Retrofitting Public Buildings for Energy and Water Efficiency: Part 2 Retrofitting Guidelines

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Queensland Department of Housing and Public Works
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EXECUTIVE SUMMARY

This is the first progress report of the SBEnrc project 1.43*: Retrofitting Public Buildings for Energy and Water Efficiency*. This is part 2 of the report which presents the progress in the development of retrofitting guidelines. The financing mechanism for carrying out the retrofitting project has been reported in part 1 of this project progress report.

Retrofitting existing building for energy and water efficiency has been reported to be an effective measure for reducing global energy and water consumptions as well as greenhouse gas emissions because, i) building sector accounts for 40% and 25% of the global energy and water consumptions, respectively, and contributes up to 30% of global greenhouse gas emissions and ii) the replacement of existing buildings by new buildings is only around 1-3% annually. Recognising its importance, many governments and international organisations have put significant effort towards energy efficiency improvement in existing buildings.

In this report, a comprehensive review of available national and international building retrofitting guidelines as well as research progress in the development of a comprehensive retrofitting guideline has been carried out. From the review, two types of building retrofitting strategy have been identified: National level retrofitting strategy for existing building stock and individual building retrofitting guideline.

The national level building retrofitting strategies can assist the governments in establishing long-term strategies. Given that the vast majority of existing building stock were constructed prior to the development of any energy performance benchmarking system, a national level building retrofitting strategy is required to stimulate the building renovation rates highlighting different steps to achieve the national energy efficiency as well as emission reduction target. The European Commission suggested 5 key steps for its member state to develop national building renovation strategy. In addition, a number of other European organizations (BPIE, EURIMA, CA Joint Working Group) also proposed renovation roadmaps for existing building stocks. Among the reviewed national level retrofitting strategies, the nine step procedure developed by CA Joint Working Group is found to be the most comprehensive one. The suggested steps are *Vision and time horizon, Stakeholder engagement, Market characterisation, Key barriers and challenges, Techno-economic appraisal, Financing, Policy measures, Shaping the offer – growing market confidence and Implementation.* In these nine steps, the tasks in the later stages generally influenced by the outcomes of the earlier stages. However, it is possible that there may also be some reverse interactions which lead to a degree of iteration or adjustment to the outcomes or earlier stages. In this guideline, a set of questions are outlined for each step which will help the authorities to arrive at well integrated and coordinated strategies for their country.

In contrast, the individual building retrofitting guideline includes information about necessary steps that is required to retrofit an individual building for energy and water efficiency. The individual retrofitting guidelines from USA, UK, Singapore, India and Australia have been reviewed and compared. The "Advanced Energy retrofit guide" from U.S. department of energy is found to be the most comprehensive one among them. The guide begins with an introduction to key concepts underpinning energy efficiency projects; discussions of goal setting, project planning, and performance tracking illustrate the process for initiating energy efficiency projects. It also explains energy audits, financial analysis, and financing options, to provide the remaining elements needed for a strong business case. In addition, the guide considers three levels of building retrofit measures and suggests a number of retrofit packages for each level. The suggested retrofit options as well as cost-benefit analysis are customized for five different climates of USA which has broadened the applicability of the guides to a wide range of situations. The guide concludes with a discussion of measurement & verification (M&V) and operation & maintenance (O&M) strategies to ensure that the energy savings expected from the upgrades are achieved and persist over time.

The guidelines for UK, Singapore and Australia are developed based on "*existing building survival strategies"* from ARUP. Similar to the USA one, these guidelines also reported different levels of retrofit measures. A simple table is proposed to determine the level of refurbishment required based on existing building performance and conditions. A list of possible retrofitting initiatives have been presented including level of retrofit, capital cost, effect on occupant thermal comfort, benefits with respect to sustainability and benefits of owner. However, the guideline did not consider the risks involved in retrofitting projects and financing mechanism for funding the retrofitting project. In addition, nothing has been mentioned about M&V and O&M strategies for post-retrofitted buildings. In Australia, City of Melbourne also developed a retrofitting methodology as part of their 1200 building retrofitting program which has financing, M&V and O&M strategies but excludes cost benefit analysis and selection of optimum retrofit measures methodology. The Indian guideline is found to be similar to the guideline developed by ARUP except that nothing is mentioned about retrofitting level and possible retrofitting initiatives.

However, none of the existing guidelines include analysis of potential risks involved in a retrofitting project. Researches on building retrofitting process revealed that risk analysis is important to ensure that the energy performance predicted during retrofitting decision making stage is achieved once the building is in use. It was reported that inaccurate predictions are becoming more problematic for the industry as new financing schemes such as Environmental Upgrade Agreements (EUAs) and Energy Performance Contracting (EPCs), relying on predicted savings are introduced locally and internationally. Various causes for the mismatch between prediction and actual measurements have been identified from the existing literature on energy performance gap.

Development of national level building retrofitting strategy is beyond the scope of current SBEnrc 1.43 project and therefore has not been considered in the development of retrofitting guideline in this project. Based on the review of individual retrofitting guidelines and research progress in this area, a possible building retrofitting guideline has been proposed at the end of this report. This proposed guideline has been developed addressing the limitations of previous guidelines. It will be finalised after consultation with project partners and following the feedback from the case study. The questionnaires and templates for the case study is currently being developed by the Swinburne University project team.

1. Introduction

Energy and water scarcity as well as environmental pollution have become key challenges for sustainable development of the whole world. The building sector accounts for 40% and 25% of the global energy and water consumptions, respectively, and contributes up to 30% of global greenhouse gas emissions (SBCI 2009). The Australian Government is a large consumer of electricity and natural gas and public sector commercial buildings are responsible for nearly 10% of Australia’s greenhouse gas emissions (Australian National Audit Office 2012). The federal and state governments occupy more than 25% of commercial building stock in Australia and the energy consumption in their office buildings constitute around 28% of total energy consumption in public sector, excluding defence operational fuel and defence establishments (Commonwealth of Australia 2013). Therefore, it becomes obvious that energy efficiency of buildings is a key component of reducing global energy use and climate harmful emissions. Considerable water and energy savings can be made through retrofitting buildings with efficient air-conditioning and hot water systems, bathroom amenities, etc. (Willis et al. 2013). While new buildings are designed to meet building energy efficiency benchmarks such as LEED, Green Star, NABERS, BREEAM etc., majority of the existing building stocks were built before the introduction of sustainability benchmarks and are energy inefficient. To achieve an energy use reduction in building sector, energy efficiency of existing buildings must be addressed as the replacement of existing buildings by new buildings is only around 1-3% annually (Ma et al. 2012). The implementations of energy retrofit measures (ERM) for increasing the energy efficiency of the existing buildings have been shown to have significant effect on reducing the total energy demand (Chidiac et al 2011).

During the last decade, many governments and international organisations have put significant effort towards energy efficiency improvement in existing buildings. In 2011, the Chinese government strengthened the emphasis on retrofits of government and other public buildings by issuing “Notification on Further Implementation of Energy-efficiency Retrofits in Public Buildings” (MOF and MOHURD, 2011). It requires a 10% reduction of energy consumption per m^2 for public buildings and 15% reduction for large public buildings with over 20,000 m2 of floor area by the end of 2015. In 2010, the UK government made a significant commitment to upgrade the energy efficiency of 7.0 million British homes by 2020 aiming at reducing carbon emissions by 29% (DECC 2012). The International Energy Agency (IEA) has launched a set of Annex projects to promote energy efficiency of existing buildings, such as: Annex 46 – Holistic assessment toolkit on energy efficient retrofit measures for government buildings; Annex 50 – Prefabricated systems for low energy renovation of residential buildings; Annex 55 – Reliability of energy efficient building retrofitting; and Annex 56 – Energy & greenhouse gas optimised building renovation (IEA 2011). These efforts provided policy guidance, financial assistance and technical support for the implementation of energy efficiency measures in existing buildings.

The EU Legislation of 2002 “Directive on Energy Performance of Buildings (EPBD)” asserts the necessity to increase energy efficiency for new and existing buildings. In addition, the directive emphasizes the need to develop certain methodologies to determine energy performance of buildings and to prepare energy certificates. National methodologies, consistent with the structure of the directive, are mandatory for EU and candidate countries (EPBD 2002). The EPBD is considered as a significant legislative component in EU energy efficiency policy, and was adopted to contribute to the Kyoto commitment, securing energy supply and competitiveness.

In US, the Energy Policy Act of 2005, expanded under the Energy Independence and Security Act of 2007, requires that all existing and new federal buildings in USA lead by example. Existing buildings must reduce energy consumption 30% by 2015, compared with 2003 levels, through building upgrades and efficient appliances. New buildings must achieve efficiencies of 30% better than ASHRAE and IECC codes. The Federal Energy Management Program (FEMP) assists federal agencies in meeting these goals. FEMP helps federal agencies identify and engage sources of financing for efficiency upgrades, such as Energy Savings Performance Contracts, Utility Energy Service Contracts, and federal and state incentive programs. FEMP also offers energy audits and guidance for equipment purchases (Doris et al. 2009).

In Australia, Energy Efficiency in Government Operation (EEGO) policy was introduced in 2006 (Department of the Environment and Water Resources, 2007) according to which minimum performance standard for government office buildings should be NABERS (National Australian Built Environment Rating System) 4.5 star. In 2008, the City of Melbourne launched a program to retrofit 1200 CBD buildings to achieve 4.5 NABERS star by 2020 (Wilkinson, 2013). Since 2008, 25% of office buildings in the Melbourne CBD have been retrofitted under this program. In addition, the Commercial Building Disclosure (CBD) programme, which came into effect on the 1st November 2010, requires the owners of Australia’s large commercial office buildings to provide energy efficiency information to potential buyers or lessees (CBD 2016). While there are a number of policies to retrofit existing buildings to minimize emission and energy consumption, there is still lack of a comprehensive strategy to guide retrofitting process efficiently and cost-effectively.

This report aims at providing a comprehensive review on available national and international building retrofitting guidelines as well as research progress in the development of a comprehensive retrofitting guideline. The strengths and limitations of the available retrofitting guidelines are evaluated. In addition, the potential barriers and challenges involved in the building retrofitting process have also been discussed. Finally, a building energy retrofitting guidelines for Australia which includes all necessary steps, has been proposed.

2. Review of current building retrofitting guidelines

The available building retrofitting strategy can be divided into two types: National level retrofitting strategy for existing building stock and Individual building retrofitting guideline.

2.1 National level existing building retrofitting strategy

The national level building retrofitting strategies can assist the governments in establishing long-term strategies. Given that the vast majority of existing building stock were constructed prior to the development of any energy performance benchmarking system, a national level building retrofitting strategy is required to stimulate the building renovation process highlighting different steps such as future target, nature of existing stock, cost-benefit analysis process, financing sources, implementation and post occupancy evaluation process.

2.1.1 The European Commission's Energy Efficiency Directive

In order to provide guidance to Member States on development of National Energy Efficiency Action Plans (NEEAPs), as required by the Energy Efficiency Directive (EED): Article 4, European Commission suggested that building renovation strategy should address the following issues:

1. Provide an overview of the national building stock based, as appropriate, on statistical sampling.
2. Identify cost-effective approaches to renovations relevant to the building type and climatic zone
3. Provide information on policies and measures to stimulate cost-effective deep renovations of buildings, including staged deep renovations
4. Demonstrate a forward-looking perspective to guide investment decisions of individuals, the construction industry and financial institutions.
5. Provide an evidence-based estimate of expected energy savings and wider benefits.

2.1.2 **Building Performance Institute Europe (**BPIE)'s **Renovation guidelines**

In order to assist Member States in developing their national renovation strategies, BPIE (2013) developed a guide, published in February 2013, setting out the key steps in the process of strategy development, including a checklist of policy initiatives for Member States to consider. The five phases, and component steps, are presented in Figure 1:

Figure 1 BPIE's 5-phase approach to for building renovation strategy development

Phase 1: Identifying Key Stakeholders & Information Sources

Key to successful delivery of an ambitious yet achievable renovation strategy are preparation, planning and leadership. Given that the strategy will influence an important sector of the economy for decades to come, a strategy development team needs to be pulled together to include input from representatives of Government ministries with responsibility for policy on energy, the building sector (including housing/communities), regions, industry, finance and the economy. Lead responsibility also needs to be clarified. Input from external stakeholders such as sectoral experts, the finance community and representative industry bodies will also be invaluable within the project team.

