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Attaining sustainability in built environment: Review of green retrofit measures for existing buildings

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Abstract Building retrofit is a critical measure for achieving sustainability in architecture and built environment. It adopts the use of a variety of retrofit technologies to enhance building energy performance at a beneficial cost-effectiveness. This may include certain approaches of building envelope improvement, mechanical systems improvement etc., while keeping the building indoor environment comfortable for human. Besides retrofitting of building envelope and the mechanical system, the improvement of operating and management practices should also be considered for whole general improvements. Therefore, this paper presents a brief overview of previous studies on retrofit measures, its application, performance evaluation and related challenges on a variety of buildings are provided. Furthermore, it defines an average mix of retrofit measures and ranks the related challenges for various building typologies. The objective of this study is to lay a foundation for building researchers, practitioners and decision-makers to effectively evaluate retrofit measures for achieving sustainable building performance globally.

1. Introduction

The detrimental environmental condition experienced globally can be tied to the anthropogenic activities of humans, which results to the emission of greenhouse gases [1, 2]. One basic contributor of this is the high global energy consumption, with existing building blocks accounting for about 20-40% in most countries [3]. To lessen the deteriorating environment, adequate sustainable mechanisms must be implemented to reduce energy consumption. And since building blocks contribute a large share in global energy consumption, it is considered that reducing the impact of buildings on energy consumption and environmental pollution will be a step towards attaining sustainability [4]. One way to achieve this is by green retrofit of existing buildings. Retrofitting buildings have the tremendous potential to reduce building energy consumption by 30-40% [3]. Building retrofits can be defined as the modification of existing buildings with facilities for ease of operation, improvement of efficiency and reduction of environmental disturbance. This may include certain measures of building envelope improvement, mechanical systems upgrading etc., while keeping the building indoor environment comfortable for humans. Generally, building retrofit measures are categorized into five major aspects: building envelope, equipment system, new technology updating (renewable energy sources), energy



conserving behaviors, energy management and control system. The application of these retrofit measures demands a knowledge of the dynamics of the individual/combined retrofit measures and their associated challenges. However, this is subject to intensive research and analysis, which varies with different building types. To this regard, this study proposes a method for developing a suitable retrofit mix for different building types. The paper explores through 29 study cases of energy retrofit of different typologies and cities, with applicable principles to other cases and their related challenges

2. Methodology: studies on building retrofit technologies for different type of buildings

Different retrofit technologies have different effect on different area and building types. A proposed technology for a given building type in a particular city might not be applicable for the same/other building types in a different/same city. Hence, it is crucial to review retrofitting technologies for energy saving potential in different type of buildings globally [4]. In this article, 29 papers were reviewed. Based on this, an average mix of adoptable retrofit measures for each building type and a summary of proposed issues affecting these measures were estimated. Owing to space limitation, a brief review of selected papers on retrofit measures for different buildings and their outcome are shown in Table 1.

2.1. Average retrofit mix for different building types

From the results, the adopted retrofit measures are rated based on their degree of applicability to various building types. Based on this data, a mix of suitable retrofit measures for each building type is generated. This is computed from the normalised average impact to the building energy performance as thus:

$$D_i(\%) = \frac{\sum_{x=1}^p \left(\frac{n_i}{\sum_i^N n_i} \times 100\% \right)}{p} \quad (1)$$

where D_i 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, p is the number of a particular building type reviewed, and N is the number of retrofit measures adopted.

2.2. Common challenges for each retrofit measure

Despite the benefits, each retrofit measure is challenged by several factors to a different extent. From the reviewed studies, common challenges and their average impact on each retrofit measures are obtained. The impact of each challenge on the retrofit measures was roughly weighed based on facile counts of surveyed studies and distributed within the range 1 – 10 (1= less challenging impact and 10 = highly challenging impact). This simplistic method was chosen to briefly and clearly evaluate the impact of each challenge both within and across the retrofit measures. The weighed impact was estimated using the formula:

$$Weighed\ Impact = \sum_{j=1}^M \left(\frac{C_{ij}}{C_{ij,max}} \times 10 \right) \quad (2)$$

where C_{ij} is the number of counts for each challenge (j) against a retrofit measure (i), $C_{ij,max}$ is the value for the challenge with maximum count within a given retrofit measure, and M is the number of common challenges considered. Although this does not provide a global assessment of the relationship between individual retrofit measures and the degree of impact of their associated challenges, however it provides a makeshift insight about this relationship from the perspective of international experts and studies in this field.

