BUILDING ENERGY EFFICIENCY R&D Roadmap

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EXECUTIVE SUMMARY

Energy consumption in the building sector is trending upwards due to increasing population and higher economic activity in most parts of the world. In Singapore, buildings (including residential and non-residential) consume about half of the country's electricity. It is hence essential to focus on energy reduction in this sector via technologies that can significantly improve the energy efficiency of buildings, while ensuring their liveability and long term sustainability.

This roadmap outlines R&D pathways to improving energy efficiency within the building stock via technology improvements and policy recommendations. These R&D pathways span across four technological focus areas integral to building energy efficiency and six commercial building types that are relatively more energy intensive (Figure A.1).

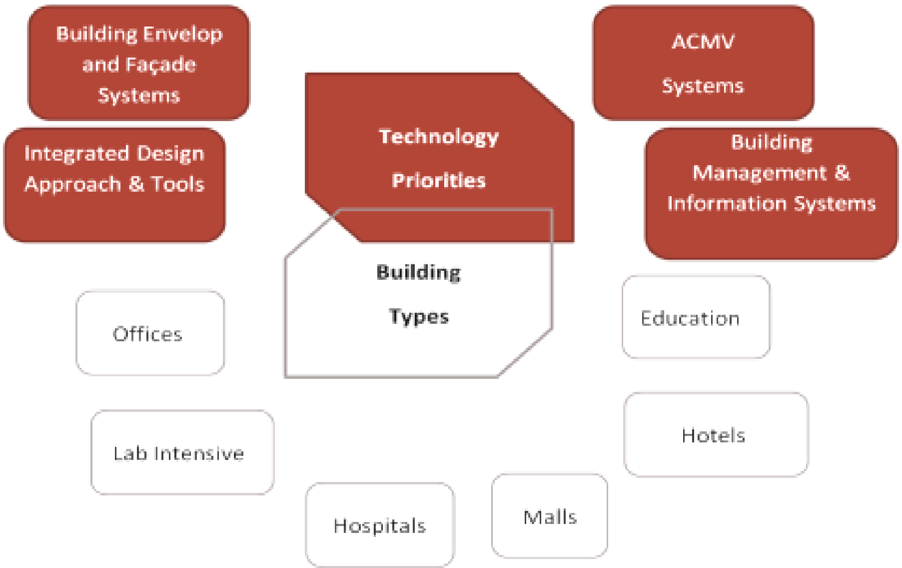

Figure A.1: Scope of the Building Energy Efficiency Roadmap

This roadmap was developed via a consultative process that included local and international experts, academics, industry professionals and policy makers. These experts were engaged via interviews, focus group discussions and workshops conducted between January to December 2013. The key findings from this exercise are presented here.

- **<u>Targets</u>**: The key indicator for building energy efficiency performance would be the normalised Energy Efficiency Index (nEEI) expressed in kilo-watt-hours (kWh) of electricity consumed per square meter (m^2) per year. The roadmap targets to achieve improvements in the nEEI by 40% (moderate adoption) to 60% (aggressive adoption) over current best-in-class buildings (GM Platinum as a proxy) by year 2030.

- **Key Challenges:** The key challenges to achieving the goals and targets of the roadmap were identified as follows:

Table A.1: Summary of Technical and Non-Technical Challenges

Technical Challenges	Non- Technical Challenges
Lack of test-bedding opportunities[1]	Lack of policies and incentives for developing technologies from R&D to market adoption
Inefficient Operation, Maintenance and Management (OM&M)	OM&M with short term contracts
Lack of specific technologies that can holistically address the issues around retrofitting of existing buildings	Lack of right knowledge, awareness and training of facility personnel in OM&M domain
Lack of in-depth, up-to-date knowledge of actual performance	Risk aversion on taking up of new technologies due to lack of information, awareness, validated data, and incentives
Over sizing of systems and equipment due to uncertainty of end-user energy profile and over provision to meet regulatory standards	Lack of in-depth knowledge on costs of technologies
Lack of easy to use software for integrated design, modelling, simulation, and analysis	Lack of accountability of consultants and design team on actual performance of the building
Lack of data availability and measurement verification	
Lack of accurate integrated design process and execution (building design based on whole life cycle, cost benefit, risk analysis and social impact)	

- **Technology Identification:** Different technology priorities were deliberated within each of the four focus areas and then voted upon to formulate a list of 52 technologies that need to be further developed in the R&D pathways towards achieving significant improvement in energy efficiency of buildings in Singapore. The top ten are listed below. There were also several studies identified and suggested to be conducted as ground-work before embarking on the technology development. A complete view of these technologies and studies is provided in **Appendix V**.

[1] This challenge might be seen also as non-technical in terms of insufficient infrastructure, financial support etc.

Table A.2: List of top ten technologies by focus areas

Focus area	Technology theme	Desired Outcome
ID	Integrative Design Tools for multi-criteria optimisation	Optimise for whole building approach to maximise efficiency and minimise negative impacts
ID	Building modelling and predictive controls	Analyse energy use in real-time and take predictive control actions based upon model outputs
ACMV	Decouple ventilation and cooling	Separating latent and sensible loads can improve chiller plant and air-distribution efficiencies
ACMV	Self-adapting distributed air-conditioning systems for users	Flexibility of air distribution systems that dynamically adjusts with space and time
ACMV	Innovative sensible cooling	Improve energy efficiency and occupant comfort via reduction in air flow and enhanced control
ACMV	Displacement ventilation system	Optimised ventilation flow to reduce energy required for air movement
BMIS	Embedded intelligence in software	Software detects sensor anomalies during operation to enable faster and more effective decision making
BMIS	Automated Fault Detection, Diagnostics, and Interaction (FDDI)	Alert facility manager and instantly provide sequential instructions to resolve operational problems
BMIS	Adaptive controls based on occupant comfort	Take control actions to tailor building provisions based on occupancy data and user preferences
BMIS	Electricity consumption database	Organized data set used for enhanced operational efficiency and benchmarking performance

- **Emissions Reduction Potential:** A number of scenarios were created to analyse adoption of technologies and policy recommendations outlined in the roadmap. The energy savings resulting from technology adoption were found to potentially reduce cumulative CO_2 emissions in the building sector by 22 – 28% in 2013- 2030 over the business-as-usual scenario.

1. INTRODUCTION

1.1 RATIONALE OF BUILDING EE

In 2000, Singapore's Greenhouse Gas (GHG) emissions totalled 38.79 million tons of CO_2-equivalent (NEA 2010). Under a Business-as-Usual (BAU) scenario, this figure is projected to double by 2020 to 77.2 million tons of GHG, Buildings account for a significant proportion of projected BAU emissions: 13.8% are expected to be produced by buildings and 7.6% by households (Figure 1.1). Singapore has committed to reduce GHG emissions by 7 – 11% below 2020 BAU levels (NCCS, 2012).

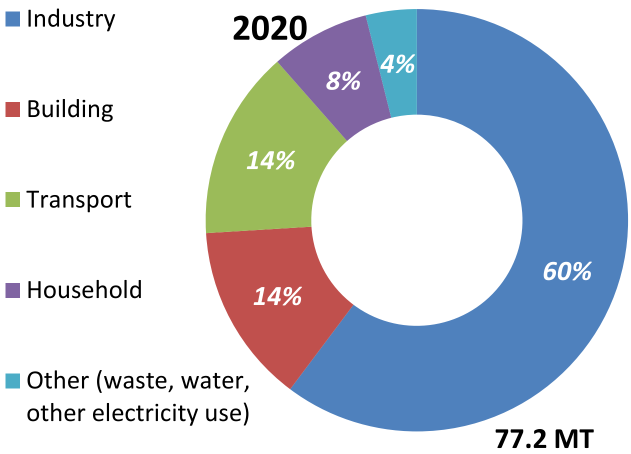

Figure 1.1: Singapore Projected 2020 Business As Usual (BAU) GHG Emissions[2] (NCCS, 2012)

To decrease carbon emissions, Singapore must work to improve overall energy efficiency to reduce electricity end use.

In Singapore, buildings (including residential and non-residential) are responsible for around half of the country's electricity consumption. The highest normalised Energy Efficiency Index (nEEI) related to electricity consumption per floor area per year is found in commercial buildings and building types such as shopping malls, hotels, hospitals, and offices (see Figure 1.2). Typically, the majority of non-residential building electricity consumption is attributed to cooling (60%) and mechanical ventilation (10%). The remaining share goes to lighting (15%), lifts & escalators (10%) and other sources (5%) (see Figure 1.3).

[2] Note: Figure refers to total greenhouse gas emissions. Greenhouse gases other than carbon dioxide (CO_2) are converted to CO_2 equivalent. The sectorial contributions do not add up to 100% due to rounding of the respective percentages to one decimal value.