Phase 2: Technical and Economic Appraisal

In this phase, the technical potential for improving the energy performance of the building stock is determined and the range of renovation options appraised and costed. The starting point is to gain a full understanding of the building stock through a bottom-up summation of the different building typologies, construction styles, ages, climatic zones, occupancy, ownership patterns and the like.

In appraising the economic potential, a key component that is frequently overlooked is the monetisation of the benefits that arise alongside the energy cost savings. The issue here is that most of the other benefits discussed previously accrue to society at large, rather than to the investor. These benefits should be quantified and factored into the economic appraisal of the renovation strategy at a national level. In this way, the cost of any public subsidy provided to stimulate deep renovation could be more than offset by the national economic benefits that result from, for example, increased employment or reduced health expenditure.

Phase 3: Policy Appraisal

The purpose of the policy appraisal phase is, firstly, to review in some detail the current policy landscape affecting building renovation, and secondly, to identify the changes to policies and additional policies that will be necessary to unleash the building renovation market.

Phase 4: Drafting & Consulting on The Renovation Strategy

This phase brings together the technical and economic appraisal undertaken in phase 2 with the review of policy options in phase 3 in order to generate a range of possible future pathways or roadmaps for the long term renovation of the national building stock. Depending on the timing and strength of different policy levers, different rates of renovation can be modelled and the resulting investment and benefits horizons profiled and quantified.

Phase 5: Finalisation, Publication & Delivery

At this stage, the national renovation strategy is published by the governments and steps are taken to mobilise the necessary resources to implement the strategy.

2.1.3 European Insulation Manufacturers Association (EURIMA)'s Renovation Roadmap

Renovation Roadmaps for Buildings was published in January 2013 by The Policy Partners for Eurima (European Insulation Manufacturers Association). It highlights eight key elements of a building renovation roadmap, which are summarised below:

1. **A high-level of ambition** with a long-term perspective and high-level political ownership to provide key actors with enough lead-in time and certainty to plan and prepare for changes as well as a sufficient planning horizon for sustainable change to become visible and materialise. For the EU's building stock, a 2050-horizon is identified as the best option.

2. **Clear and ambitious targets**, including intermediate milestones. Research has demonstrated that, by 2050, the EU building stock can reduce its final energy consumption for heating and cooling by 80%, with a reasonable annual rate of renovation.

3. **Support and collaborative involvement from all levels of Government, market actors and stakeholder parties**. Good roadmaps are supported by all parties involved, including in their ambitions as well as their short-term plans. All parties also have a role in their implementation and are responsible for fulfilling that role. All parties need to be consulted early on in the development process, and sufficient attention given to parties' concerns.

4. **Flexible but focused iterative development**. Roadmap development is iterative, focusing on goals and directions. It also involves accepting that strategies and action plans may need to be adjusted after some years of implementation. Although roadmaps focus on long-term goals, actions need to reflect the possibilities and limitations of the market at any given moment. Tailoring of actions is required throughout the implementation of a roadmap.

5. **Take a holistic approach, addressing the whole building stock**, the whole sector and all relevant issues including technologies, construction, skills, financing, removal of legal and regulatory barriers and engaging building owners.

6. **Integrate energy performance with broader societal goals** and build on the strength of market parties. This includes focusing on employment impacts and taking into account changes in society, demographics and housing needs.

7. **Include flexible, creative thinking, beyond what has been tried before**. Good roadmaps encourage innovation in technologies and markets, but also collaboration between parties, so that there is on-going cost and efficiency improvement of building renovations.

8. **Inclusion of financial support, consumer education, and organisational support**. These "market enablers" are essential to bring building owners to a level of understanding of the benefits that building renovation can provide, to ensure the supply chain can deliver, and to make it easy to finance the investment.

2.1.4 The EU Joint Concerted Action Working Group's 9-step renovation strategy

A set of Assistance Documents has been developed by a Joint Working Group drawn from three EU 'Concerted Action' projects (EPBD, EED and RES, corresponding to the three EU Directives) under the Intelligent Energy Europe programme. Published in November 2013, it has been prepared as a resource to encourage and assist Member State authorities in the development of their renovation strategies, with active hyperlinks to additional sources of information (Joint working group 2013). At its core is a nine step approach to strategy development, presented in Figure 2.

1. **Vision and time horizon**: Issues and questions to consider in setting a vision and time horizon for the long term strategy, and associated targets and milestones.

2. **Stakeholder engagement**: Issues and questions to consider in securing stakeholder engagement, understanding, alignment and commitment.

3. **Market characterisation**: Issues and questions to consider in segmenting, profiling and seeking tounderstand the marketplace of existing buildings, their owners/ occupiers/ investors, in order to identify the potential for energy performance improvement.

4. **Key barriers and challenges:** Issues and questions to consider in assessing and overcoming key challenges and barriers to mobilisation of this sector.

5. **Techno-economic appraisal:** Issues and questions to consider in assessing the technical, economic and other costs and benefits of building energy renovation, from individual investor, national exchequer and societal perspectives. This includes tackling of constraints and conflicts.

6. **Financing:** Issues and questions to consider in quantifying, sourcing, designing and delivering the necessary finance, and in managing risk.

7. **Policy measures:** Issues and questions to consider in assessing options and formulating policies to stimulate, coordinate and regulate large scale delivery of quality renovation activity.

8. **Shaping the offer – growing market confidence**: Issues and questions to consider in developing actions to create investor trust and confidence across the market segments.

9. **Implementation**: Issues and questions to consider in the process of mobilising the full breadth and depth of action for effective delivery in the short term and on the long term vision.

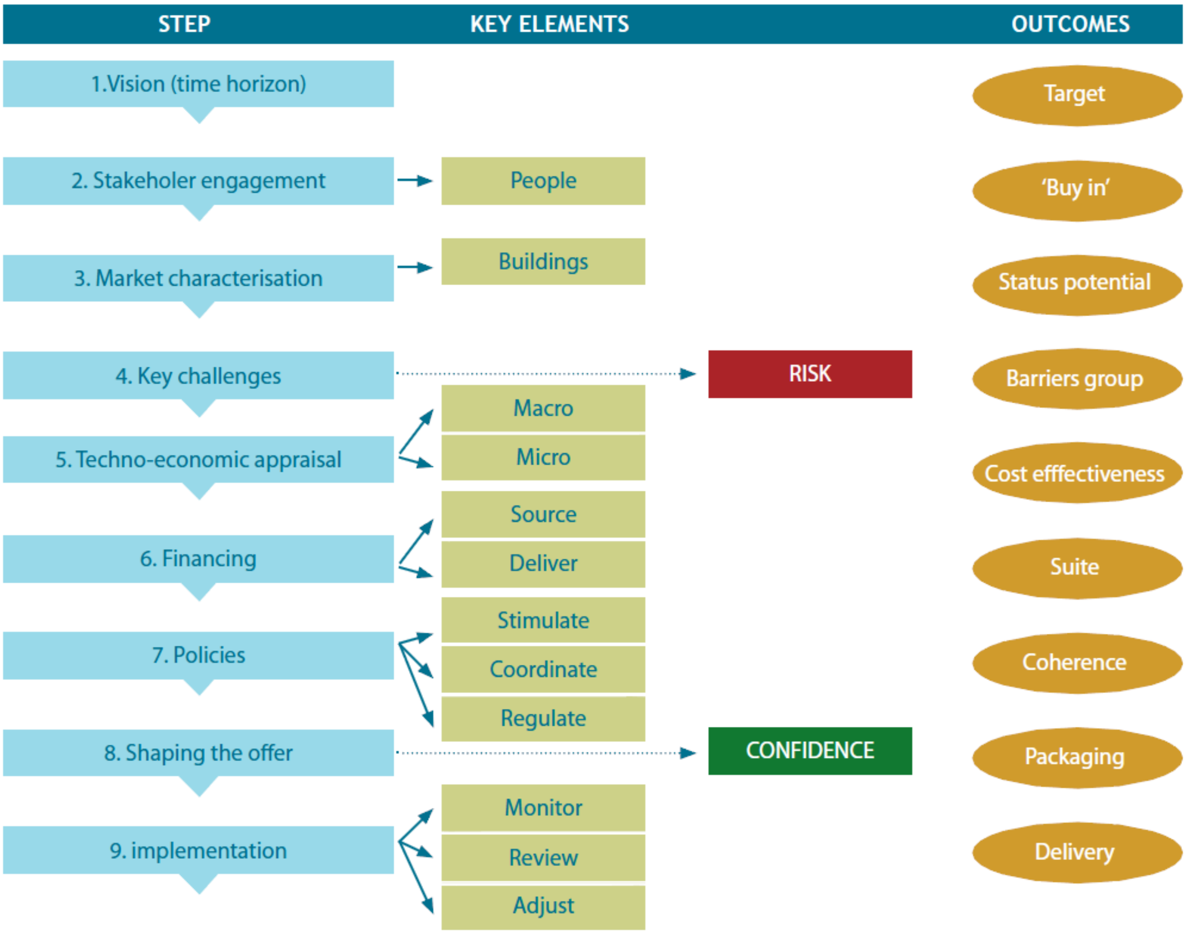


Figure 2 Concerted Action 9-steps towards a renovation strategy

2.2 Building retrofitting guidelines

This type of guideline includes information about necessary steps that is required to retrofit an individual building for energy and water efficiency.

2.2.1 U.S. Departement of Engery's Advanced energy retrofit guideline

The U.S Department of Energy developed an advanced energy retrofit guide (U.S Department of Energy, 2012) for office buildings to provide guidance as well as financial payback metrics for the most common energy efficiency measures. This guide provides a practical roadmap for effectively planning and implementing performance improvements for existing buildings.

Figure 3 shows the flow chart of the retrofitting project according to advanced energy retrofitting guideline. The guide begins with an introduction to key concepts underpinning energy efficiency projects; discussions of goal setting, project planning, and performance tracking illustrate the process for initiating energy efficiency projects. It also explains energy audits, financial analysis, and financing options, to provide the remaining elements needed for a strong business case. This section lays the foundation upon which energy efficiency project options are built in the subsequent sections.

Office buildings have widely varying designs and uses, and building owners and facility managers face a variety of financial constraints. To address the diversity, this guide presents three levels of upgrade options in the subsequent sections: (1) Implementing operations and maintenance (O&M) improvements through Existing Building Commissioning (EBCx), (2) standard retrofits, and (3) deep retrofits. Significant savings can often be achieved with minimal risk and capital outlay by improving building operations and restructuring maintenance procedures. This process, commonly known as existing building commissioning, or EBCx. A nationwide study of commissioning projects by

Lawrence Berkeley National Laboratory found that office buildings typically realized 22% energy savings through EBCx, with an average simple payback period of 1.1 years. Standard retrofit measures provide cost- effective and low-risk efficiency upgrade options including equipment, system and assembly retrofits. Deep retrofit measures require a larger upfront investment and may have longer payback periods than O&M or standard retrofit measures. Another layer of diversity is created by the dependence of retrofit options on climate, so the upgrade options for standard and deep retrofits are customized for five different climates. This multi-level and multi-climate approach broadens the applicability of the guides to a wide range of situations.

The guide concludes with a discussion of strategies to ensure that the energy savings expected from the upgrades are achieved and persist over time. The first of these strategies, are to implement a measurement and verification (M&V) program, together with the upgrades, to ensure that improvements are operating as intended. The second key strategy is to optimize operation and maintenance (O&M) activities to maintain and continually improve building performance.