3. Discussion of result and recommendations

3.1. Discussion of results

Applying Equations (1) and (2), along side Table 1, globally adopted retrofit measures and extent of application for different building types is presented in Figure 1, and their associated challenges summarized in Figure 2. The results from these figures are elaborated below:

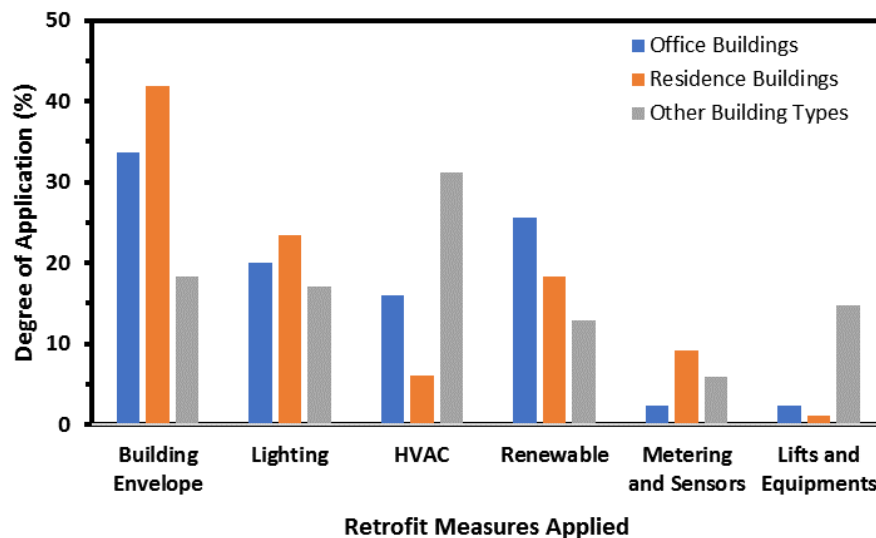


Figure 1. Degree of application of different retrofit measures to building types.

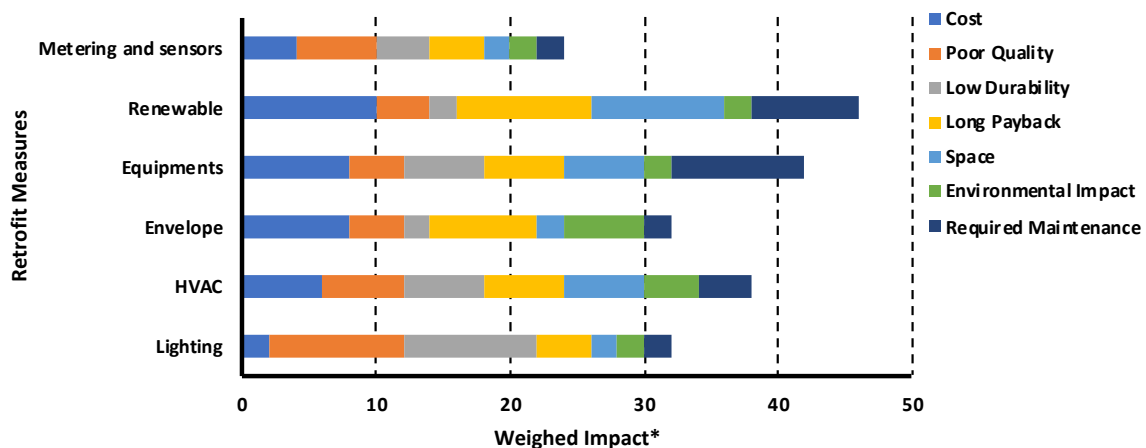


Figure 2. Retrofit measures with its associated challenges.

