carbon refurbishment solutions for high-rise residential buildings in a sub-tropical climate
- A total of 88 sustainable refurbishment approaches are identified of which 39 are relevant to Hong Kong's climatic and building characteristics
- Apart from energy savings and carbon emissions, cost, human intervention, environment and culture should be considered when making sustainable refurbishment decisions.