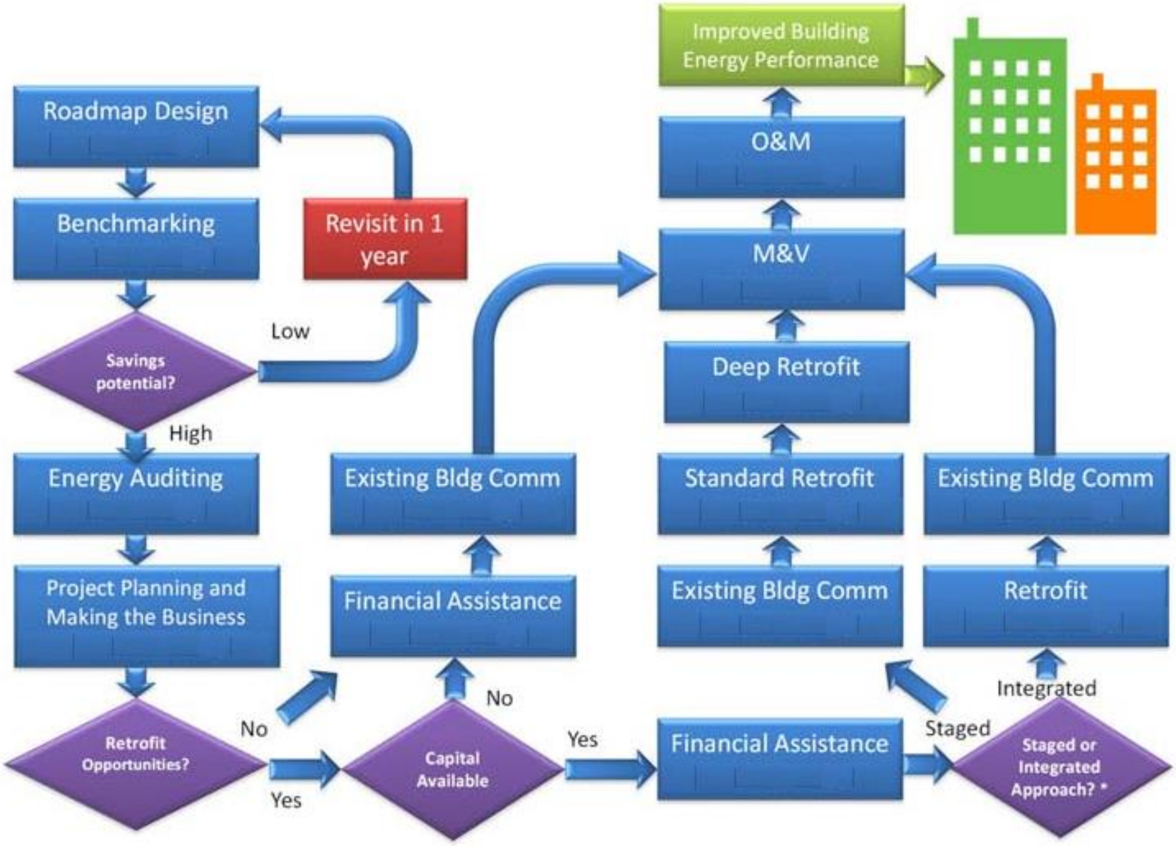


Figure 3 Project planning flow chart provided by advanced energy retrofitting guideline

2.2.2 UK's Building renovation strategy

This Building Renovation Strategy has been developed by Department of Energy and Climate change of United Kingdom in order to fulfil their obligation under Article 4 of the Energy Efficiency Directive as mentioned in section 2.1.1. The Strategy draws upon existing research and policy documents published by the UK Government to provide an overview of the UK's building stock and its energy efficiency performance, and the existing policies that are designed to enhance the performance of the UK's building stock. The Buildings Energy Efficiency Survey project showed that significant energy savings could be achieved in non-domestic buildings through the implementation of cost effective measures, primarily in space heating, particularly through the installation of measures like insulation, draught proofing and building control systems. Ultimately a change in fuel source for heating will be required to help meet the UK's target to reduce carbon emissions reductions by 80% by 2050.

The suggested cost effective measures to reduce energy consumption are:

Electrical energy efficiency: The most cost effective retrofit energy efficiency measure is lighting. This includes installing presence detection control and replacing lamps and fittings.

The use of smart meters will enable occupiers to better understand their energy consumption and encourage both energy efficient building operation, such as switching off PCs when not being used, and also the purchase of energy efficient equipment, such as printers and fridges.

Switching monitors off as part of an energy management programme is one of the top energy saving measures in non-domestic buildings.36

The efficiency of motors in fans, pumps and lift mechanisms can be improved by installing variable speed drives, automatic controls to switch them off when not required, and effective management, repair and maintenance.

Heating energy efficiency: Heating energy can be reduced by implementing relatively simple and cost effective measures such as programmable thermostats, reducing room temperatures, installing more energy efficient boilers, optimising system start times, and installing TRVs. Cost effective insulation measures can include installing roof and wall (cavity and internal) insulation, and low emissivity glazing.

Low carbon energy supply: Ground source and air source heat pumps can be used for heating and cooling.37 Viability for retrofitting ground source heat pumps will be dependent on land availability around the building for installing the underground pipes.

The cost effectiveness of combined heat and power (CHP) systems is highly site specific. A common cost effective retrofit application is the replacement of a boiler with a CHP unit in a central energy centre for a hospital or university campus.38

Behavioural measures: Significant potential has been identified from behavioural savings, particularly associated with the roll out of smart meters. There is a much greater range of control options for energy consuming systems which can be retrofitted in non-domestic buildings compared with domestic properties. This includes simple devices such as TRVs as well as full Building Energy Management Systems retrofitted with minimum disruption through the use of wireless meters and sensors. Product innovation is producing much more intuitive user interfaces and visual displays for these systems leading to greater engagement and understanding of energy consumption patterns by occupants.

International engineering consulting firm ARUP (ARUP UK 2008) has developed a 5 step survival strategies for the existing building stock of UK. It outlines the issues experienced by building owners and occupiers and sets out a five step process (Figure 4)for developing a strategy to turn a tired asset into one that benefits users, communities, the environment, business and the balance sheet.

The first step towards upgrading an existing property is to understand its current status, or baseline. In order to establish a building's baseline, the owner needs to assess two primary issues: current performance and operations of the building, and how the building is positioned against the current code and regulatory requirements. At this step, Energy and water auditing is carried out to determine the areas of largest consumption and target areas for improvement. In addition, a condition audit is also carried out to determine the current condition and expected remaining economic life of a building's component. Based on the reports of building condition and performance, the level of refurbishment required is decided.

The next step is maintenance and purchasing review step which doesn't cost much, but can lead to significant performance improvements. The outcomes of this step will include maintenance procedure changes and repairs to building fabric, controls, ventilation, refrigeration, lighting, hot water, and motors and drives. The case studies showed that significant improvements can be made with minimal cost through purchasing review, energy procurement, improved maintenance regimes and re-commissioning building services.

After establishing a baseline and assessing the building's operations, the next step is to focus on where the owners want the building to go. A great deal of consideration should be given to this process before any building works are contemplated and cost plans prepared. Understanding the goals and aspirations will serve as a driver in developing a specific upgrade plan for a given property. It is important to also make sure these are in line with the target level of performance that is achievable for a particular building.

Step #1 Determine your baseline and appropriate level of refurbishment

Step #2 Review your building maintenance, housekeeping and energy purchasing

Step #3 Establish your targets and goals

Step #4 Select your optimal upgrade initiatives

Step #5 Make your survival strategy happen

Figure 4 Five step survival strategies for existing buildings in UK

The next step is to identify optimum upgrade initiatives. There is no one solution or approach for any building upgrade; each initiative needs to be assessed based on its merits and the building in question. The key parameters that are considered while selecting the optimum retrofitting options are level of refurbishments, capital cost and qualitative benefit of the initiative to sustainability, building occupants and owner. A list of 195 initiatives has been provided to help the owner to get started.

The final step is to implement the selected retrofit options to the building and deliver the benefits of reduced energy consumption, water use and other efficiencies. Decisions have to be taken regarding the sequence of retrofitting implementation: Will the upgrades be phased progressively or will they all be carried out at once? Depending on the works to be implemented, tenants or occupants may need to be relocated temporarily.

2.2.3 Singaporean building retrofit guidelines

In Singapore, a six step process has been developed by Building and Construction Authority (BCA) Singapore based on retrofitting strategies from ARUP to turn a tired asset into a more competitive, more sustainable and more efficient one (BCA Singapore 2010). The proposed six step process has been outlined in Figure 5. The difference between the original ARUP guideline and Singapore guideline is that in ARUP guideline decisions regarding level of refurbishment required is taken in step one whereas in Singapore guideline the decision is made at step 4. The list of suggested initiatives has been updated for Singapore perspective.

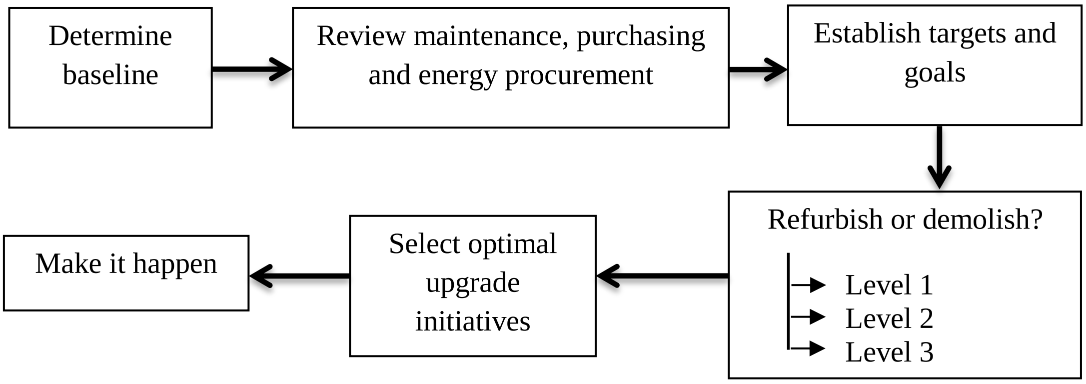


Figure 5 Singapore's six-step building retrofitting process

2.2.4 Australian Existing buildings survival strategies / guidelines

In the Australian context, the "Existing buildings survival strategies: A toolbox for re-energising tired assets" retrofitting guide (ARUP AUS 2008) is considered as one of the best practice guidelines available to the retrofitting industry. In this guide, the upgrading of existing office buildings can be achieved through the implementation of a six-step plan, including determining the baseline, establishing goals & targets, reviewing building maintenance, housekeeping and energy purchase strategy, crunching time: establish or demolish, and selecting optimal upgrade initiatives and getting started. This guideline is mostly similar to that of Singapore discussed in section 2.2 except that step 3 in the Singapore guideline is now step 2 in Australian guideline and step 2 in Singapore guideline is step 3 in Australian guideline.

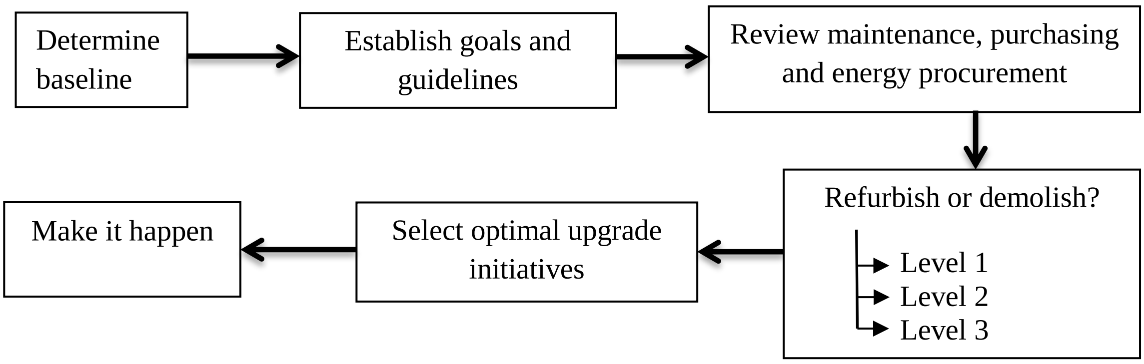


Figure 6 Australia's six-step building retrofitting process

2.2.4.1 City of Melbourne's 1200 building retrofitting program

The City of Melbourne council also developed a building retrofit map under their 1200 Buildings program which is shown in Figure 7 (The City of Melbourne 2010). The baseline assessment step determines how much energy and water the building consumes undertaking an energy/ water benchmarking tools NABERS and Green Star. The retrofit action plan stage explores different retrofit strategies, selects optimum strategies through necessary analysis and determines funding sources. The next stage is the "undertake retrofit works" were retrofit action plan is implemented. At this stage one has to communicate with tenants (if applicable), apply for planning/building approval if necessary, organize builder to carry out the work etc. In the annual update stage, the progress of retrofit implementation is monitored and compared with the retrofit action plan to see whether the project is in right track. Once the retrofitting is completed, commissioning of the retrofitted building is undertaken to achieve the best result in the complete work stage. The building tenants/managers and contractors are trained to ensure optimum ongoing operational efficiency. Finally, the building is re-assessed one year after the completion of final works to quantify the extent of savings.