3.1.1. Building envelope/insulation. Upgrading building facades and envelopes (roofs, floors, walls, shading, windows, and air tightness) have shown tremendous contributions as energy conserving measures across all building types [5-8]. Green roofs and walls are highly recommended measures [9]. Furthermore, high reflective windows with double glaze. They are more soundproof, air-tight and safe. Other alternatives are windows with thermal frames, which can prevent heat losses thereby improving air conditioning efficiency. Costing, long payback periods [10] and introduction of additional environmental impact [11, 12] are notable challenges encountered by these measures

Table 1. Summary of various studies on building retrofits.

Building Type	Major Retrofit Measures	Methodology	Major Results	Ref
Office Buildings				
10 different building across Europe	Insulation upgrade, double-glaze windows, additional shading, improved ventilation (ceiling fans, economizer cycle, evaporative cooler), high efficient fluorescent lamps with electronic ballasts, HVAC, and heat recovery systems.	prototype expert system software tool, RetroLite	Due to building variability especially regional climatic variability, it is difficult to generalize retrofit measures. However, it can be deduced that global retrofitting yields the highest energy consumption reduction across all climatic regions.	[13]
Empire State building New York USA	windows replacement, insulated reflective barriers, tenant day-lighting, chiller plant retrofit, new air handling unit, controlled ventilation, installation of digital controls, and tenant energy management.	Energy and financial modelling	38% energy savings is obtainable from whole-building (commercial) retrofit when compared to ca. 15-30% from conventional commercial building retrofit, saved CO ₂ emission over the next 15 years: 105,000 metric tones.	[14]
Disused wine storage building in Taiwan built in 1979	Installation of roof garden, water meters, rainwater capture system, waterless toilets and urinals, blanket insulation, solar shading, interior glazing, HVAC upgrade, IEQ control, and management plan.	hybrid approach combining A* graph and genetic algorithms (GA)	Energy consumption reduction: 39–43%, reduction in life cycle energy cost and CO ₂ emissions	[15]
Office building in Edmonton, Ottawa and Vancouver	heat recovery, day-lighting, boiler efficiency economizer, preheat upgrade, and lighting load reduction.	EnergyPlus Simulation tool	Energy savings: 20% in electricity consumption, and 30%, 32% and 19% reduction in natural gas for Edmonton, Ottawa and Vancouver respectively.	[16]
Office building situated in Pretoria, South Africa	Windows and lighting upgrade, insulation of walls and roof, upgrade of HVAC system, and PV power supply installation.	multi-objective optimization was solved by genetic algorithm (GA)	Within 6 years, energy savings achieved: 761.6 MWh; cost savings: \$81,003. Lighting retrofit is the most cost-effective option followed by HVAC retrofit. Long payback period for PV system and building envelope retrofit.	[10]
66 office buildings in Hong Kong	Insulations of walls, roof and floors, upgrade of windows, shading, chiller units and air-conditioners, use of energy efficient lightings and improvement of ventilation	Monte Carlo and regression analyses	higher efficiency chiller units and fresh water cooling tower (FWCT) systems significantly reduced cooling energy demand.	[17]

6 public buildings across Europe	new surface thermal insulation, renovating old facades and roof, upgrading insulation, windows, HVAC and lightings, solar-assisted heating systems, wind turbines, condensing gas boilers, and PV panels	coupling field data with referenced eco-profiles and inventory data	Envelope thermal insulation (high-efficiency windows, and thermal insulating boards) had the most significant benefits (energy and emission savings). Upgrading insulation, lighting and glazing components provided particularly efficient solutions.	[5]
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Residential Buildings