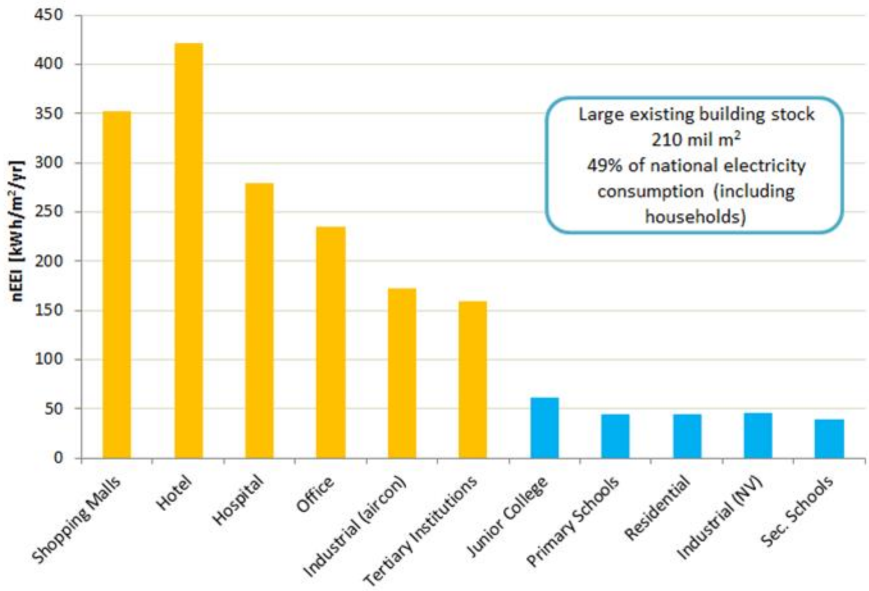

Figure 1.2: Energy consumption in existing building types (BCA, 2012a)

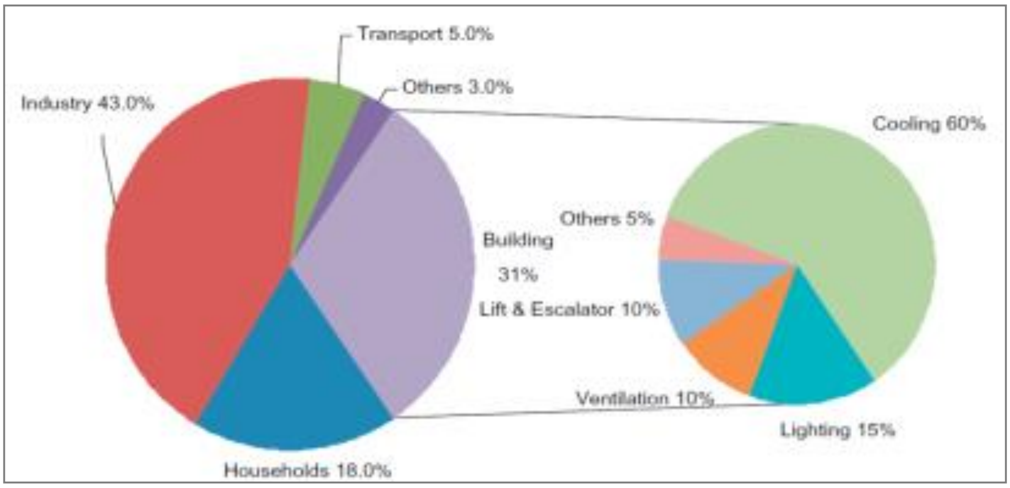

Figure 1.3: Typical electricity consumption by end-use in Singapore and in the building sector (Chua et al., 2013)

The Building Control Act includes newly mandated measures for achieving Green Mark certification for all new and existing post-retrofit buildings, auditing cooling systems every three years, and submitting energy consumption and other related data. The goal is to have at least 80% of commercial and public buildings Green Mark certified by 2030 (BCA, 2013a).

The potential for energy efficiency in buildings has not been fully realized due to lack of systematic evaluation and adaptation of technology. To help address this issue, the Building and Construction Authority (BCA) of Singapore has led the development of this R&D Technology Roadmap for Building Energy Efficiency that extends through 2030. Each stakeholder within the building sector has different motivations, and a concerted effort is required to understand their motivation towards supporting and objecting the adoption of various technologies for energy efficiency. For example, developers and investors prefer quick economic gains from their buildings and may not invest in technologies with long payback times unless it is aligned clearly to their longer term strategies and vision and helps sustain their competitive advantage. A technology roadmap process facilitates a systematic analysis of various technology options and provides a clear pathway for institutional investments in technology development for sustained benefits in the long term.

1.2 CURRENT AND ON-GOING INITIATIVES

A 3rd Green Building Masterplan has just been formulated by BCA with the ***vision of making Singapore "A global leader in green buildings, with special expertise in the tropics and sub-tropics – enabling sustainable development and quality living".*** The Masterplan is structured into three key strategic goals focusing on (i) Continued Leadership; (ii) Proven Sustainability Performance; and (iii) Collaboration and Engagement with Stakeholders. Research, development and demonstration (RD&D) will play a more critical role in the next phase of development for green buildings.

Current support for applied research and development (R&D) and infrastructure such as test bedding facilities that enable RD&D activities to be carried out are tabulated as follows:-

Figure 1.4: Overview of RD&D incentives/schemes and infrastructure

Overview of RD&D incentives/schemes	
MND Research Fund (MNDRF)	To encourage and support applied R&D that will raise the quality of life and make Singapore a distinctive global city, in alignment with MND's Vision and Mission.
MND-A*STAR grant calls	Jointly funded by MNDRF and A*STAR, the grant calls seek to promote R&D collaboration between Singapore public sector research organisations and private companies in the building and construction industry through joint research projects to address the pressing challenges faced by the industry.
Energy Innovation Research Programme (EIRP)	An industry-centric research competitive grant call programme that is funded by the National Research Foundation and administered by EDB/BCA. S$15 million has been allocated to support the development of energy efficient and cost-effective solutions for buildings in the tropics.
Innovation Grant (iGrant)	Funded by MNDRF and administered by BCA, the $5 million iGrant seeks to help the entire building and construction value chain (developers, consultants, builders, and suppliers) to conduct small scale R&D projects with near term commercialisation potential.

Infrastructure/ Test-bedding platforms	
Zero Energy Building (ZEB) @ BCA Academy	The Zero Energy Building (ZEB) is BCA's flagship R&D project under its 2nd Green Building Masterplan. Based in BCA Academy and officially opened on the 26 Oct 2009, the ZEB is the first in South-east Asia that was retrofitted from an existing three-storey institutional building. The ZEB was conceived with the following objectives in mind: • to serve as a test bed for integration of Green Building Technologies (GBT) in existing buildings • to be a hub for practitioners and students in the study of energy efficiency and green buildings
BCA's User Test-Bed Facility (UTBF)	The User Test-bed Facility (UTBF), at the new BCA Academy building, is being developed to study the inter-dependency of building systems and effective controls. This facility will further boost test-bedding opportunities. Taking reference from Lawrence Berkeley National Lab's FLEXLab initiative, the UTBF will feature a rotatable lab simulating an office environment with flexible plug 'n' play configuration to facilitate test-bedding of emerging green building technologies.

1.3 OBJECTIVES OF ROADMAP

The following are the objectives of the roadmap:

- Develop a R&D Roadmap for Buildings Energy Efficiency and provide recommendations for short (2013-2016), medium (2016-2020) and long-term (2020-2030) time horizons
- Identify priorities, gaps, and development timelines of technologies and processes
- Define targets for buildings energy efficiency and study their impact on carbon emissions
- Provide a clear pathway for R&D investments
- Identify relevant policies and their interdependencies to meet national goals
- Identify and prioritise industry challenges and opportunities to accelerate development and deployment of available technologies, including demonstration strategies
- Define actionable plans and evaluate their effectiveness periodically

This roadmap has been developed through a consultative process involving several local and international domain experts, researchers, industry professionals and policy makers. The process consisted of various interviews, group discussions, workshops and data analysis that were facilitated by a team from the Energy Research Institute at Nanyang Technological University (ERI@N) and Nexight Group (roadmapping consultants).

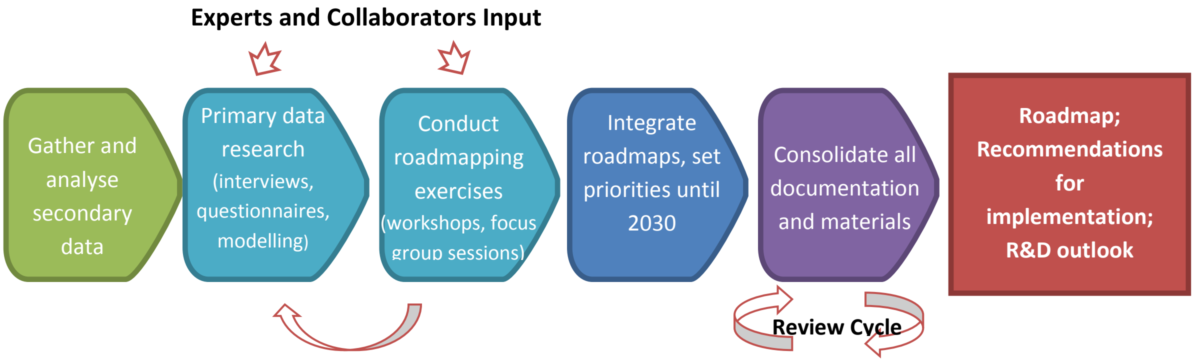

Figure 1.5: Roadmap process and methodology

2. CURRENT AND FUTURE PATHWAYS FOR BUILDING EE AND FOCUSED TECHNOLOGIES

Over the course of interviews, workshops, and focus group meetings with domain experts across government, industry, and academia, there were four key areas identified pertaining to building energy use: Integrated Design (ID), Building Envelope and Façade System (BEFS), Air-Conditioning and Mechanical Ventilation (ACMV), and Building Management and Information System (BMIS). Different technology priorities were deliberated within each of the four focus areas and then voted upon to formulate a list of 52 technologies that need to be further developed in the R&D pathways towards achieving significant improvement in energy efficiency of buildings in Singapore. The top ten are listed below. There were also several studies identified and suggested to be conducted as ground-work before embarking on the technology development. A complete view of these technologies and studies is provided in **Appendix V.** The following sections will describe the current state-of-the-art, impending gaps, and technology development pathways for each focus area.