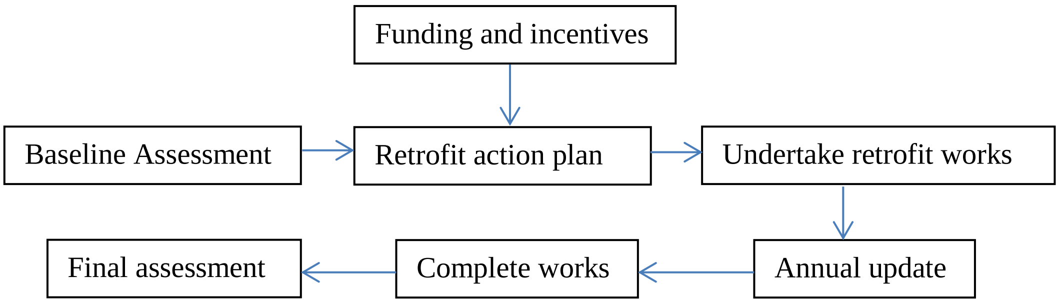


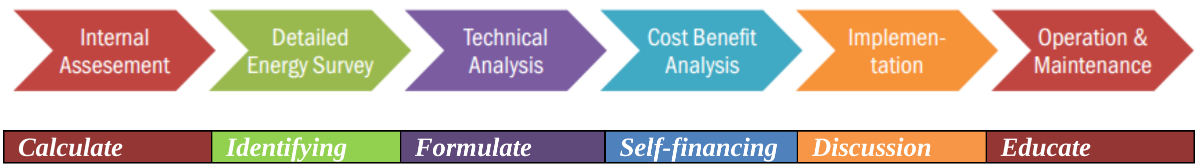
Figure 7 City of Melbourne's 1200 building retrofitting process

The eight point check list for non-residential building owners and managers are provided by NEEBP (2014):

1. Understand a building is an energy using system.
2. Understand the main routes to energy efficiency
3. Include energy efficiency in the design process
4. Do a whole building energy assessment
5. Know the roles of those involved with the alteration.
6. Choose energy efficient products and make sure that they are used
7. Check and inspect
8. Tune and maintain for energy efficiency

2.2.5 Indian energy efficiency retrofit roadmap

The goal of this roadmap is to define various levels of efforts needed for energy efficiency in existing commercial buildings and thus provide a reference steps for building owners, managers, government entities and other consumers sharing different levels for energy assessments & procedures in India. There are six main steps in this roadmap (Figure 8) for energy efficiency retrofits in existing buildings (TERI 2013).



building gross area *Review energy bills* *Estimate energy performance index*	*goals* *Team selection* *Energy Mapping of buildings* *Data collection* *Questionnaire review* *Data segregation & Measurement*	*action plan* *Benchmarking assessment* *Performing Energy Simulation* *Formulate retrofit action strategy*	*retrofitting model* *Partnering with energy services company*	*with facility manager* *Operational schedules and characteristics* *Conducting site visits*	*maintenance staff about building efficiency parameters.* *Monitor performance of energy system* *Identify areas for further improvements*

Figure 8 India's existing building energy retrofits roadmap (TERI 2013)

The internal assessment includes 1) determining the building total built-up area, 2) Collecting utility bills for at least one year to calculate total energy used. 3) Calculation of energy performance index (EPI) which is the ratio of total annual energy used to the total built-up area (kWh/sq.m./year) and 4) Comparison of the calculated EPI having similar characteristics with climatic zones.

Next step for carrying out the retrofit measures, after assessing buildings' energy performance for energy conservation in the building is to carry out detailed energy survey with the help of energy auditing team for understanding the energy system for the building.

Technical analysis step studies the data from the energy survey, including energy consumption and peak demand analysis. It identifies and provides technical parameters by selecting electrical products option through energy simulations. With more extensive data collection and engineering analysis, this plan provides most of the information which can be acted upon. Based on the retrofits options available for energy efficiency, detailed analysis are carried out by formulating action plan, benchmarking assessment and analysis through software.

For a commercial building, after finding out the option with technical analysis, capital payback calculations are needed to be performed to choose the best retrofit option as per the user requirement and budgetary constraints. Some measures are very cost intensive and can be eliminated with discussions; low-cost options can be used.

Once the retrofit plan is finalized after conducting a thorough cost benefit analysis, the next step is to work on implementing the retrofit. Proper project planning should be done in terms of assigning appropriate timelines, understanding the commitment and involvement mechanism as well as project finance so that the implementation is seamless.

To ensure recurring energy savings of a building, it is essential to include all the required parameters within the gamut of operation and maintenance. Educating maintenance staff about building efficiency parameters along with financial and non-financial benefits can prove the key measure in the energy efficiency in the existing buildings. Goal should be to maximize building operational efficiency with better health and comfort of occupant.

3. Building retrofit barriers and challenges

3.1 Barriers

Numerous barriers against energy efficiency uptake have been identified by BPIE(2011) thrugh a detailed survey of across 29 countries. The survey identified four main categories of barriers that have a particular impact on existing buildings. Figure 9 presents a schematic summary of the four main categories of barriers:

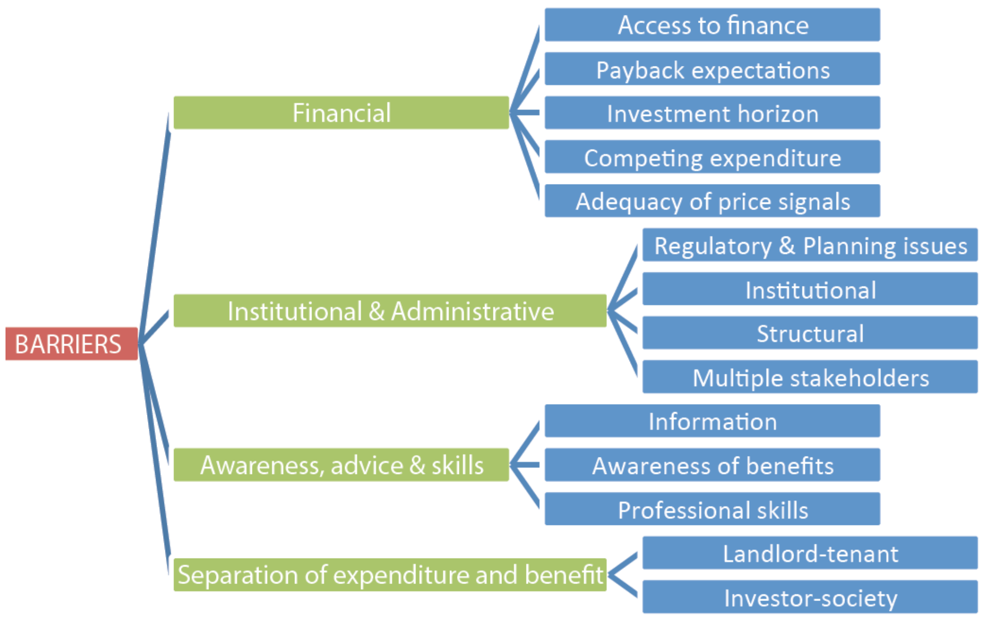


Figure 9 Main types of barrier encountered in building renovation (BPIE 2011)

Table 1 describes the barriers of energy efficiency uptake in more details.

Table 1 Barriers of building energy efficiency uptake (BPIE 2011)

Financial barriers	
Access to finance	One of the most cited barriers to investing in energy efficiency measures
Payback expectations/ investment horizons	Time taken for the initial outlay to be recouped is a major barrier. Decide against retrofit investments that do not pay for themselves within 3-5 years
Competing purchase	Prioritise what are perceived as core investments in staff and

decisions	equipment over energy costs
Price signals	Have a higher propensity to undertake energy retrofit investments, if the financial incentive associated with it is sufficiently large.
Institutional and administrative barriers	
Regulatory & planning issues	Fragmentation, delay and gaps in the regulatory action of public planning have not allowed the public sector to be the driver for improved energy efficiency in buildings.
Institutional	There is a bias among institutional investors more familiar with (and hence more comfortable with) supply- side investments and large-scale financing, rather than generally smaller (and "more risky") projects on the demand side
Structural	Average age of the building stock is increasing because of a low demolition rate. Because of the age of buildings, the landlord-tenant dilemma makes it difficult to ameliorate the existing building stock.
Multi-stakeholder issues	It can be very difficult to agree on energy saving investments in multi-owner buildings if many different property owners have to either approve a decision or make a financial contribution.
Awareness, advice and skills barriers	
Information barrier	In some cases consumers are not aware of or do not fully comprehend the effectiveness of specific technologies. This may lead to scepticism over implementing a technology especially if two or more professionals give supposedly conflicting advice as to the best way to renovate.
Awareness of potential/benefits	While there is a general appreciation that energy saving is a "good thing", there remains a lack of understanding of the energy, cost and carbon savings from different measures
Skills & knowledge related to building professionals	Skill shortages exist in both the contractor market responsible for effective installation of energy saving measures, as well as in professional services, with few architects and designers familiar with how to specify a low energy renovation
Separation of expenditure and	

benefit	
Split-incentive barrier/ landlord-tenant barrier	The problem originates from the fact that one person or organisation owns a building and someone else uses it. For the owner, any investment has to bring a benefit which is not necessarily through energy savings, unless it is a situation where the landlord pays the energy bills (this may sometimes be the case). Since the tenant does not own the facility, any investment in lowering energy bills has to be seen as financially advantageous for both actors. This often leads to a stalemate with nothing happening

3.2 Challenges

Almost none of the above barriers relate to market or technical issues. This is understandable since the lack of activity resulting from the financial, structural and other barriers have not allowed many, if any, of the market and technical barriers to emerge or become apparent. The barriers undoubtedly exist as latent risks. If conditions were to change dramatically and demand for low energy renovations suddenly increased there would inevitably be issues regarding shortages of materials, components and human resources (BPIE 2011). Figure 10 represent some of the major challenges that have to be considered in developing a robust and comprehensive retrofit strategy.

Figure 10 An illustration of the main risks which need to be addressed for market uptake (BPIE 2011)

Supply chain

Market and supply chains will certainly develop over time but short term we are facing risks. For example, a significant shortage of material, components and suitably skilled labour could lead to renovation work not including low energy measures.

Quality of Workmanship

Another side-effect of a significant increase in demand could be the rapid growth of contractors offering to undertake low energy renovation work, which if not appropriately regulated or managed, could give rise to poor workmanship and even some serious short term failures.

Technical failure

A similar and potentially more troubling concern that has been voiced by many in the industry is the risk of building-in long term failure risks that may not emerge for a decade or more. if such failures began to occur on a large scale in several years they could result in a massive loss of confidence and a halt in major renovation programmes. Technical failure may include inaccurate energy savings prediction, new energy efficient materials, construction technique etc.