Multi-family block of 14 apartments in Sweden	Oil-fired boiler, heat pump, and hot-water accumulator	OPERA model using Mixed Integer Linear Programming (MILP) optimization method	Adding a hot-water accumulator significantly reduced electricity usage for water and space heating. Optimal building heating method was found by using only heat pump.	[18]
15 years old 2-storey building, Kuwait	Wall and roof insulation, glazing system, and decrease of window area	DOE-2.1E building simulation program and simple payback method	Annual energy consumption achieved with this retrofit measure is 293 kWh/m ² in hot and arid climates	[6]
427 random houses in Malaysia	retrofitting incandescent lamp with more efficient compact fluorescent lamp (CFL)	Energy and payback calculations from collected data	total potential monetary savings of about RM 141, 282 and 423 million for 25%, 50% and 75% retrofit for 5000 operation hours respectively.	[19]
Typical houses in multiple locations of United States	Wall retrofits (cladding, insulated cladding), and air sealing methods (tapes, insertion of low & self-expanding foams, loose-fill fiberglass, traditional caulking and exterior trim variations)	Energy modelling and experimental tests	10% estimated annual utility cost savings. Additional savings can be achieved either by low-e storm windows or replacement with vinyl-framed double-paned windows.	[7]
2-storey, a basement & inhabited loft space.	insulation, energy efficient windows, better air-tightness, upgraded ventilation, central heating, solar boilers, and PV panels	Analysis of metering data and actual installation costs	improved insulation, air-tightness, energy efficient windows, upgraded ventilation and central heating provided more benefits than solar boiler and PV-panels.	[20]
2-storey, single-detached brick house in Ontario, Canada	insulation (roof, wall and basement floor), windows (glazed) and doors replacements, air-tightness, heat pump, solar thermal, and energy efficient appliances.	Ecological footprint by Life Cycle Analysis (LCA)	Improved energy efficiency by 80% with environmental payback period less than 2 years. But introduced additional environmental impacts.	[11]

3 buildings of different ages in Tianjin, China	Form (enclosed staircase, balcony, atrium, open-ground floor space, shading, pitched roof, green roof, etc.), insulation (external wall, roof, floor, hall), replacing windows, Sub-metering, room temperature control, Solar thermal & PV, energy-saving lamps.	Building simulation tools (BSTs): Design Builder v3 (Design Builder Software Ltd. 2012), PHOENICS 2012 (CHAM 2012) and Ecotect (Autodesk 2011)	Estimated energy and CO ₂ savings for 1981 residence (78.1% and 92.6% respectively); 1995 residence (66.6% and 66.6% respectively); and 2002 residence (36.9% and 44.6% respectively).	[21]
10 residential buildings in northern temperate zone of China	pipeline upgrade and building envelope construction (insulating exterior wall, replacing windows with PVC-plastic steel windows, replacing exterior doors with iron doors, and painting exterior wall with white varnish, talc, and cellulose).	Actual measured energy consumption	12.5% and 15.6% energy-saving rates for heat supply by heat exchange stations and the heat consumption of buildings respectively. Energy loss was caused by 32.8% increase in the excess heating rate.	[8]

Hotel Buildings

6 Hotel buildings	HVAC upgrade, lighting retrofit (installation of energy saving LEDs and lighting schedule), equipment schedule, and occupancy rate.	eQuest modeling predicting energy-savings potentials of energy retrofit measures	lighting and equipment schedules have the most significant effect on the accuracy of the model for hotel buildings, followed by occupancy rate and COP of the chillers	[22]
295 hotels in different climate zones of China,	building envelop retrofit, internal and external lighting replacement, and HVAC upgrades	designer simulation tool (DeST)	EUI of hotels in cold zone, hot summer/cold winter zone and hot summer/warm winter zone are respectively 100–155, 140–245 and 136–213 kWh/(m ² ·a).	[23]

University Buildings

5 buildings in Melbourne University	Upgrade of existing lighting systems with some replacements with magnetic and electronic ballasts and triphosphor globes (T8 32W & T5 21W)	simple energy and cost estimations	10% reduction in CO ₂ emission and 13–65% energy saving depending on lighting retrofit option. However, the retrofit technologies are quite expensive.	[24]
Partially-retrofitted university building in Ireland	replacing windows with double-glazing windows, upgrade of heaters and thermostatic radiator valves (TRVs), and additional wall insulation.	Occupant surveys (ASHRAE 55 and CBE IEQ) and physical measurements to assess IEQ parameters.	ad-hoc retrofitting of the façade did not make any significant difference to IEQ and occupants continued to adapt personally to the existing conditions	[12]

School Buildings

Nursery school building in Athens, Greece	green roof system	experimental investigation and simulation using TRNSYS 15.1	building energy consumption reduction: 6–49% and for its top floor: 12–87%	[9]
Secondary school building in Pisa, Italy	NZEB retrofit: windows replacements external insulations of walls and roofs, installation of venetian blinds, solar thermals and PV systems, and water-source heat pump	energy simulation (EC700 Edilclima and SEAS 3 (ENEA – University of Pisa)) and economic evaluation	Reduction in thermal energy by 48%, with an annual consumption of 129,454 kWh. Long payback periods of the retrofit measures, due to low yearly energy uses in the existing configuration.	[25].