2.1 INTEGRATED DESIGN (ID)

Integrated Design (ID) aims to improve operational aspects of buildings by optimizing the building's initial design. This is accomplished by including in the early design phases all the key building stakeholders, viz. architects, mechanical engineers, structural engineers, building owners, building tenants, design consultants, related agency officials, etc. The integrated design approach requires all members of the building stakeholder community to approach the technical planning, design, construction, and operation of a building with the objective of balancing aesthetics, safety, cost-effectiveness, functionality and sustainable design.

There are a number of tools to aid the ID process ranging from tools to aid visual representation and database of building components such as Building Information Modelling (BIM), to software tools to conduct dynamic simulation of building energy performance such as IES, Design Builder, Ecotect, Energy Plus, OpenStudio, TRNSYS, etc. While these tools are able to facilitate the design process, there were a number of gaps identified in the use of such tools in the local context:

- Lack of use of the Integrated Design process
- Lack of accurate and validated models
- Lack of accurate data for benchmarking
- Easy-to-use modeling toolkits for ID are not available for all stakeholders

The essential technologies and studies required to bridge the above gaps were discussed and prioritized during the roadmapping process. The following chart represents the technology pathway for development of ID tools. The chart is organized across various time horizons based on projected lengths of time each technology would need to be developed before providing useful results. For example, near term technologies are expected to yield useful results two years after research begins while long term technologies are expected to yield useful results ten years after research begins. The figure is also colour-coded to represent preliminary studies (grey) and expected progress of technology readiness level throughout the research process (light pink for basic research to dark red for deployment).

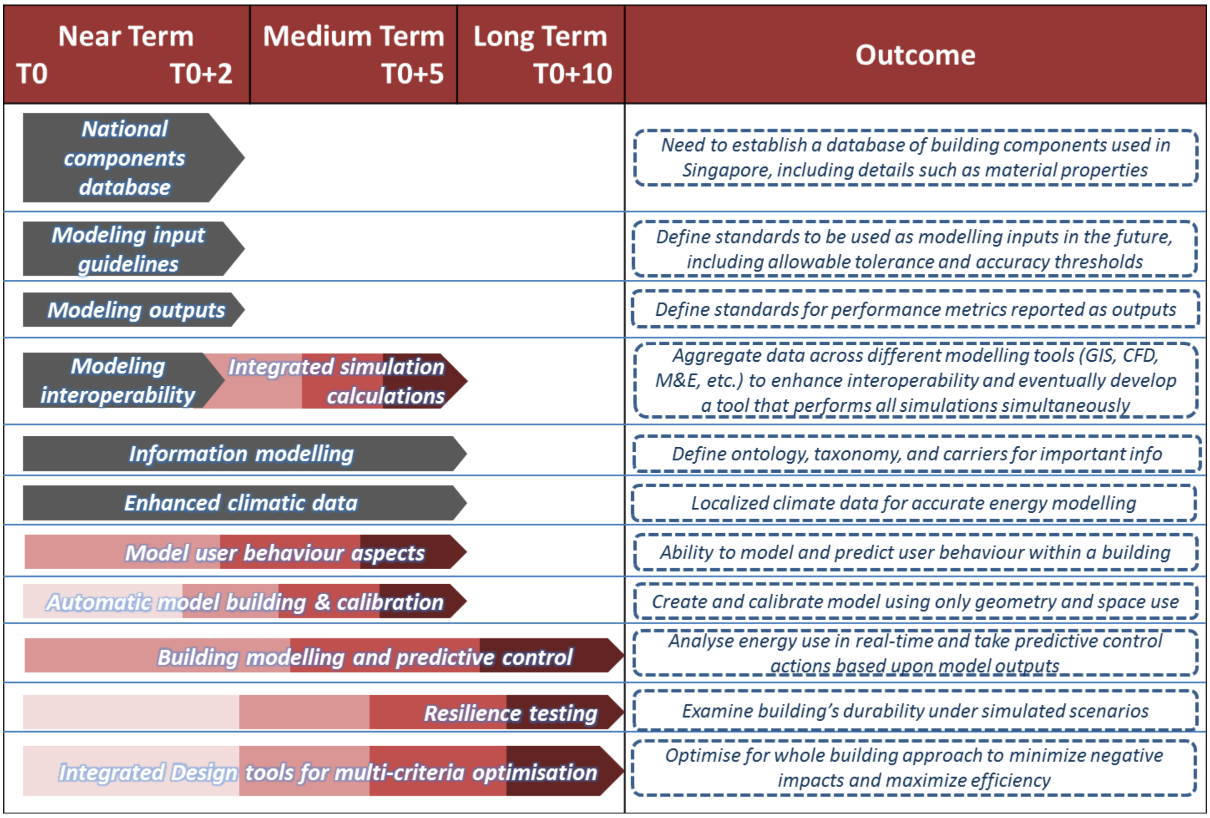

Figure 2.1: Technology pathway for ID technologies

2.2 BUILDING ENVELOPE AND FAÇADE SYSTEM

One of the essential considerations in building design, engineering, and operation of an energy efficient building is the Building Envelope and Façade System (BEFS). Rather than serving as a static enclosure, the building skin has the potential to redirect and filter daylight, provide natural ventilation, manage heat transfer, and enhance occupant wellbeing by establishing visual and physical connection between the internal and external environments (Hegger, 2007). The components that affect performance of BEFS are construction materials, thermal insulation, fenestration, glazing, shading devices, and design parameters such as window-to-wall ratio, massing, aspect ratio, and orientation.

Because occupant interaction with the façade (e.g. opening a door or window) can greatly affect building energy use, facade performance cannot be understood in isolation, but rather must be considered as a building component whose performance is interconnected with not only building systems but also with occupant thermal and visual comfort.

There are various façade technologies that have evolved over the years in Europe and other developed regions. A notable low energy building design methodology with strong emphasis on BEFS is the "Passive Haus", which is based on the following principles:

Table 2.1: Design Principles of Passive Haus

Design Principle	Technology Examples
Solar Control Facades	• Spectral selective solar control • Angular selective solar control • Solar filters • Exterior solar control
Daylight Façade	• Sunlight redirection • Sky light redirection
Double Skin Façades and Natural Ventilation	• Heat extraction • Night time ventilation • Mixed mode and natural ventilation
Active Façade System	• Demand responsive program • Active load management window strategies
Green Envelope Systems	• Integrated vertical green wall systems (rain water harvesting system) • Integrated green roofs/ cool roof system/ solar day light tubes
Climate Responsive Optimized Façade Technology	• Dynamic shading • Automated operable windows and skylights • Thermochromic and electrochromic glazing
Energy Generation	• Building Integrated Photo Voltaic (BIPV) system • Integrated wind turbines

However, not all façade technology can be directly adopted in Singapore's tropical environmental conditions. The following gaps were identified for BEFS technology development in the Singapore context:

- Lack of effective passive and active design strategies for building envelopes
- Lack of technology adaptation for the tropics
- Ineffective usage of Envelope Thermal Transfer Value (ETTV) for design

BEFS technology areas with high energy savings potential in Singapore include parametric studies for shading devices, optimization of natural ventilation and envelope performance for the tropics. The following figure shows the technology development pathway for BEFS technology that was synthesised from the roadmapping process.

Near Term T0 – T0+2	Medium Term T0+5	Long Term T0+10	Outcome
Study of performance indicators			*Establishment of performance indicator matrix for benchmarking and better evaluation*
Standardized guidelines			*Standardized input of simulation results for BIM submission*
Development of dynamic shading systems			*Optimized design and application of accurate façade systems for the building based on orientation*
Enhancing Natural Ventilation			*Reduce cost of artificial cooling within the building*
Tools for on-site façade performance			*Establish performance targets based on live / realistic measurements*
Design for reusability and disassembly			*Use less virgin materials to reduce costs*
Multi functional facade			*Use for energy storage/ power/ food generating devices*
Optimized facades based on outdoor-dependent dynamic controls			*Reduce energy consumption based on reacting to changes in outdoor environment*
Integration of air-conditioning systems in facades (dehumidification and cooling)			*Reduce energy consumption and equipment space of air-con systems*

Figure 2.2: Technology pathway for BEFS technologies

2.3 AIR CONDITIONING & MECHANICAL VENTILATION

Air Conditioning and Mechanical Ventilation (ACMV) system can account for more than 50% of total building energy consumption. A further energy consumption breakdown for ACMV systems shows that chillers can consume up to 55% and fans up to 35% (Figure 2.3).