Disturbance

Another barrier that has yet to emerge is the practical issue of what happens to the building occupier when a major renovation is being undertaken. It is probably seen a barrier at the moment given that occupants may not want to entertain the disruption involved in a major building renovation. In most cases deep renovation can only be implemented in a vacant building which will involve practical and financial barriers associated with re-locating the occupant for the period of the retrofit.

4. Review of research on building energy and water retrofit strategies

Figure 11 illustrates a systematic approach to identifying, determining and implementing the best retrofit measures for existing buildings according to Ma et al (2012). The overall retrofit strategy consists of two parts: (a) strategic planning and models/tools selection and (b) major retrofit activities in the whole building retrofit process. The strategic planning and models/tools selection are to provide necessary information and resource support for retrofit activities. The author stressed that regular monitoring of building system operation and frequent review of the operational data in the persistence period (i.e. post-retrofit period) are needed to ensure that the system continues to operate in an efficient manner. This is essentially important for performance contracting projects that need to continuously determine energy savings.

The retrofitting starts with establishing goals, building audit and energy performance monitoring of an existing building. Latter, audit data is used to develop a base-case simulation model. If audit data is positive for retrofitting, the base case simulation model is used to quantify the energy benefits of different retrofit measures. There are a number of whole-of-building energy simulation packages, such as EnergyPlus, eQUEST, DOE-2, ESP-r, BLAST, HVACSIM+, TRNSYS, etc., that can be used to simulate the thermodynamic characteristics and energy performance of different retrofit measures. Lee et al (2015) presented a DEEP (database of energy efficiency performance) approach that provides a direct resource for quick retrofit analysis of commercial buildings. DEEP, compiled from the results of about ten million EnergyPlus simulations, enables an easy screening of ECMs (energy conservation measures) and retrofit analysis. The simulations utilize prototype models representative of small and mid-size offices and retails in California climates.

By using appropriate economic analysis tools and risk assessment methods, the performance of a range retrofit option is assessed quantitatively. A number of decision support tools have been developed by previous researchers to select the optimum retrofit option based on costs, risk or any preference of stakeholders. A review of the available decision making tool have been presented in Appendix 1. The next stage is the implementation of selected retrofit measures on-site. Test and commissioning (T&C) is employed to tune the retrofit measures to ensure the building and its services systems operate in an optimal manner. The final phase is validation and verification of energy savings. Once the retrofit measures are implemented and well-tuned, standard M&V methods can be used to verify energy savings. A post occupancy survey is also needed to understand whether the building occupants and building owners are satisfied with the overall retrofit result. Similar approach can also be adopted for sustainable water retrofitting of building.

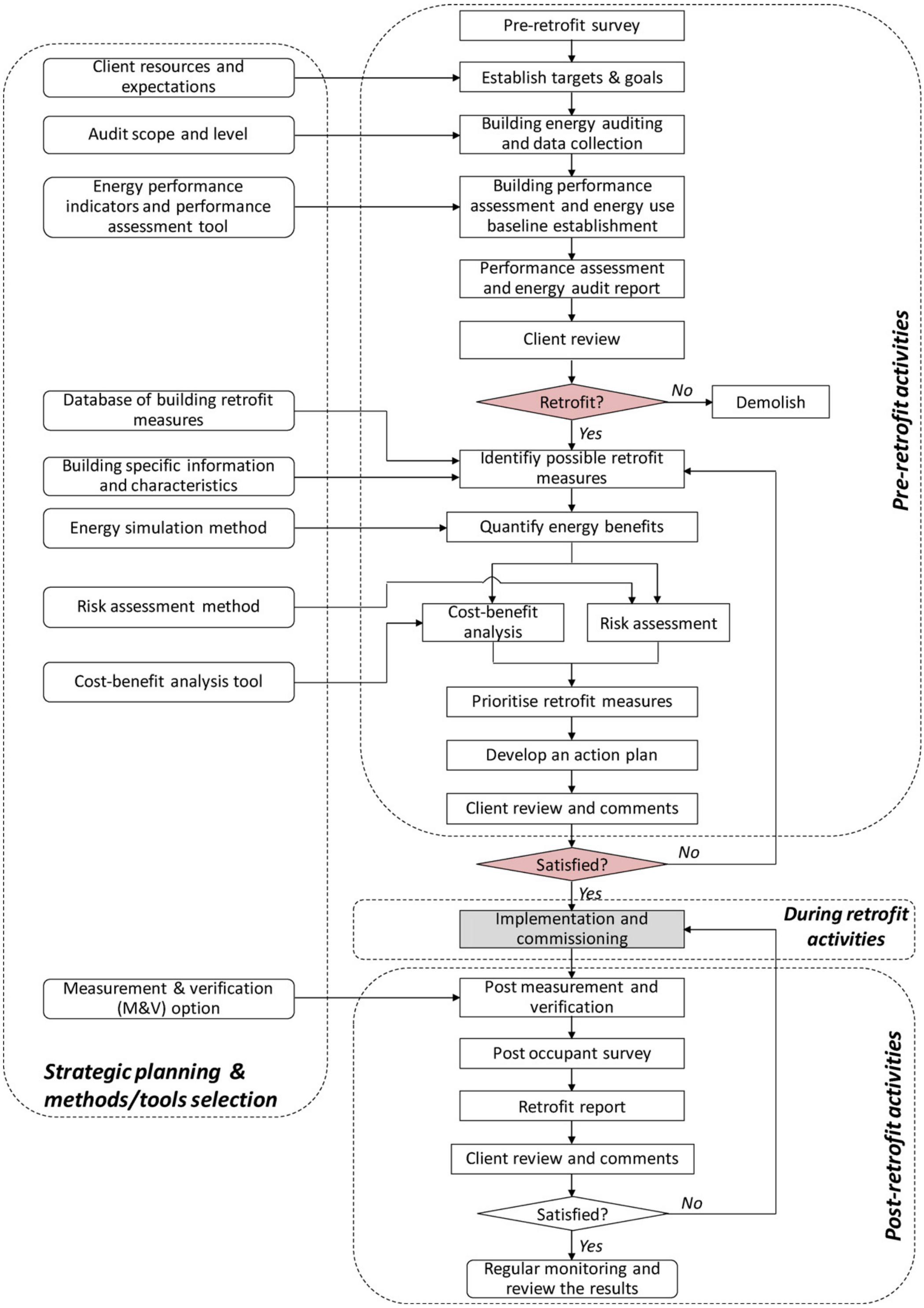


Figure 11 A systematic approach for sustainable building retrofits. (Ma et al 2012)

4.1 Categories of retrofitting measures

A significant amount of research has been carried out to develop and investigate different ERMs in order to improve energy performance of existing buildings. A review of the effectiveness of different ERMs has been presented in Appendix. From the review, the ERMs of buildings can be categorised in to following five categories presented in Table 2.

Table 2 Categories of building energy retrofit measures

Categories	Retrofit technologies
Building Envelope	• Improvement of fabric insulation level • Weather stripping windows and doors/ Increase air tightness • Use energy efficient window glazing, etc.
Passive technologies and energy efficient equipment	• Use of window shading to reduce solar heat gain in summer • Night ventilation • Use of thermal storage materials (e.g. phase change materials) • Energy efficient equipment and appliances, etc.
Lighting Upgrade	• Use of high efficiency lamps • Use of time scheduled control • Improvement of luminaries and installation of reflectors, etc.
HVAC, Building management and control	• Improve occupant behaviour through education • Use of heat recovery unit in HVAC • Replacement of inefficient HVAC equipment (e.g. Boiler, condenser etc.) • Use of BMS. • Adjusting the set-point, etc.
Renewable Energy	• Install Solar PV/PVT systems, wind power systems, geothermal systems, biomass systems etc. • Buy green power.

Table 3 Categories of building water retrofit measures

Categories	Retrofit Technologies
Water appliances	• Use higher star rated appliances (shower head, tap, flush tank washing machine etc.)
Water recycling	• Use of rainwater tank • Use of recycled water for gardening, toilet flush etc.
Maintenance	• Inspect water pipeline for leakage

4.2 Causes and risks of energy performance gaps

With the increasing demand of energy efficiency, the building industry is faced with the challenge to ensure that the energy performance predicted during retrofitting decision making stage is achieved once the building is in use. However, significant evidence suggests that buildings are not performing as designed. Building retrofit projects requires large investment, technology and equipment upgrade and change of occupant behaviour, which is associated with many challenges arising from technical issues such as energy simulation tool, architectural and engineering design options, equipment selection, construction workmanship, material quality, occupant behaviour and future weather predictions. The uncertainties involved in those factors can lead to large discrepancies between real and predicted energy savings which can frustrate building owners, engineers, investors and can hinder the investment for energy efficient retrofitting (Sun et al., 2016). The mismatch between the predicted and actual energy performance, known as "performance gap" (Figure 12), can be as much as 2.5 times the predicted energy consumption (Wilde 2014).

Inaccurate predictions are likely to become significantly more problematic for the industry as new financing schemes such as Environmental Upgrade Agreements (EUAs) and Energy Performance Contracting (EPCs), relying on predicted savings are introduced locally and internationally. The retrofitting case study of Lee et al. (Lee, Lam et al. 2013) showed that the chance achieving mean value of energy savings through installation of proposed retrofitting measures is only 47% because of the uncertainties involved, which means there is a substantial risk if the EPC goes ahead without any risk analysis of the retrofitting projects. Hence, the development of building energy retrofit decision model is crucial to carry out building retrofitting projects in Australia systematically and efficiently considering potentials risks.

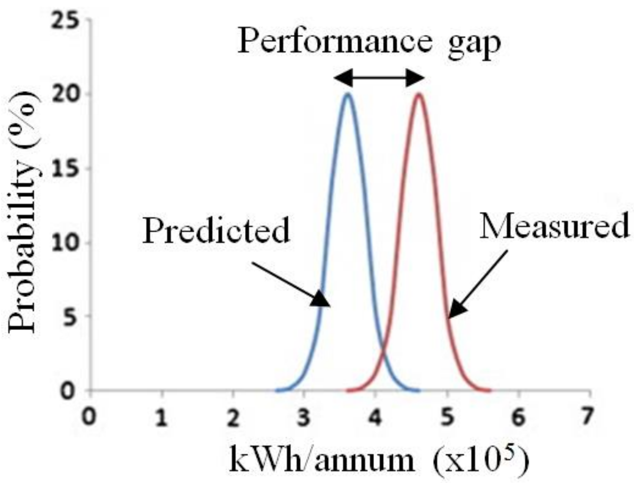


Figure 12 The energy performance gap (Wilde 2014)

Literature on the energy performance gap suggests various causes for the mismatch between prediction and measurements. These causes can be grouped in three main categories: causes that pertain to the design stage, causes rooted in the construction stage (including handover), and causes that relate to the operational stage (de Wilde 2014).

Within the design stage, Issues can start from mis-communication about performance targets for the future building between client and design team, or between the members of the design team (Newsham et al. 2009, Morant 2012). A further key problem is that design teams often cannot fully predict the future use (functions) of the buildings; operational requirements and conditions might thus be subject to significant change (Korjenic and Bednar 2012, Dasgupta et al. 2012). The second cause of a performance gap within the design stage relates to modelling and simulation as they are the key components of any prediction. Any use of incorrect methods, tools or component models will result in unreliable predictions and a gap later down the line.

During the construction stage, performance gap may arise from lack of attention to insulation and airtightness and not building according to specification (de Wilde 2010). Finally, the operational side also contributes to performance gap. Occupant behaviour is often different from the assumptions made in the design stage and is often cited as the main reason for the performance gap (Korjenic and Bednar 2012, Dasgupta et al. 2012, Haldi and Robinson 2008, Menezes et al. 2012). Table 4 summarised main cause of discrepancies between predicted and actual energy performance of buildings.