Historical Buildings

<i>Elmi-Pandolfi</i> building in Foligno, Italy	smart carbon fiber reinforced polymers (CFRP) with embedded fiber optic sensors	real-scale experimentation and basic calculations	‘smart’ composite technology is effective for detecting crack openings.	[26]
<i>Palazzo dell’Aquila Bosco-Lucarelli</i> building, Italy	modification of indoor set point temperatures, better air-tightness, replacement of traditional gas boiler with condensation methane heater, adopting efficient fenestration systems, and upgrade of lighting devices	in-field analysis and numerical modeling using EnergyPlus	22% reduction in building energy demand with a discounted payback period of 11 years	[27]

3.1.2. Lighting. Installation of appropriate lighting and control systems like motion and daylight sensors are another effective means of conserving energy across all building types [10, 19, 22]. However, it is less applicable to HVAC and insulation when considering other building types. Replacement of traditional lighting systems with energy efficient lighting systems should be the first step to green retrofit. Although energy efficient systems are relatively costly, most of which have questionable quality, short lifetime and low luminous efficacy when compared to conventional systems [24].

3.1.3. Heating & cooling. Installation of new and efficient air conditioning treatment units, heat pumps, evaporative coolers and adequate ventilation measures will improve indoor air quality and temperature [18, 20, 22]. This is very important in buildings where indoor air condition is paramount. Although, this measure is also posed with high cost, quality and durability of the system [11], it is considered to contribute extensively towards energy reduction in buildings if appropriately upgraded [10, 17].

3.1.4. Renewable energies. Solar/PV-assisted units and integrated wind turbines are the notable renewable energy systems that contributes significantly to building energy conservation [20]. They are recently being adopted, but a great percentage of existing buildings are yet to implement these measures. This is due to the associated high costs and long payback period [10, 25, 28].

3.1.5. Energy regeneration systems. Use of energy regeneration systems can improve energy efficiency by about [28]. This includes variable-frequency and variable-voltage drive systems. These

systems convert the mechanical energy of gravity-driven motors to electricity and can be applied to lift systems.

3.1.6. Sensors and maintenance measures. In general, sensors are deemed resourceful for enhancing building energy performance [21, 26]. These sensors include temperature, motion and smoke sensors. These are classified under energy conservation management and aid in monitoring and regulating operation of a system to the desired set values. Subsequently, preventing excesses in energy consumed by these systems.

For optimum improvement in building performance, a whole building ('deep') retrofit is recommended. However, further studies on economical evaluation are needed in this regard. Optimal retrofit package should account for indoor environmental quality, occupancy requirement, energy efficiency and cost-effectiveness. In addition to the listed challenges in Figure 2, general unquantifiable barriers confronting building retrofits include behavioural limitations of occupants and building owners; and issues with quantification of non-monetary benefits like internal air and environmental quality.

3.2. Recommendations

As elaborated above, each retrofit measure faces numerous difficulties towards its application and implementation. Nonetheless, several supporting measures can be put in place to address these difficulties. From the reviewed papers, recommended supporting measures are divided into 10 sub-areas under three classes: 1. Information (adopting education and communication schemes to facilitate data recording and promote awareness, 2. Finance (installing financial schemes to support investment and economics of retrofits) and 3. Technology (physical process and socio-political contexts to facilitate building retrofit). The breakdown of these supporting measures are presented in Figure 3. For further elaboration with cited references, refer to Table 1 of [29].