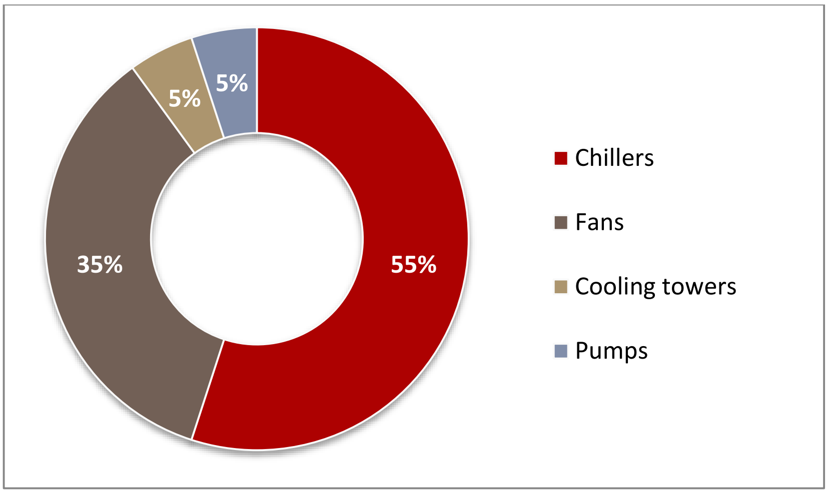

Figure 2.3: Energy consumption breakdown for ACMV Systems (Aircon Primer, 2011)

Most ACMV systems in Singapore can be broadly classified into two types: unitary systems and central air-conditioning systems.

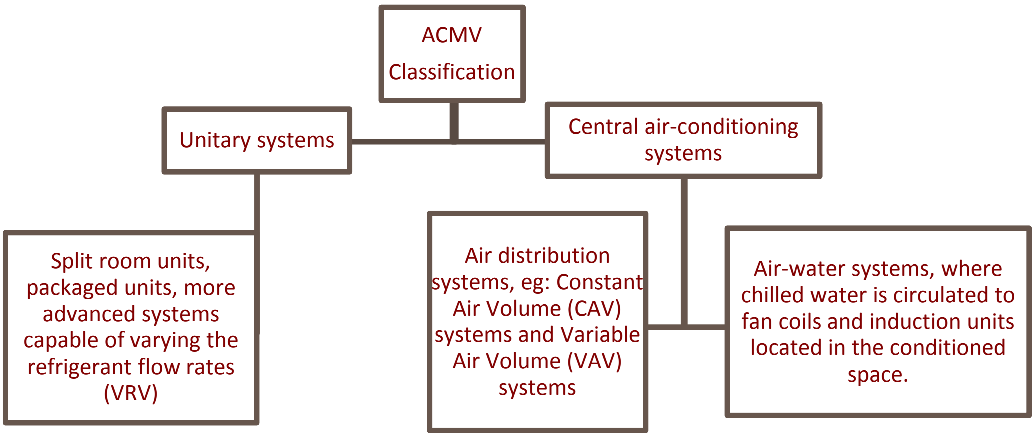

Figure 2.4: Unitary and central air-conditioning systems in Singapore (Aircon Primer, 2011)

The report on Energy Savings Potential and RD&D Opportunities for Commercial Building HVAC Systems prepared by Navigant Consulting for the U.S. Department of Energy (DOE)[3] identifies and summarizes a wide range of technologies in varying stages of development that could reduce commercial ACMV energy consumption (EERE, 2011). The top ten technologies are described in the following table.

[3] Available online http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/savings_potential_comm_hvac.pdf (retrieved 13.03.2013).

Table 2.2: Top ACMV Technologies from US DOE Report

Technology	Description
1. Thermoelastic Cooling	Thermoelastic cooling systems utilise shape-memory metal alloy that alternately absorbs or creates heat through its thermoelastic characteristics.
2. Aerosol Duct Sealing	Aerosol duct sealant systems are used to find and plug air holes in ducts, without having to locate them first. The system pushes an adhesive-aerosol sealant through the duct network and deposits the sealant in the holes. The technology reduces the leakage in a building, which reduces the load on the building's cooling and air delivery systems.
3. Dedicated Outdoor Air System	A dedicated outdoor air system (DOAS) separates the ventilation air from the primary recirculating air system. DOAS delivers the correct amount of ventilation without compromising thermal comfort and allows the entire HVAC system to operate more efficiently.
4. Permanent Magnet Motors	Permanent magnet (PM) motors use specific ferrous magnets integrated in either the rotor or stator to produce many benefits over the typical induction motor. The use of imbedded magnets allows for a simpler mechanical design that runs quieter and with less vibration.
5. Switched Reluctance Motors	Switched reluctance DC motors (SRM) have been in use since the 1800s but have not seen wider application due to their higher noise and lower peak efficiency than other motor types. The rise of low-cost power electronics allows SRMs to become quieter with greater controllability. Because of this, SRMs become an attractive motor choice for HVAC systems looking for high-efficiency during part-load conditions.
6. Bernoulli Cooling Cycle	Bernoulli heat pumps use mixtures of rare gases as a working fluid to produce cooling. The working fluid is pumped through a Venturi neck and changes temperature as it travels through the neck. This effect can drive a heating or cooling system.
7. Thermoelectric Cooling Cycle	Thermoelectric cooling systems create a cooling effect by applying voltages across specialized thermoelectric materials. This solid-state technology may become highly efficient once fully mature, but it requires additional long-term research to increase the performance of the current thermoelectric materials.
8. Duct Leakage Diagnostics	Leakage in commercial HVAC duct systems wastes energy associated with fan usage and thermal conditioning. Diagnostic testing methods exist to alert building operators of the presence of leaks so they may be repaired.
9. Zephyr Ceiling Tiles	By replacing a conventional drop-ceiling, Zephyr ceiling tiles (ZCT) use the low relative humidity of return air to provide additional space cooling. The return air flows over a wicking material in the ZCT, cools the ceiling, and reduces the need for traditional cooling.
10. Ductwork in the Conditioned Space	Duct leakage is a main source of thermal energy loss in existing buildings. If ducts were installed within conditioned spaces, then this leakage would still enter the desired location and not be lost within ducted space away from occupants.

Technology areas with high energy savings potential in Singapore include *dehumidification, ventilation,* and *energy recovery.* Singapore's climatic conditions include high moisture content (or high latent cooling load), thus requiring high amounts of energy to dehumidify indoor air. Technologies that can remove moisture from the air using less energy can help achieve significant savings in energy costs. Another area of opportunity to improve energy efficiency is to provide healthy indoor environments with high air distribution effectiveness. Therefore, ventilation in buildings is a significant area for R&D. Energy recovery strategies (for sensible and latent heat load) also hold great potential for reducing energy consumption and improving overall energy efficiency. Application of BMIS has the potential to maximise the benefits of ACMV technologies by optimising the processes with proper controls[4].

The following gaps were identified for ACMV technologies in the Singapore context:

- Ineffective space utilization
- Lack of technology adaptation for the tropics
- Low equipment efficiency and cost effectiveness

The essential technologies and studies required to bridge the above gaps were discussed and prioritized during the roadmapping process. As ACMV systems are complex, the technology themes were organized into three groups: Energy Recovery & Aircon Equipment, Micro-Climatic Air-Con Systems, and Air Distribution & Ventilation Systems.The following chart represents the technology pathway for the development of ACMV technologies under these 3 different technology themes (Figure 2.5, Figure 2.6 & Figure 2.7).

[4] Note: For controls, refer to focus area "Building Management and Information Systems"

Near Term T0 – T0+2	Medium Term T0+5	Long Term T0+10	Outcome
Energy recovery potential via materials			*Study of novel materials with properties with high potential to recover thermal energy (eg: carbon composites, PCMs, methods using adsorption heat transformation*
	Natural Refrigerants		*Characterise energy savings potential and environmental benefits of natural refrigerants*
	ACMV system with architectural implications		*Study effects of architectural designs and implementations on ACMV systems*
	High temp chilled water system		*Improve overall performance of chiller plants via high chilled water supply temperature*
	Auxiliary system adaption in design & operations		*Inclusion of auxiliary system design for architectural considerations (minimise over-sizing and under-sizing)*
	Low temperature heat rejection		*Use systems that can automatically optimize the trade-off between tower fan and chiller energy consumption*
	New materials for dehumidification & thermal cooling		*Improve performance of dehumidification and cooling with use of novel materials such as zeolites, silica gel, methanol, and activated carbon combined with different heat sources*
	Recover heat for dehumidification		*Identify and right-size systems based on availability and quality of heat source*
	Designing for small ΔT heat transfer		*Maximizing efficiency by placing cooling systems closer to the heat sources*
	Maximizing cooling and/or dehumidification from thermally activated sources		*Identify new techniques and combination of novel materials to maximize heat and mass transfer*
		Modular compact chillers	*Develop highly efficient thermally powered adsorption cycles that could be driven by low temperature heat sources*
		Polygeneration: Optimisation of temperatures and cascades for district systems	*Optimize waste heat recovery to enhance the overall performance of large scale district cooling systems*
		New refrigerants and refrigerant cycles (e.g., magnetic, thermo electric, etc)	*Develop and improve upon new nanomaterials, nanofluids, new cooling cycles (such as thermotunneling, magnetic, thermoelectric, Bernoulli, thermoelastic, etc)*

Figure 2.5: Technology pathways for energy recovery & air-conditioning equipment technologies

Near Term T0 – T0+2	Medium Term T0+5	Long Term T0+10	Outcome
	Innovative sensible cooling		*Improve energy efficiency and occupant comfort via reduction in air flow and enhanced control*
	Personalized ventilation and cooling; Modularity		*Devise accurate ventilation strategies for every individual with intelligent controls*
		Self-adapting distributed air-conditioning systems for users	*Flexibility of air distribution systems that dynamically adjusts with space and time*

Figure 2.6: Technology pathways for micro-climatic air-conditioning system technologies