Table 4 Causes of discrepancies between predicted and actual performance

Design stage	Design Assumptions	The input of data into a building energy model relies significantly on assumptions, which often go unchallenged. These are usually made at design stage when many aspects of the building's function and use are unknown or uncertain. This can result in oversimplified and/or unrealistic inputs regarding the built quality and fabric performance, occupancy patterns and behaviour as well as the management and control of the building and its services.
	Modelling tools	Building energy modelling software can contain fundamental errors embedded in the equations used by the program, leading to inaccuracies in the predictions. The choice of software should also consider the specific type of building being modelled and should allow for adequate representation of the building itself as well as its use and operation. The correct use of tools alone is insufficient; the tool user/analyst/modeller also needs to have the right knowledge and skills and the ability to apply these in the right manner. Even with a correct model applied by a well-trained analyst, all predictions remain subject to fundamental uncertainties, especially with regards to variation in aspects such as actual weather conditions, occupancy schedule, internal heat gains, and plug loads
Construction stage	Built Quality	The in-use energy performance of a building is affected by the quality of its construction. Issues such as gaps in the insulation and thermal bridging are common, but are rarely considered in the predictions of energy consumption. Moreover, changing requests from clients and/or value engineering exercises can result in significant deviations from what was originally specified. Yet these alterations are rarely

		fed back into the energy model.
Operational stage	Management and controls	Facilities managers (FM) have control over central plant equipment, accounting for a great portion of the energy consumption in a building (especially in highly automated buildings). Good management and controls can result in an efficient operation of the building services whilst inappropriate strategies can result in unnecessary waste of energy. Frequent energy audits as well as re-commissioning exercises can help maximise the efficiency of building services, avoiding unnecessary energy waste.
	Occupancy behaviour	Building occupants do not always have direct control over building services such as heating and cooling, yet even in highly automated buildings, occupants can affect their energy consumption by influencing the internal conditions (e.g. opening windows, blocking air inlets/ outlets, etc.). Assumptions regarding occupant behaviour often lead to a mismatch between input for any calculations/ simulations and actual values for internal gain and plug load. In terms of water consumption and saving analysis, there has been differences between the theoretical and actual reported savings when retrofitting water use appliances from a low star rating (e.g. 2 star shower head) to a higher star rating (e.g. 4 star). People may compensate their low flow rate showerhead with having a longer shower (Willis et al. 2010).
	Weather scenario	If the real weather varies significantly from the assumed weather during design stage, it will introduce discrepancies between actual and predicted energy consumptions. Rainwater harvesting and storage using rain tanks is often considered as a water saving measure when retrofitting buildings but there is considerable uncertainty in the supply reliability of this source due to weather fluctuations and even more water-related energy uncertainty (Talebpour et al 2014, Vieira et al. 2014).

4.3 Risk analysis

Risk analysis is essential to transform risk in practice to simulations and provide decision makers with a sufficient level of confidence to select and determine the best retrofit solutions. The first step of risk analysis in building energy performance prediction is to determine the uncertainty distribution of input parameters. Uncertainty parameters can be divided in three categories: physical, design and scenario uncertainty (Hopfe and Hensen 2011). Physical uncertainties are due to uncertainties in physical properties (such as conductivity, specific heat solar absorbance, thickness of materials). Their existence is inevitable; however, they can be identified and quantified with measurements and tests. Design parameters uncertainties can be described as design variations that occur during the planning process. Scenario uncertainties include changes in parameters during the operating stage of the buildings such as occupancy pattern, behaviour, internal load, weather etc. Taking scenario uncertainties into account is very important when considering design robustness and future adaptability of the building. Uncertainties in physical parameters and user behaviour have significant influence on the prediction of building energy consumption. The details of risk analysis methodology have been presented in Appendix.

5. Discussion

In this report, a comprehensive analysis of national level building retrofitting strategies, individual building retrofitting guidelines of several countries and research to date on building retrofitting strategy have been carried out. In addition, barriers and challenges against the uptake of building retrofitting measures have been explored.

Among the reviewed national level retrofitting strategies, the nine step procedure developed by EU Joint Working Group is found to be the most comprehensive one. In these nine steps, the tasks later stages generally influenced by the outcomes of the earlier stages. However, it is possible that there may also be some reverse interactions which lead to a degree of iteration or adjustment to the outcomes or earlier stages. In this guideline, a set of questions are outlined for each step which will help the authorities to arrive at well integrated and coordinated strategies for their country. In addition, the proposed nine step procedure addresses the renovation strategies of EED Article 4 from European commission:

(a) an overview of the national building stock based, as appropriate, on statistical sampling – Step 3;
(b) identification of cost-effective approaches to renovations relevant to the building type and climatic zone – Steps 3 and 5;
(c) policies and measures to stimulate cost-effective deep renovations of buildings, including staged deep renovations – Steps 5 and 7;
(d) a forward-looking perspective to guide investment decisions of individuals, the construction industry and financial institutions – Steps 2, 5, 7 and 8;
(e) an evidence-based estimate of expected energy savings and wider benefits – Steps 3, 5 and 8.

However, development of national level building retrofitting strategy is beyond the scope of current SBEnrc 1.43 project and therefore has not been discussed further in this report.

Table 5 shows the comparison of individual building retrofitting guidelines discussed in section 2.2 as well as the proposed retrofitting guidelines in this project. The proposed retrofit guideline has been developed based on the available retrofitting guidelines and previous research outcome. The table points out that the “Advanced Energy retrofit guide” from U.S. department of energy covers all steps of the proposed retrofitting guidelines except risk analysis. The U.S retrofit guideline discussed about three levels of building retrofit measures and suggested a number of retrofit packages for level. The suggested retrofit options as well as cost-benefit analysis are customized for five different climates of USA which has broadened the applicability of the guides to a wide range of situations. In addition, the possible approaches for financing the retrofitting projects have been listed. This guideline concludes with strategies for measurement & verification (M&O) and operation & maintenance (O&M) of retrofitted buildings. Measurement and verification (M&V) is the practice of measuring, computing and reporting the results of energy saving projects. Proven M&V strategies provide a means to accurately estimate the energy savings by making adjustments to account for these fluctuations, allowing the comparison of baseline and post-installation energy use under the same conditions. Operations and maintenance (O&M) is the combination of mental (operations) and physical (maintenance) activities that are required to keep a building and its energy systems functioning at peak performance. Operations focus on the control and performance optimization of equipment, systems, and assemblies. Maintenance typically refers to routine, periodic physical activities conducted to prevent the failure or decline of building equipment and assemblies.

The guidelines for UK, Singapore and Australia are developed based on "*existing building survival strategies*" from ARUP. Similar to the USA one, these guidelines also reported different levels of retrofit measures. A simple table is proposed to determine the level of refurbishment required based on existing building performance and conditions. The guidelines also include two separate tables for assessing building performance and conditions. A list of possible retrofitting initiatives have been presented including level of retrofit, capital cost, effect on occupant thermal comfort, benefits with respect to sustainability and benefits of owner. However, the guideline did not consider the risks involved in retrofitting projects and financing mechanism for funding the retrofitting project. In addition, nothing has been mentioned about M&V and O&M strategies for post-retrofitted buildings.

In Australia, the retrofit process developed by 1200 buildings program includes financing, M&V and O&M strategies. However, their proposed retrofit process does not include any methodologies for risk analysis, cost benefit analysis and selection of optimum retrofit measures. Finally, the retrofit guideline of India Proven M&V strategies provide a means to accurately estimate the energy savings by making adjustments to account for these fluctuations, allowing the comparison of baseline and post-installation energy use under the same conditions. Operations and maintenance (O&M) is the combination of mental (operations) and physical (maintenance) activities that are required to keep a building and its energy systems functioning at peak performance. Operations focus on the control and performance optimization of equipment, systems, and assemblies. Maintenance typically refers to routine, periodic physical activities conducted to prevent the failure or decline of building equipment and assemblies.

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Table 5 Comparison building retrofit guidelines of different countries and proposed strategy

Guideline compenents	USA	UK (by ARUP)	Singapore (by ARUP)	Australia (by ARUP)	Australia (City of Melborune 1200 Buildings retrofitting Program)	India
Baseline assessment	√	√	√	√	√	√
Energy Audit	√	√	√	√	√	√
Project planning • *Establish targets* • *Analyse potential barriers and challenges*	√	√	√	√	√	√
Exploration of retrofit measures • *Level 1* • *Level 2* • *Level 3 etc.*	√ √ √ √	√ √ √ √	√ √ √ √	√ √ √ √	√ √ √ √	√ [2]
Making business case of retrofit • *Cost-benefit analysis using simple payback period* • *Life Cycle Analysis*	√ √	√	√	√		√
Risk analysis *Investment risk* *Performance risk*						
Selection of optimum retrofit measures	√ [1]	√ [1]	√ [1]	√ [1]		√ [1]
Financing	√				√	
Implementation	√	√	√	√	√	√
Measurement and Verification (M&O)	√				√	
Operation and maintenance (O&M)	√				√	√

[1]Without considering risks
[2] did not divide retrofit measures in different levels.

In Australia, the retrofit process developed by 1200 buildings program includes financing, M&V and O&M strategies. However, their proposed retrofit process does not include any methodologies for risk analysis, cost benefit analysis and selection of optimum retrofit measures. Finally, the retrofit guideline of India touched almost every step of the proposed retrofit guideline except, risk analysis, financing and M&O strategies. Although the guideline discussed about selecting different retrofit measures no differentiation was made between the levels of retrofit options.

In Summary, the existing retrofit guidelines of different countries do not cover every aspects of building retrofitting process. The retrofitting guideline from U.S department of Energy is found to be the most comprehensive but does not consider the risks involved in retrofitting process. Therefore, in the present study, a retrofitting guideline has been proposed including every step required for building retrofitting process and presented in Table 5.

6. Retrofitting Case study

The retrofitting case studies will be carried out in retrospective approach. In other words, several retrofitted buildings in th emajor cities across Australia will be studied to map the retrofitting process implemented, key decision making criteria used and main decision making process followed, and draw the lessons learned from these retrofitted building projects. The outcomes of the case studies will be used to verify the proposed Autralian National Building Retrofitting Guidelines as part of the outcomes from this research.

Below are some sample questions to ask during case studies.

Baseline Assessment

1) What performance indicators were used for baseline assessment (Pre-retrofit conditions) of this Building?

PCA Quality Grade Matrix	Indoor Environment (NABERS)
NABERS Energy rating	Others _______________
NABERS water rating	

Building audit

1) What types of audit was carried out?

Energy Audit	
Water Audit	
Condition Audit	
Occupant Satisfaction Audit	
Building Management Audit	
Indoor Environment quality Audit	

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8. Appendix – Review of retrofit teachnologies and risk-based decision mking models

8.1.1 retrofit technologies

Hestnes and Kofoed (2002) evaluated a set of retrofit strategies designed for ten existing office buildings in Denmark, England, France, Germany, Greece, Italy, Norway, Sweden and Switzerland. The retrofit strategies considered include combinations of building envelope improvements, the use of passive cooling techniques, lighting, and HVAC improvements. The results showed that it is possible to significantly reduce the use of purchased energy in existing office building through implementing passive and low energy retrofitting technologies.

Dascalaki and Santamouris (2002) investigated the energy conservation potential of combined retrofitting actions for five building types in four different climatic regions in the European continent. The studied actions involve interventions on the building envelope, HVAC and artificial lighting systems as well as integration of passive components for heating and cooling. Interventions affecting the performance of the building in the global aspect were also assessed. Due to the particularities associated with each building as well as the regional climatic variability, it was not possible to generalize the conclusions drawn from their study. However, analysis of the results revealed common trends in the energy performance of different building types and permitted to extract information on the most suitable retrofitting interventions in each.

From their study with single and multiple retrofit measures (various retrofit combination of HVAC, lighting, window glazing etc.) Chidiac et al. (2011a) concluded that reduction in energy consumption through the application of multiple retrofit measures is not the sum of the impact of individual retrofit measures. The effectiveness depends upon their interactive effects. A screening methodology was further developed by the authors (Chidiac et al 2011b) in order to determine the feasibility and cost effectiveness of different retrofit measures for office buildings. This methodology uses the concept of building archetype modelling to develop a database, which is then employed to formulate a set of mathematical equations to estimate energy consumption of office buildings based on a set of key variables.