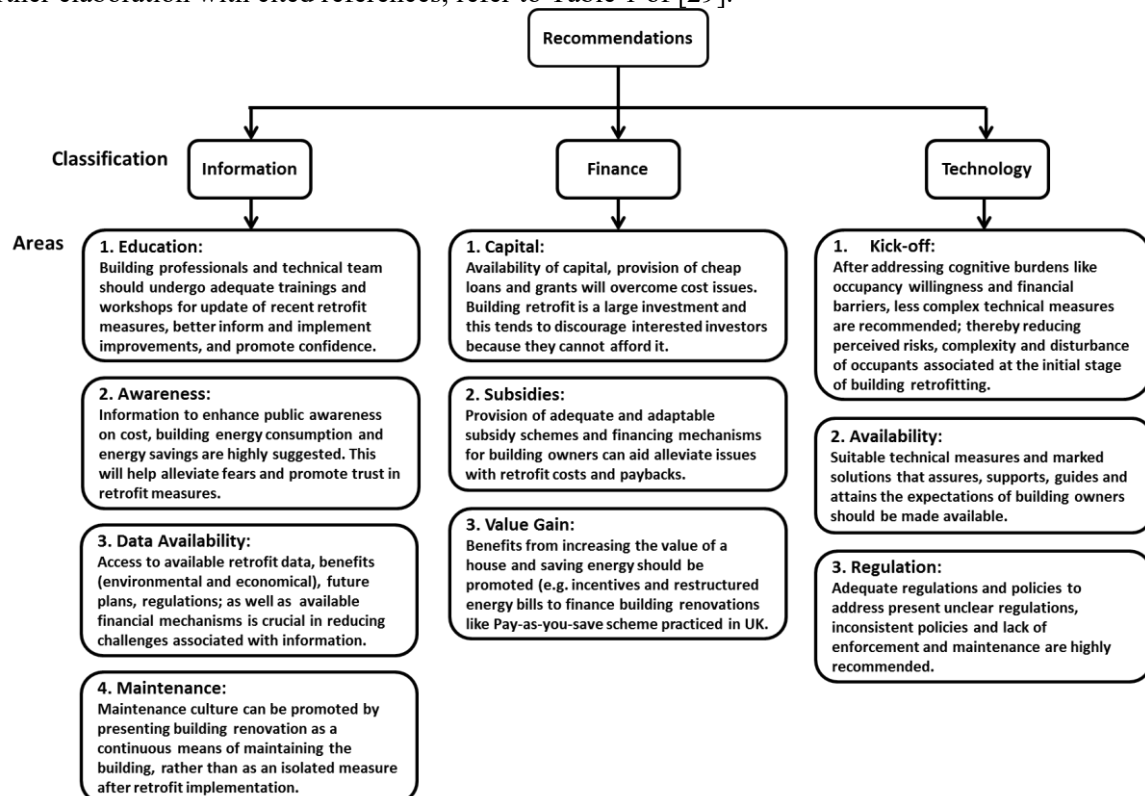


Figure 3. Recommendations to alleviate challenges pertaining to retrofit measures (extracted from [29]).

4. Conclusions

This article presents global building retrofits with a brief overview of previous studies on retrofit measures, its application, performance evaluation, challenges and suggested recommendations. Based on this, energy performance data and challenges for each retrofit measure were collected and analysed for office, residential and other building types. Findings from the review show that

- The most impactful retrofit measure for office and residential buildings is the building envelope, which comes second after heating and cooling systems for other building types. Renewable sources of energy and lighting are also important retrofit measures for office and residential buildings.
- Renewable source of energy and retrofitting building equipment like lifts are more exposed to challenges, common of which are costs and long payback periods. However, these setbacks can be addressed with suitable subsidy programs and governmental support.
- Coupled with this, it is recommended that promoting and implementing necessary regulations in this regard; and establishment of maintenance and management measures are necessary to ensure retrofitted buildings are continually sustainable and green.

The analysis provided in this study is limited to the selected reviewed papers, and does not provide a global assessment of the relationship between individual retrofit measures for each building types and the degree of impact of their associated challenges. However, it only provides a makeshift insight about this relationship. Moreover, the study does not account for geographical location and its respective climate condition. In further research, this crude assessment will be adopted in evaluating optimum mix of building retrofit measures for various cities, particularly those with high urbanization rate, in further research.

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