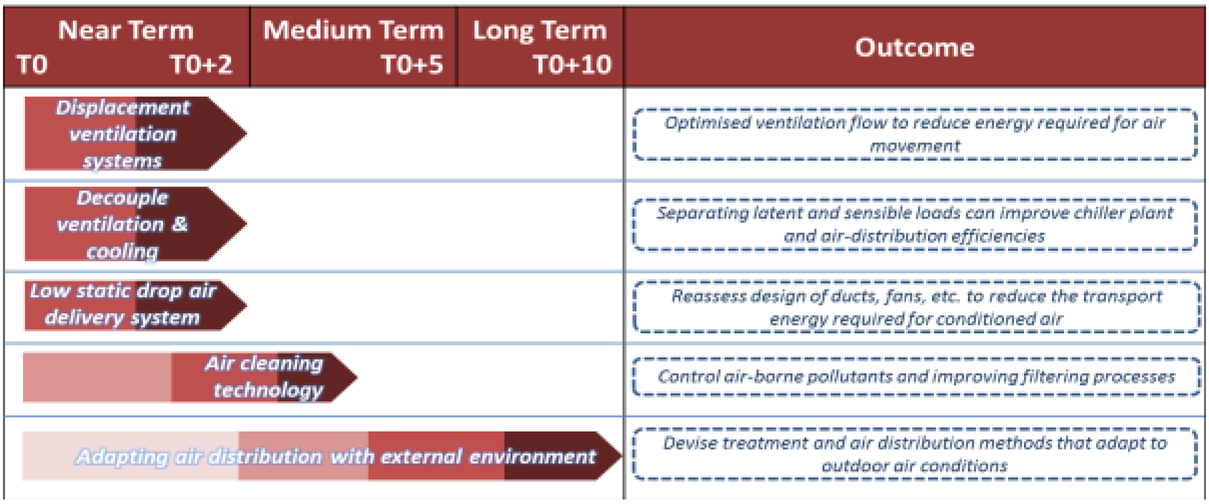

Figure 2.7: Technology pathways for air distribution & ventilation system technologies

2.4 BUILDING MANAGEMENT & INFORMATION SYSTEM

Building Management & Information System (BMIS) typically focuses on the measurement and dissemination of operational data related to occupancy comfort and energy use. For example, sensors are placed throughout the building to measure temperature and humidity levels, which are then relayed to a control algorithm that determines whether to run certain building services equipment or shut it off. For this reason, it is important to ensure that sensors are taking accurate measurements and that control algorithms are calibrated correctly.

Another important aspect of BMIS is the actions that facility managers take as a result of what information the dashboard interface conveys. For example, if specific sensors can detect anomalies in pressure in a specific section of ducting, then the facility manager could interpret that anomaly as a possible duct leakage problem that requires attention. As a result, it is important that the dashboard interface shows important information regarding equipment health, status and maintenance issues that the facility manager will not realize without personal inspection. This will simplify the facility manager's task as well as reduce the amount of operational hours at decreased building efficiency due to unattended faulty system. A visual overview of all the components monitored by the BMIS is shown in Figure 2.8.

Figure 2.8: Components of Building Management System (Urvil, 2013)

According to multiple technology roadmaps developed in USA (Urvil, 2013; Harris, 2012), wireless sensing and self-diagnosis are two key improvements that can be prioritized for sensing and control networks. Another report "Energy Savings Potential and RD&D Opportunities for Commercial Building HVAC Systems" cited the top three techniques and technologies of BMIS as the ability to carry out continuous commissioning (quickly address operation problems through continuous monitoring), support regular maintenance programming (constantly track equipment maintenance), and finally support retro-commissioning (re-calibrate the system to maintain optimal performance given recent operational characteristics) .

A survey suggested that 82% of buildings are installed with BMIS, but only 2% of the building managers are able to use them for targeting energy use. It was suggested that only 30% of the data collected from the BMIS is analysed and put to use (BCA, 2012a). The following gaps were identified for BMIS technologies in the Singapore context:

- Lack of inter-operability and communication between various BMIS solutions
- Lack of accurate sensors and controls
- Lack of automated data organization
- Lack of information availability to end user
- Lack of cost effective sensing equipment
- Lack of incorporation of BMIS components in Mechanical & Electrical Engineering packages

The essential technologies and studies required to bridge the above gaps were discussed and prioritized during the roadmapping process. BMIS technology themes were organized into three groups: Dashboards, Data Mining, and Sensors & Data Acquisition. The following chart represents the technology pathway for development of BMIS technologies (Figure 2.9, Figure 2.10 & Figure 2.11).