Ardente et al (2011) presented the results of an energy and environmental assessment of a set of retrofit actions implemented in the framework of the EU Project ‘‘BRITA in PuBs’’ (Bringing Retrofit Innovation to Application in Public Buildings – no: TREN/04/FP6EN/S07.31038/503135). The results showed that the most significant energy savings benefits are mainly related to improvement in the envelope thermal insulation (high-efficiency windows, and thermal insulating boards). Substitution of insulation, lighting and glazing components provided particularly efficient solutions. In all the case studies, renovation of HVAC plants and lighting systems provided significant energy benefits. Both for solar and wind plants, a generally overestimated energy production at the design stage was observed with respect to that monitored. That involved lower energy savings and higher payback indices than those predicted.

Griego et al (2015) indicated that the most cost-effective potential for energy conservation in both new and existing offices is achieved by reducing office equipment loads and more efficient lighting technology and controls. Over 49% annual energy savings can be achieved cost-effectively for both retrofit and new construction commercial office buildings. Aste and Pero (2012), presented an iterative methodology for energy retrofit of commercial buildings, together with a specific application on an existing office building. A reduction in primary energy consumption by 40% was achieved in the analysed case study through improving building envelope only, without intervention on HVAC plant, lights or other technical systems.

Ascione et al (2014) investigated the effect, during the cooling season, of the addition of latent heat thermal energy storage materials (LHTES) on the exterior building envelope. The results showed that significant cooling energy savings is possible if the proper LHTES material is selected depending on the local climate. However, it was reported that the LHTES material does not allow the same benefits throughout all months of cooling season.

Wang et al (2014) adopted a modified bin method to propose and optimize the energy efficiency retrofit (EER) schemes. An existing office building in Tianjin was selected as an example to demonstrate the procedures of formulating the design scheme. Two retrofit schemes of heating, ventilating and air-conditioning (HVAC) systems were proposed after the energy efficient retrofit (EER) of building envelops. It was reported that the thermal performance improvement of building envelops must be evaluated simultaneously along with the EER of HVAC systems. Otherwise, the energy saving goal would not be reached or even may end up with low energy efficiency because of the overload of building itself. With comprehensive consideration of energy efficiency and economic benefits, the recommended retrofit scheme that could improve the overall energy efficiency by 71.20% was determined.

Fiaschi et al (2012) performed energy analysis of public buildings (schools, offices, sport centres) and utilities (lighting) in Certaldo, Italy. In each case, possible retrofitting, including the introduction of renewable energy (such as photovoltaic PV or solar thermal), was analysed from both the energetic and economic points of view. The results showed that installation of PV modules guarantees an annual savings between 4.5% and 5% with respect to the annual cost of electricity. Upgrade of wall insulation lead to energy savings of approximately 40–50%, which agrees with the average values available in the literature for similar buildings. Regarding the sport facilities, the major energy savings (63%) were achieved with the installation of solar thermal collectors, especially for the swimming pool.

Virote and Neves-Silva (2012) reported that even though the energy efficient technologies are becoming more and more efficient, human behaviour still plays a very important role in the overall building energy consumption. Careless behaviour can add one-third to a building's designed energy performance, while conservation behaviour can save a third (Nguyen and Aiello 2013). Saelens et al (2011), analysed the influence of occupant behaviour on the energy performance and thermal comfort of a typical office floor equipped with a thermally activated building system (TABS) using TRNSYS. The results revealed that occupant behaviour has a considerable influence on the cooling demand and thermal comfort. It was shown that encouraging people to actively switch off the lights not only saves on the energy demand for lighting but also reduces the cooling demand and overheating issues.

Nguyen and Aiello (2013) concluded from their analysis that occupancy-based control can result in up to 40% in energy saving for HVAC system. Regarding lighting systems, also up to 40% of the lighting electricity could be saved by adopting a combination of modern control strategies, such as daylight harvesting, occupancy sensing, scheduling and load shedding. However, while conceptual benefits of occupant-related building control approaches have shown energy saving benefits, their feasibility must be confirmed in real-life installations. A number of occupant activity recognition technologies and approaches are discussed in reference (Nguyen and Aiello 2013).

Ferreira et al (2012) developed a neural network based predictive control model to control existing HVAC in buildings and showed that up to 50% energy savings can be achieved by having the model based predictive controller determining the operation of HVAC.

8.1.2 Retrofit decision support model

In order to optimize energy or cost savings from retrofit strategies, accelerating the adoption of ECMs (energy conservation measures) in buildings a number of retrofit analysis toolkits have been developed by previous researchers. Lee et al (2015) provided an up-to-date review of the features and capabilities of 18 building energy retrofit analysis toolkits that provide energy and cost savings solution for commercial buildings. Hong et al. (2015) developed a retrofit analysis toolkit for small and medium commercial buildings. This energy retrofit analysis toolkit, known as Commercial Building Energy Saver (CBES), calculates the energy use of a building, identifies and evaluates retrofit measures in terms of energy savings, energy cost savings and payback. The toolkit provides a rich set of features including: (1) Energy Benchmarking providing an Energy Star score, (2) Load Shape Analysis to identify potential building operation improvements, (3) Preliminary Retrofit Analysis which uses a custom developed pre-simulated database and, (4) Detailed Retrofit Analysis which utilizes real-time EnergyPlus simulations. CBES includes 100 configurable energy conservation measures (ECMs) that encompass IAQ, technical performance and cost data, for assessing 7 different prototype buildings in 16 climate zones in California, USA. The case study showed that CBES provides a new contribution to the field by providing a straightforward and uncomplicated decision making process for small and medium business owners, leveraging different levels of assessment dependent upon user background, preference and data availability.

Doukas et al (2009) presented of a decision support model for the identification of the need for intervention and further evaluation of energy saving measures in a typical existing building, based on the systematic incorporation of BEMS data (loads, demands and user requirements). The model was developed based on the experience database through systematic incorporation of energy data collected from the building energy management system to calculate building performance indicators (PIs). The calculated PIs are then compared with the corresponding standard PIs to evaluate building energy performance. The model’s output consists of a proposals’ list assigned to the categories (lighting, heating, cooling, electromechanical equipment and general) of the building described and at the same time financially evaluated so that each final list is to have an hierarchy from the most profitable to the less one regarding criteria such as net present value, the payback period and the internal rate of return.

Flourentzou et al. [91] presented an interactive decision aid tool (TOBUS) for office building diagnosis and decision making regarding suitable retrofitting methods. The software includes several modules, each of which address a particular aspect of the diagnosis including building description and dimensions, building diagnostics, indoor environmental quality, energy use, retrofit scenarios, cost analysis, and reporting results. It can support the user in establishing a complete file of building state and help to identify the actions required to upgrade building performance.

Juan et al. (2010) developed an integrated decision support system to recommend a set of sustainable renovation actions for existing office buildings. Figure 13 shows the architecture of this decision support system, which was developed based on the consideration of trade-offs among renovation cost, improved building performance, and environmental impacts. The optimal solution was determined using an optimisation technique that combines A* graph search algorithm with genetic algorithms (GA).

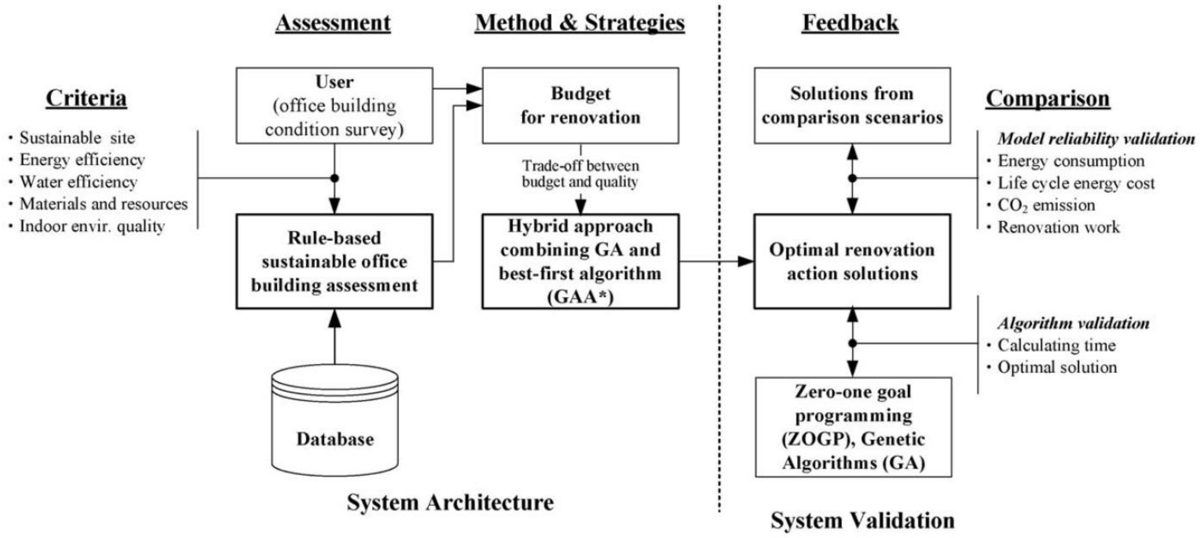

Figure 13 Architecture of decision support system by Juan et al (2010)

Hillebrand et al. (2014) introduced a new software tool to guide the retrofit optimization process for private and public office stock holders. The tool includes a detailed analysis of typical retrofit options for the building envelope and its supply system. In an automated calculation of retrofit options resulting in up to 64 combinations of measures, these bundles of measures are evaluated and visualized according to energy and CO_2-saving criteria as well as economic ratings. Regarding the economic evaluation, both detailed conventional economic analysis and advanced real options analysis was implemented for choosing between retrofit alternatives. The results of the energy, ecological and economic efficiency evaluation shows that a generally preferred retrofit option cannot always be identified. Specifically, for the test case, the best-rated economic refurbishment possibility leads to the largest increase in final energy demand amongst all options considered, which points out the necessity of a multi-criteria evaluation.

Rey (2004) developed a multiple criteria methodology for evaluating office building retrofit strategies. This methodology takes into account environmental, socio-cultural and economic criteria simultaneously. Shao et al (2014) presented a multi-objective optimization approach for decision making regarding optimum retrofit options. The framework contains an analysis procedure to be carried out by design team and a numerical procedure of optimization carried out by computer. The analysis procedure, which contains a quality function deployment model, allows the design team to identify and quantify stakeholders' concerns and needs in order to set up the optimization model properly according to the characters of the building. It is reported that inadequate consideration of stakeholders' requirements in the early design stage is a major cause of poor performance of construction project. In the optimization stages, the building performance assessment model consists of different modules to calculate the numerical indicators in terms of the selected design criteria. The methodology combines these approaches and is applied to buildings as a whole.

SBEnrc (2012) created a survey tool, the '*Performance Nexus'*, to evaluate the performance of different interventions focusing on the performance of and interaction between (1) green design elements, (2) indoor environment quality, (3) occupant experience, (4) agreements and culture, and (5) building management. The objective was to improve the energy performance of commercial buildings while fostering a productive environment, using these five interdependent factors. It was suggested that the '*Performance Nexus'* is a low cost, low complexity tool that can be used across the sector and around the world to encourage the greening of existing commercial buildings through a focus on enhanced productivity.