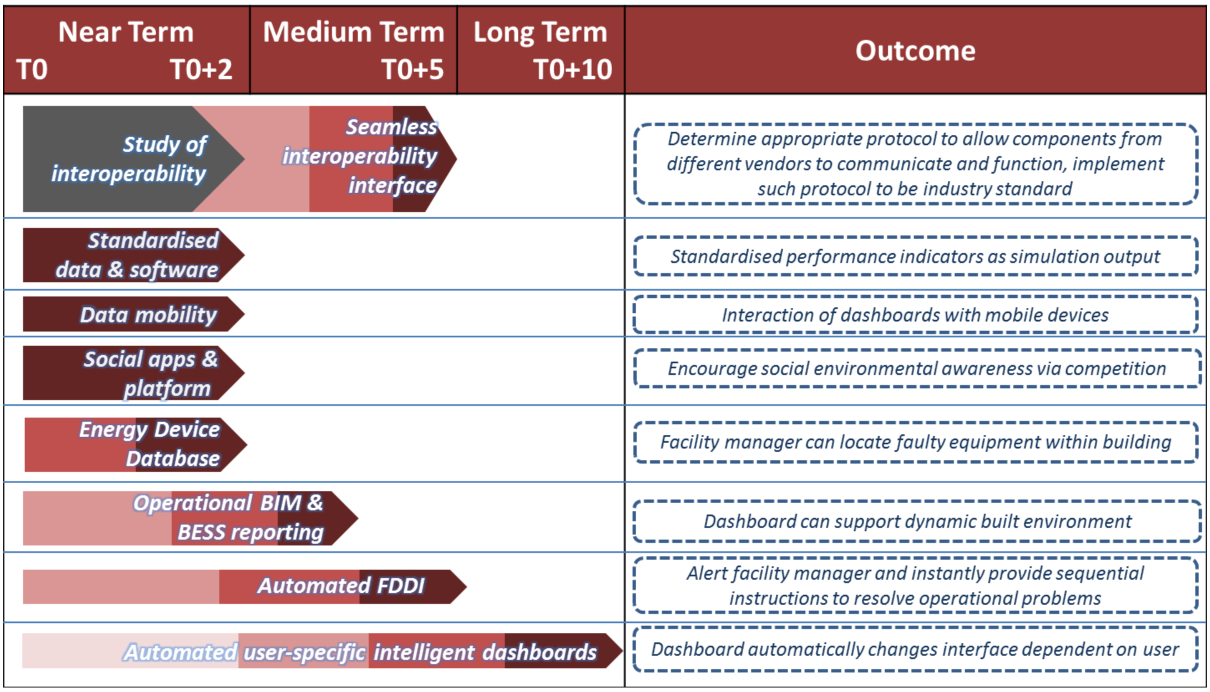

Figure 2.9: Technology pathways for dashboard technologies

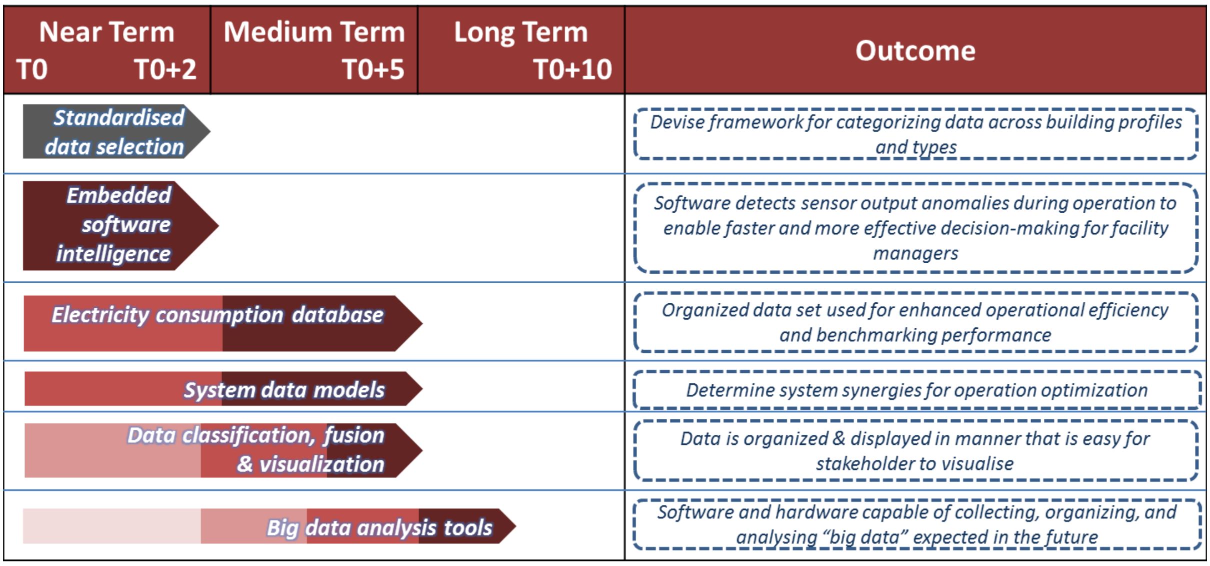

Figure 2.10: Technology pathways for data mining technologies

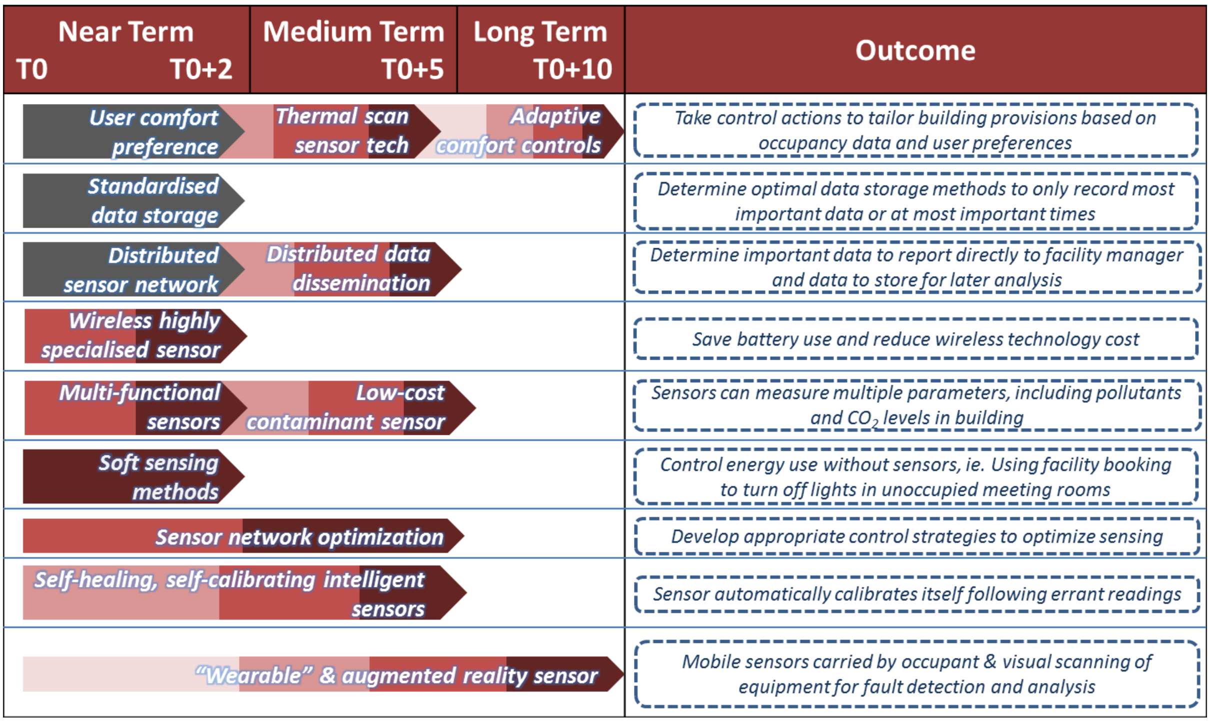

Figure 2.11: Technology pathways for sensor and data acquisition technologies

2.5 PRIORITIZING TECHNOLOGY RESEARCH AND DEVELOPMENT

Each technology identified in the focus group discussions was prioritized with an evaluation tool to provide recommendations regarding R&D priority areas and funding programs. A rating and scoring process was conducted for each technology by the consultant team across four criteria: benefits in terms of energy savings potential, cost and complexity associated with the technology implementation ("cost-complexity"), alignment to Singapore's national goals, and risks associated with the technology development. Scoring results across the four criteria were displayed within one figure using bubble charts. Bubble size correlated to benefits, bubble colour correlated to cost-complexity, horizontal position correlated to risk, and vertical position correlated to alignment.

In order to outline high- and low-priority technologies, a weightage scheme (see Table 2.3) was applied to the scoring results in the previous section. The prioritisation results for the top and bottom ten technologies can be found in Figure 2.12.

Table 2.3: Overall Weightage for Criteria and Sub-criteria

Criteria	Description	Weightage
Benefits	Energy efficiency improvement potential	20%
Cost-complexity	Cost and complexity of implementing technology	11%
Alignment	Develop locally via R&D vs. adopting from outside Singapore; economic value addition and job creation; application to multiple building types; applicable to other industries (RE, transport, etc)	44%
Risks	Risk of late delivery; risk of lacking adequate R&D facilities and infrastructure; risk of lacking adequate workforce and expertise	25%

Label	Top 10 Technologies
BMIS-9	Embedded intelligence in software
ACMV-14	Decouple ventilation & cooling
BMIS-22	Adaptive controls based upon occupancy
ACMV-12	Self-adapting distributed air-con systems
ACMV-10	Innovative sensible cooling
ACMV-13	Displacement ventilation systems
BMIS-6	Automated FDDI
ID-6	ID tools for multi-criteria optimisation
ID-5	Building modelling and predictive control
BMIS-10	Database for identifying electricity consumption patterns

Label	Bottom 10 Technologies
ACMV-3	Use of recovered heat for dehumidification
ACMV-1	Auxiliary system adaption
BEFS-3	Tools for measuring on-site façade performance
ID-1	Model user behaviour aspects
ACMV-15	Air delivery system with low static drop
BEFS-5	Multifunctional facades
ACMV-4	Low temperature heat rejection
ACMV-17	Adapting air distribution with external environment users
ACMV-16	Air cleaning technologies
ACMV-5	Designing for small ΔT heat transfer

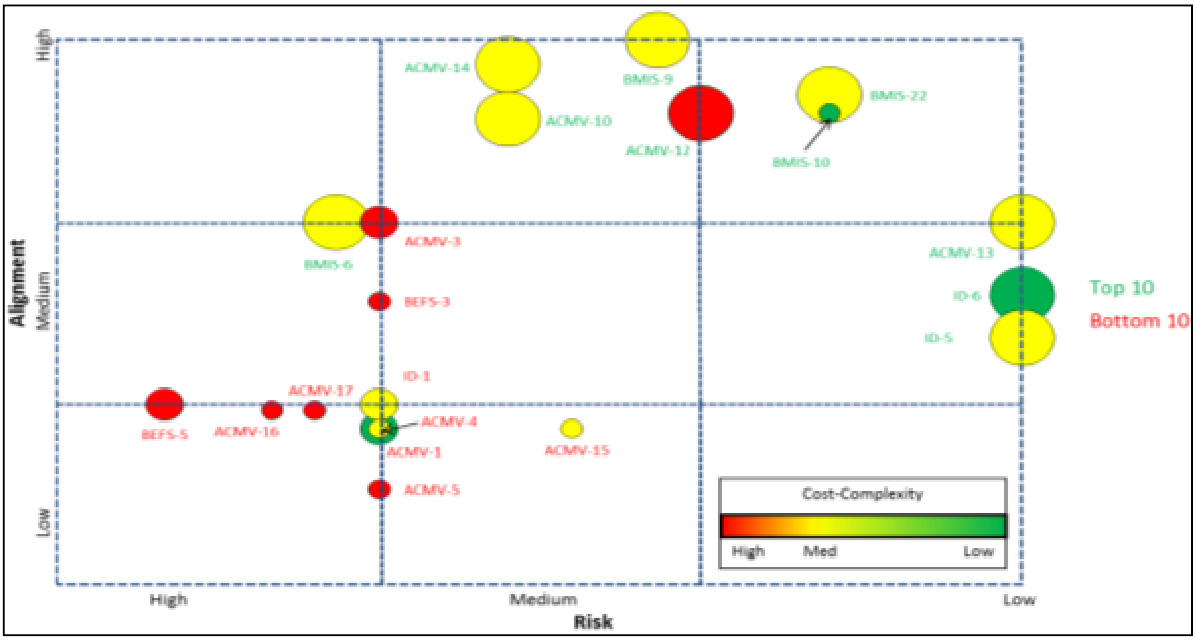

Figure 2.12: Top and Bottom Ten Prioritised Technologies

3. POTENTIAL FOR ENERGY EFFICIENCY IMPROVEMENTS

3.1 TECHNOLOGY ADOPTION SCENARIOS

In order to assess potential energy efficiency improvements due to technology adoption, normalised Energy Efficiency Index (nEEI) measured in kWh/m^2/year was adopted as a proxy as it was considered the most relevant metric. Building energy models of GM Platinum buildings were used to simulate high-efficiency technologies used currently and expected to be used in the future. The targets resulting from discussions during the roadmapping process and validated by the energy modelling exercise are shown in the following table.

Table 3.1: nEEI Improvement Targets over current best-in-class buildings (GM Platinum as a proxy)

Adoption Level	Time Frame		
	Short (2016)	Medium (2020)	Long (2030)
Moderate	8%	20%	40%
Aggressive	15%	30%	60%

A number of scenarios in the future were looked into. These are a combination of policy measures and the energy efficiency improvement listed above.

Table 3.2: Assumptions Regarding Levels of Technology Adoption for Energy Efficiency Improvements

Scenario	Adoption Level	Remarks
1	Business as Usual	Assumes baseline energy use does not change, matches current GM statistics as of 2013
2	Mandatory GM Certification for New Construction	All new construction in Singapore must meet GM Certification standards
3	Scenario 2 + Retrofit for GM Certification	To achieve BCA's goal of 80% GM Certification for Singapore's building stock by 2030, existing buildings must undergo retrofit projects to achieve GM Certification
4	Scenario 3 + Moderate Technology Improvement	Technology improves with conservative Energy Efficiency targets
5	Scenario 3 + Aggressive Technology Improvement	Technology improves with aggressive Energy Efficiency targets

3.2 POTENTIAL ENERGY SAVINGS

Using the five technology adoption scenarios above, the annual electricity consumption of buildings can be projected until 2030. This was done by collecting historical data for values of constructed floor areas and nEEI of each building type within the roadmap's scope. Each scenario is compared to Scenario 1 (Business as Usual) in order to provide an equal comparison. The results of this projection are shown in the following table. Cumulative savings are summed from 2013 to 2030.

Table 3.3: Projections for Electricity Savings (Cumulative 2013- 2030)

Scenario	Cumulative Savings (GWh)	% Cumulative Savings
1	-	-
2	13,498	4.6%
3	17,050	5.8%
4	66,009	22.3%
5	84,027	28.4%

3.3 POTENTIAL CO_2 EMISSION SAVINGS

To calculate potential CO_2 emission reductions as a result of technology adoption scenarios, electricity consumption was multiplied by grid emission factor. The grid emission factor relates to how much CO_2 is emitted when electricity is generated in Singapore. According to latest Energy Market Authority data from 2012 (EMA, 2013), 0.4977 kg of CO_2 are emitted for every kWh of electricity generated. Since historical values for Singapore's grid emission factor provide no clear trends for projection, it was assumed that this value would remain constant until 2030. Using the results for electricity savings in Table 3.3, the resulting carbon emission savings are shown in the following table.

Table 3.4: Projections for Carbon Emission Savings (Cumulative 2013- 2030)

Scenario	Cumulative Savings (Million tonnes)	% Cumulative Savings
1	-	-
2	6.7	4.6%
3	8.5	5.8%
4	32.9	22.3%
5	41.8	28.4%

3.4 ECONOMICS OF BUILDING ENERGY EFFICIENCY DEPLOYMENT

The economics of improving building energy efficiency was assessed from the perspective of building owners. This required collection of data related to costs associated with construction process of both new and retrofit projects as well as electricity prices. As there are no clear trends in EMA's electricity price over the past three years, it was assumed that the electricity price would remain a constant 0.2608 SGD/kWh as it was in October 2013. The following table shows the results for cumulative net cost from 2013 – 2030 that takes into account additional costs to install high-efficiency technology and the resulting savings in electricity costs. This is also expressed as a cumulative net carbon emissions abatement cost 2013 – 2030.

Table 3.5: Economic Projections of Technology Adoption Scenarios

Scenario	Cumulative Net Cost (Million SGD)	Cumulative Net Carbon Abatement Cost (SGD/ton)
2	-334	-50
3	-1,021	-120
4	-558	-16
5	8,195	171

Results show that Scenario 5 is the only case without net savings. This is because the 112% increase in capital expenditure required to transition from moderate to aggressive technology adoption only results in 40% increase in electricity cost savings.

This table shows that the scenarios that are policy-driven save money for building owners over the long run as the net savings are greater than cost of adoption.

4. CHALLENGES AND OPPORTUNITIES

4.1 CHALLENGES

Several challenges for achieving goals and targets for building energy efficiency were identified during the roadmapping process. The key challenges, categorised into technical and non-technical challenges, are listed in Table 4.1.

Table 4.1: Key Challenges to Achieve Roadmap Goals and Targets

Technical Challenges	Non- Technical Challenges
Lack of test-bedding opportunities[5]	Lack of policies and incentives for developing technologies from R&D to market adoption
Inefficient Operation, Maintenance and Management (OM&M)	OM&M with short term contracts
Lack of specific technologies that can holistically address the issues around retrofitting of existing buildings	Lack of right knowledge, awareness and training of facility personnel in OM&M domain
Lack of in-depth, up-to-date knowledge of actual performance	Risk aversion on taking up of new technologies due to lack of information, awareness, validated data, and incentives
Over sizing of systems and equipment due to uncertainty of end-user energy profile and over provision to meet regulatory standards	Lack of in-depth knowledge on costs of technologies
Lack of easy to use software for integrated design, modelling, simulation, and analysis	Lack of accountability of consultants and design team on actual performance of the building
Lack of data availability and measurement verification	
Lack of accurate integrated design process and execution (building design based on whole life cycle, cost benefit, risk analysis and social impact)	

4.2 OPPORTUNITIES

Despite the above challenges, there are also several opportunities for Singapore to be at the forefront of Building Energy Efficiency technology development. With the ongoing initiatives highlighted in section 2.2, it can be seen that there is already a lot of impetus for technology development in this area. This roadmap points out some specific directions for furthering the technology development efforts in Singapore.

[5] This challenge might be seen also as non-technical in terms of insufficient infrastructure, financial support etc.

As ACMV is the largest contributor of energy consumption in buildings, this is logically the most impactful area for technology development for energy efficiency improvements. Due to the hot tropical climate of Singapore, there is high demand for cooling and dehumidification in order to maintain occupant comfort. The technology choices for this important building provision has to be best suited for tropical conditions and several technology options and guidelines from developing countries have to adapted in order to achieve optimum performance in local conditions.

There has been a number of technology themes suggested for ACMV and the following technology options and strategies present unique opportunities for Singapore considering their overall energy savings impact and alignment to local context, as well as their low cost-complexity and development risks:

1) **Decoupling ventilation & cooling:** The goal of this technology option is to completely separate the processes of providing cooling and distributing air. One good example is DOAS (Dedicated Outdoor Air System). Combinations such as DOAS and dual temperature chillers can enable highly energy efficient chiller plant systems. It also opens up the opportunity to use new approaches to dehumidification of outside fresh air such as moisture absorption technologies that are much lower in overall energy consumption when compared to conventional dehumidification by cooling air below the dew point. At the same time, the sensible cooling load (cooling of equipment, people, etc.) can be achieved by **innovative sensible cooling** approaches such as radiant cooling via chilled beams, ceilings and floor panels that are placed directly in the space to be cooled. However, further research and development needs to happen in order to avoid problems caused by excessive condensation within the space, as well as costs associated with installation and operation of such technologies.

2) **Self-adapting distributed air-con systems:** In view of the inherent 'smartness' expected from users of technologies these days, air-conditioning and other systems should be able to adapt to occupant preferences within a room. This however poses a great challenge to conventional air ducting schemes, especially when taking into account movement of occupants. Hence, further research and development need to occur to be able to make such provisions effectively. From the building controls point of view, thermal scanning technology could analyse occupants as they enter a room, relay their preferences to the BMIS, and then the BMIS would change cooling and lighting within that room accordingly. Occupants could also be assigned specific work areas which can adapt and provide the cooling and lighting matching their preferences. These technology options if developed further could offer significant energy savings potential and at the same time position Singapore as a 'smart and liveable' city.

3) **Embedded intelligence in BMIS software and automated fault correction:** Currently, control systems typically gather information measured by sensors and then send signals to modulate equipment operation if sensor outputs fall outside of an acceptable range. However, control system software do not typically generate warnings when unrealistic or questionable values are read from sensors. If software could detect anomalies in sensor outputs during building operation, facility managers could make decisions faster and more effectively regarding potentially faulty equipment. To extend this further, the detection and diagnosis of problems could be automated and presented to the facility managers via customisable dashboards and notification systems that will ensure timely solutions to faults and optimisation opportunities. This will address the challenge of inefficient operation and maintenance and provide valuable data about actual performance of the building in real-time. It will also enhance the capabilities and productivity of facility managers.

4) **ID tools for multi-criteria optimization and predictive controls:** In the long term, building stakeholders need to be able to continuously evaluate a building throughout its entire life cycle on multiple criteria. This will reinforce the need for building designers across disciplines to communicate and collaborate. There needs to be further development of Integrated Design toolkits that are user-friendly, encourage collaboration amongst various building stakeholders and perform optimisation using multiple criteria such as costs, aesthetics, comfort and energy consumption. This will avoid issues such as over-sizing of equipment or over-provision of building services, in view of costs and energy efficiency. Building modelling is often used as means of predicting how buildings will operate before construction is complete. If models could be continuously updated based upon real-time monitoring and sensing as a feedback mechanism during operation, the diagnostic process will greatly improve. This will enable control of actual performance of buildings and enhance productivity of operations and maintenance functions. This however has to be facilitated by data analysis and data mining techniques that require both hardware and software capabilities. As Singapore has a well-developed infrastructure and capabilities for information and communication technologies, there is comparative advantage to be a leader in this area.

5) **Integrated test-bedding of BEFS and other systems:** The lack of test-bedding facilities is one of the key challenges identified for technology development in Singapore. The industry is also risk-averse in the uptake and adoption of new technologies. With Building Envelope and Façade System (BEFS) technologies being a high cost building element, there is little scope for experimentation of these technologies in real-life operating buildings. However, BEFS technologies need to be adapted to the tropics as

they could influence energy consumption of air-conditioning and lighting provisions significantly. It is also important for test-bedding facilities to closely mirror real-life contexts and focus on integrated testing of various technologies (e.g. specific glazing technology in combination with lighting and air-conditioning technology) in order to avoid integration problems and counter-active energy consumption patterns in real-life scenarios. Such a test-bedding approach could ease the anxiety and risk perception of new technologies while developing local capabilities related to operation and maintenance of new technology options.

5. CONCLUSION: SUPPORTING DEPLOYMENT

The primary focus of the roadmap was to identify technologies for R&D that would push the best-in-class buildings' energy efficiency to the next level. The key focus areas for technology development have been identified along with technology pathways that would lead to improvement of building energy efficiency in the long term. The identified technologies have been prioritised and assessed for their impact on building energy efficiency improvement through insights from the energy modelling exercise and expert consultations. These EE improvements were used in conjunction with assumptions for future changes in GreenMark certification trends to project electricity consumption and emissions due to Singapore's building stock up to 2030. It was observed that the technology developments could improve the cumulative carbon emission savings by about 22 – 28% over business-as-usual scenario.