8.2 Risk-based retrofit decision making

8.2.1 Risk analysis

As presented earlier, a building retrofit is subject to many challenges such as uncertainty in savings estimation, energy use measurements, weather forecast, the changes of energy consumption patterns, system performance degradations, etc. Risk analysis is therefore essential to transform risk in practice to simulations and provide decision makers with a sufficient level of confidence to select and determine the best retrofit solutions. Figure 14 shows the steps involved in a typical risk analysis method. This step is based on the input parameters of a certain simulation program (EnergyPlus in this case) by identifying and generating probability distributions. It is possible to derive the probability distributions mathematically based on the range of values for the parameters or from specific information, manufacturer specifications for instance, directly from practice. Although it is better to include all uncertain parameters to get accurate results, this is difficult to realize due to the limitation of explicit data and time. Therefore a sensitivity analysis is required to eliminate the less important parameters and keep the most uncertain and influential ones (Spitz, Mora et al. 2012). The methods of sensitivity analysis applied in the domain of building analysis

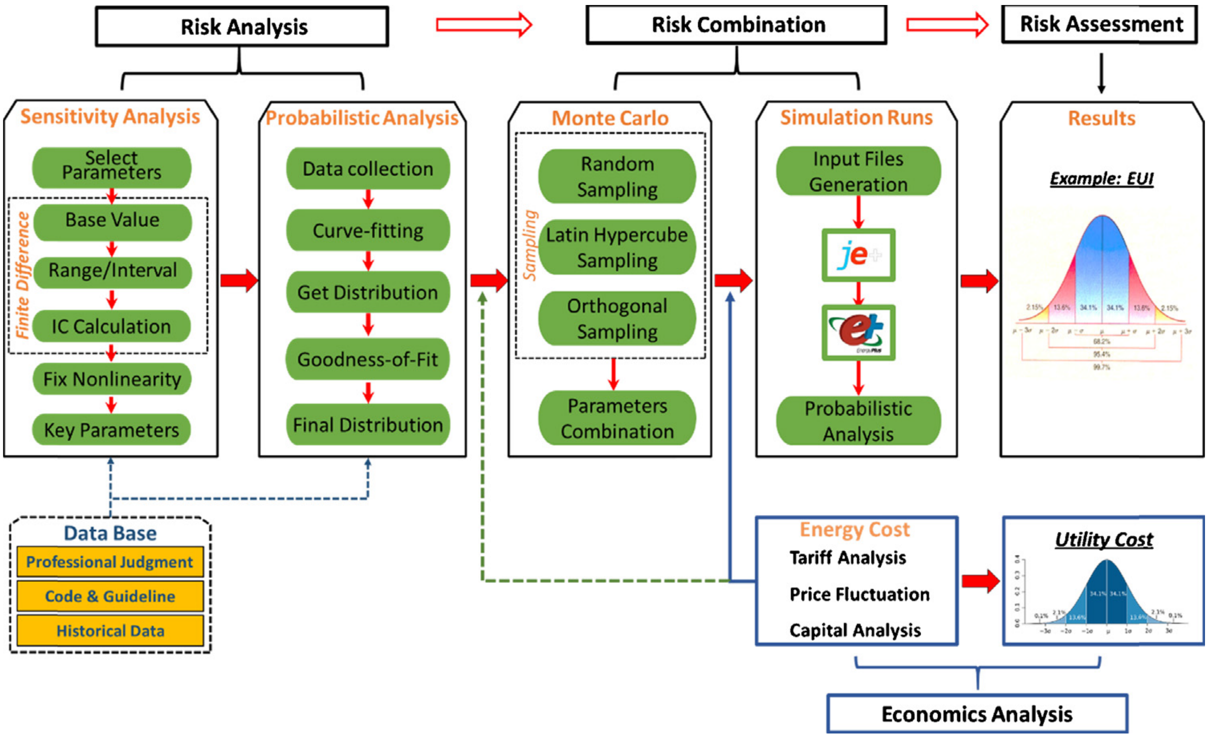

Figure 14 Risk Analysis Methodology (Sun et al 2016)

can be divided into local and global approaches. Local sensitivity analysis is focused on the effects of uncertain inputs around a point whereas global approach is more interested in the influences of uncertain inputs over the whole input space (Tian 2013). Rodriguez et al (Calleja Rodríguez, Carrillo Andrés et al. 2013) proposed a methodology to cluster unknown related parameters in sensitivity analysis to reduce the overall number of parameters and to improve the control over the sensitivity analysis. The choice of sensitivity analysis methods depends on many factors, which include computational cost of energy models, the number of input variables, the analyst’s time for a project, the familiarity of sensitivity methods (Tian 2013).

Uncertainty parameters can be divided in three categories: physical, design and scenario uncertainty (Hopfe and Hensen 2011). Physical uncertainties are due to uncertainties in physical properties (such as conductivity, specific heat solar absorbance, thickness of materials). Their existence is inevitable; however, they can be identified and quantified with measurements and tests. Design parameters uncertainties can be described as design variations that occur during the planning process. Scenario uncertainties include changes in parameters during the operating stage of the buildings such as occupancy pattern, behaviour, internal load, weather etc. Taking scenario uncertainties into account is very important when considering design robustness and future adaptability of the building. Uncertainties in physical parameters and user behaviour have significant influence on the prediction of building energy consumption.

8.2.1.1 Probability Analysis

Probability analysis is used to develop the probabilistic distribution function (PDF) for each of the identified parameters from sensitivity analysis. This is a critical step in this analysis as the PDF represents the variations of each parameter in practical situations. Those variations are bearing the small pieces of risk in energy efficient building projects (Sun et al 2016). A scalable and probabilistic methodology that can support large scale investment in building retrofits under uncertainty was recently developed by Heo et al. (2012).

8.2.1.2 Risk amalgamation

Risk amalgamation is the step to collect all small pieces of risks into whole risk. The Monte Carlo method is used to translate the uncertainty in inputs into uncertainty in outputs by determining probabilities of possible outcomes by running large amount of scenario analyses. After assigning probability distribution to selected input parameters, values from within their probability distribution are picked randomly and one simulation is undertaken. Simulations are repeated with new randomly selected values each time. Basically, values are picked from distributions of each parameter by possibility, which generates thousands of combinations. Those combinations are treated as possible cases might occur in practice, which causes the discrepancy between predicted and actual building performance (Sun et al 2016).

8.2.1.3 Risk assessment

At this stage, all the results from Monte Carlo simulation is used to establish the probability distribution of results which is used to present the risk of prediction as well as to derive more reliable prediction of building energy performance. The generated distribution curve, for both energy performance and utility cost, presents the possibility of different scenarios in reality, thus can be used for risk assessment. These curves have a wide range of usage. It could be used to calculate the expectation value, mean value, standard deviation of building energy performance metrics such as electricity. Also, it could be used to get reliability of possible outcome such as, energy performance, payback period, utility cost etc. (Sun et al. 2016).

8.2.2 Previous retrofit studies considering risks

Number of studies considering risks in building energy prediction has increased in last 5 years. In a recent case study by Silva and Ghisi (2014), up to 19.5% and 36.5% of uncertainty was reported for physical and user behaviour parameters, respectively, in prediction of heating energy consumption. In case of cooling energy consumption, up to 43.5% and 38.0% of uncertainty was reported for physical and user behaviour parameters, respectively, in the same study. Virote and Silva (Virote and Neves-Silva 2012) proposed a stochastic model to predict the occupant behaviour and occupancy pattern in an office building. Integration of the proposed occupant behaviour model in building energy simulation model demonstrated the importance of considering stochastic occupant model in improving the accuracy of energy consumption prediction. Uncertainties associated with building operational practice also have profound impact on annual energy consumption. Variation in HVAC operation was found to result in -15.3% to 70.3% variation in annual energy consumption for a medium sized office building (Wang, Mathew et al. 2012).

Building retrofitting simulation based on current weather will introduce error in the calculation of life cycle energy savings and cost savings as weather is changing due to climate change. Several studies (de Wilde and Tian 2009, Tian and De Wilde 2011) regarding building thermal performance under climate change scenerios in England showed that uncertainties in climate is not a dominant factors for heating energy prediction and it becomes a dominant factor for cooling energy prediction after 2050. Use of multiple weather files was suggested for quantifying the uncertainties in the prediction of the future performance of buildings in those studies. However, Patidar et al. (Patidar, Jenkins et al. 2011) proposed a methodology that uses linear predictors fitted using standard regression methods instead of a dynamic simulation model to calculate the risk of building overheating under future climate change scenarios. Their model was found to be computationally efficient although the developed model is not ready to simulate more complex non-domestic building.

Kumbaroglu and Madliner (2012) presented techno-economic evaluation method for the energy efficiency retrofit of buildings. Their case study indicated that energy price changes significantly affect the profitability of retrofit investments and that high price volatility creates a substantial value of waiting, making it more rational to postpone the investment.

In terms of water consumption and saving analysis, there has been differences between the theoretical and actual reported savings when retrofitting water use appliances from a low star rating (e.g. 2 star shower head) to a higher star rating (e.g. 4 star). The difference can be largely attributed to behavioural factors (Beal et al. 2013). For example, people may compensate their low flow rate showerhead with having a longer shower. Showerhead benefits have flow-on benefits to energy by reducing the demand for hot water, which is often unaccounted for in assessments (Willis et al. 2010). Rainwater harvesting and storage using rain tanks is often considered as a water saving measure when retrofitting buildings but there is considerable uncertainty in the supply reliability of this source due to weather fluctuations and even more water-related energy uncertainty (Talebpour et al 2014, Vieira et al. 2014). Modern air-conditioning systems are often considered for retrofit projects as they use considerably less water and energy than out-dated technologies. However, savings in both water and energy in practice are less certain due to differences between laboratory and the actual working conditions of these systems (Kenway et al. 2011).

In Australia, Guan (2012) reported that depending on assumed future climate scenarios and location considered, building energy consumption may rise from 0.4 to 5.1% due to climate change. Internal load density parameter was found to have significant influence on building cooling load and overheating prediction. Daly et al. (2014) reported inconsistencies in the assumptions of 'hard-to-measure' building and occupant behaviour input parameter values used for Australian office building simulation. Their case study showed more than 50% variation in the predicted energy consumptions for all studied locations in Australia, when high and low range simulation assumptions were used. The payback period of a simple lighting upgrade was found to vary from 2.4 years to 10.3 years depending on variable simulation assumptions.

8.2.3 Retrofit Decision making considering uncertainties

Decision making model selects the optimum retrofitting packages after exploration of the potential benefits and associated uncertainties of different retrofitting options. Rysanek and Choudhary (Rysanek and Choudhary 2013) used classical Wald, Savage and Hurwicz method for optimum retrofitting method decision making which evaluates different energy efficient and low carbon building retrofit measures under several techno-economic scenarios. However, the uncertainties were handled in a non-probabilistic manner. To evaluate the output in probabilistic design, effectiveness ε and robustness RP parameters were introduced by Gelder et al. (Van Gelder, Janssen et al. 2014). Here, effectiveness was defined as the ability of the design option to optimise the performance, while robustness was defined as the ability to stabilise this performance for the entire range of input uncertainties. It was recommended to consider both the effectiveness and robustness for selecting best design option for long term operation.

A decision making model based on life cycle cost benefit analysis that considers technical and economic parameters uncertainties can provide more realistic economic evaluation and reveal the investment risk of a building energy retrofitting project (Almeida, Ramos et al. 2015). Some research showed that technical building parameters have much less influence on life cycle cost benefit analysis than the economic parameters (Burhenne, Tsvetkova et al. 2013). However this might not always be the case. Ascione et al (Ascione, Bianco et al. 2015) proposed a multi-objective optimization model where the available budget for the energy refurbishment of the existing buildings was identified as constraints. For each budget scenario, the proposed methodology allows the formation of the Pareto front which represents the set of best packages of energy efficient measures (EEMs). Then total cost over the life cycle of the buildings for each of the different combinations of EEMs for each budget was calculated using both the 'utopia point method' and the 'minimum comfort level method'. Then, the one characterised by the lowest value of global cost was selected as the cost-optimal solution.

Menassa (Menassa 2011) presented a framework where traditional NPV (net present value) method of investment decision making technique was augmented by principles of modern option pricing theory. The framework was developed to account for three main scenarios encountered in retrofit projects including single stage investment, multi stage investment with option to abandon and multi stage investment with option to stage. The framework have been shown to provide a good alternative to the NPV approach when uncertainty is high, and the building stakeholder's want to incorporate more strategic investment opportunities in their analysis. Hopfe et al. (Hopfe, Augenbroe et al. 2013) proposed a methodology using AHP (Analytical hierarchy process). The conventional AHP protocol that handles only deterministic information was enhanced to include uncertainties. Their proposed method presented a viable means of collaboratively ranking complex design options based on stakeholder's preferences and considering the uncertainty involved in the designs.