The technology pathways that are identified in this roadmap need to be sufficiently supported with resources such as funding and research capabilities in order to achieve the desired improvements. There also have to be studies conducted before embarking on certain technology options to ensure relevance and increase chances of success. This has to be supplemented with technology test-bedding opportunities, which is one of the key challenges for further technology development in Singapore. It is important that such test-bedding facilities are close to real-life scale demonstration and provide opportunities for testing various technologies in an integrated manner. The findings from these test-bedding activities will be useful for directing future technology developments.

Along with technology development pathways, there was largely a consensus on the fact that technology adoption and deployment has to be accelerated in order to be able to achieve maximum benefits of building EE technologies in Singapore. It is recommended to adopt a focused approach around technology adoption and hence a concept of a **Building Energy Efficiency Hub (BEE Hub)** has been proposed. The main objectives of the proposed BEE Hub in Singapore would be to accelerate adoption and deployment of proven EE technologies in buildings, test-bed new EE technologies and solutions, and create a centre for sharing and disseminating data to expand Singapore's knowledge base of EE technology measures. **The Hub can also drive applied research in the prioritised technologies of the 4 focus areas including social behavioural studies such as human-technology interaction and their impact on energy efficiency, occupancy well-being as against energy efficiency, etc.** This can address problems like the lack of energy and buildings data,[6] the need for data verification, and insufficient knowledge about actual building performance. The BEE Hub approach in Singapore could also be used to address the current gaps such as standardizing

[6] BCA has recently started to make monitoring of building performance mandatory for building owners.

and simplifying technology auditing tools, investigating and analysing institutional business models and behavioural effects.

The BEE Hub would also be a good platform for sharing showcases of integrated design approaches and guidelines for successful implementation processes. Market and technological challenges of retrofitting would be addressed in the actual buildings (as oppose to test-beds) and will therefore help accelerate energy-efficient solutions and processes for retrofitting existing buildings in Singapore. This work would also serve to improve education, training, and awareness about energy-efficient opportunities and build deep capabilities on EE measures across the value chain (ESCOs, consultants, developers, operators, facility managers, etc.).

6. APPENDICES

Appendix I

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Appendix II

Acronyms and abbreviations

ACMV: Air Conditioning & Mechanical Ventilation
BCA: Building & Construction Authority
BEE: Building Energy Efficiency
BEFS: Building Envelope & Façade System
BIM: Building Information Modelling
BMIS: Building Management & Information System
CAV: Constant Air Volume
DOE: US Department of Energy
E2B EI: Energy Efficient Building European Initiative
EDB: Economic Development Board
EE: Energy Efficiency
ERI@N: Energy Research Institute @ NTU
FDDI: Fault Detection, Diagnostics, and Interaction
ETTV: Envelope Thermal Transfer Value
GHG: Green House Gases
GM: Green Mark
IAQ: Indoor Air Quality
ICT: Information & Communication Technology
ID: Integrated Design Approach & Tools
IEA: International Energy Agency
KPI: Key Performance Indicator
LCA: Life Cycle Assessment
LCC: Life Cycle Cost
M&E: Mechanical and Electrical
M&V: Measurement and Verification
NCCS: National Climate Change Secretariat
nEEI: Normalised Energy Efficiency Index
NRF: National Research Foundation
OM&M: Operation, Maintenance and Management
PMV: Predicted Mean Vote
R&D: Research and Development
RD&D: Research, Development & Demonstration
VAV: Variable Air Volume

Appendix III

List of stakeholders consulted and reviewers

We would like to thank all for the valuable feedback and constructive suggestions. Our sincere regrets if we have inadvertently missed out any person or organization who has contributed.

List of Stakeholders:

Name	Organization	Participation
Yusof Bin Kassim	3M	Workshop
Lim Say Leong	ABB Industry Pte Ltd	Workshop
Russell Cole	Arup	Interview, Workshop
Richard Tai	Arup	Workshop, Focus Group discussion
Michael Chin	Arup / Aurecon	Interview
Scott Munro	Arup	Workshop
Doris Oesterreicher	Austrian Institute of Technology	Interview
Sunil Moongadi Kunjayyappan	Autodesk Inc	Workshop
Sharelle Low Shu Qing	Building and Construction Authority	Focus Group discussion
Wong Ngian Chung	Building and Construction Authority	Focus Group discussion
Zhou Xu	Building and Construction Authority	Focus Group discussion
Lam Siew Wah	Building and Construction Authority	Interview
Choo Whatt Bin	Building and Construction Authority	Workshop
Leong-Kok Su Ming	Building and Construction Authority	Workshop
Ang Kian Seng	Building and Construction Authority	Workshop, Focus Group Discussion
Jeffery Neng Kwei Sung	Building and Construction Authority	Workshop, Focus Group Discussion
Gao Chun Ping	Building and Construction Authority	Workshop
Yong Ping Quen	Building System and Diagnostics Pte Ltd	Interview
Tan Boon Kuan	Carrier Singapore	Interview
Loh Rathman	Carrier Singapore	Interview, Workshop
Wang See Chenn	Carrier Singapore	Workshop
Gayle Tan	Cyclect Electrical Engineering Pte Ltd	Workshop
Kazuhide Motegi	Dai Nippon Paint Asia Pacific Pte Ltd.	Workshop
Raymond Tan	Daikin	Focus Group discussion
Lee Boon Woei	DP Architects	Interview, Workshop
Joelle Chen	Economic Development Board	Focus Group discussion
Goh Chee Kiong	Economic Development Board	Interview, Focus Group Discussion

Tan Xin Yi	Economic Development Board	Workshop
William Loh	Energeia Glass	Interview
Andrew Seah Boon Yong	Energy Market Authority	Workshop
Majid Bin Haji Sapar	Energy Research Institute @ NTU	Interview, Workshop, Focus Group Discussion
Choo Fook Hoong	Energy Research Institute at NTU	Workshop
Gerhard Schmitt	Future Cities Laboratory	Interview, Workshop
Low Loke Kiong Vincent	G-Energy Global PL	Workshop
Lui Wing Sin	GETC Asia Pte Ltd / Metro GT	Interview
Kamitani Matsuo	Hitachi Plant Technologies (Asia) Pte.Ltd.	Workshop
Yukio Fukushima	Hitachi Plant Technologies (Asia) Pte.Ltd.	Workshop
Lester Chia	Housing Development Board	Workshop
Lim Ah Hee	Housing Development Board	Workshop
Ching-Hua Chen-Ritzo	IBM	Focus Group discussion
Zhili Zhou	IBM	Focus Group discussion
Poh Hee Joo	Institute of High Performance Computing, A-STAR	Workshop, Focus Group discussion
Soong Sau Khong	Johnson Controls (S) Pte Ltd	Interview, Workshop
Terence Tan	Johnson Controls (S) Pte Ltd	Interview, Workshop, Focus Group Discussion
Koh Chwee	JTC Corporation	Focus Group discussion
David Tan	JTC Corporation	Interview
Tang Pei Luen	JTC Corporation	Workshop
Loh Wai Soong	JTC Corporation	Workshop
Uma Maheshwaran	Jurong Consultants Pte Ltd	Interview, Focus Group Discussion
Reshma Singh	Lawrence Berkeley National Laboratory	Interview, Focus Group Discussion
Stephen Selkowitz	Lawrence Berkeley National Laboratory	Focus Group discussion
Les Norford	Massachusetts Institute of Technology	Focus Group discussion
Steven Kang	Measurement and Verification Pte Ltd	Workshop
Mathieu Meur	Meinhardt	Workshop
Martin Lim	Metro GT	Interview
Jack Huang	Ministry of National Development	Workshop
Loy Liang Xian	Ministry of Trade and Industry	Workshop
Chris Ho	Mitsubishi	Focus Group discussion
Pang See Kin	Munters	Interview, Workshop
CHANG Wei-Chung, Victor	Nanyang Technological University	Focus Group discussion

Anutosh Chakraborty	Nanyang Technological University	Interview, Focus Group Discussion
Tseng King Jet	Nanyang Technological University	Workshop
Wong Yew Wah	Nanyang Technological University	Workshop, Focus Group Discussion
Yu Hao	Nanyang Technological University	Workshop, Focus Group discussion
Toh Kok Chuan	Nanyang Technological University	Focus Group discussion
Zhao Jiyun	Nanyang Technological University	Workshop
Tay Cher Seng	Natflow Pte Ltd	Workshop, Focus Group Discussion
Ho Hiang Kwee	National Climate Change Secretariat	Interview, Workshop, Focus Group Discussion
Lou Xian Fang	National Climate Change Secretariat	Workshop
Tang Tuck Weng	National Climate Change Secretariat	Workshop
Benedict Chia	National Climate Change Secretariat	Workshop, Focus Group Discussion
Ananda Ram Bhaskar	National Environment Agency	Interview, Workshop, Focus Group Discussion
Edmund Koh	National Parks	Workshop
Jonathan Cheng	National Research Foundation	Workshop
Tsoi Mun Heng	National Research Foundation	Interview, Workshop
Cheong Kok Wai	National University of Singapore	Focus Group discussion
Wong Nyuk Hien	National University of Singapore	Focus Group discussion
Chou Siaw Kiang	National University of Singapore	Interview
Nirmal Kishnani	National University of Singapore	Interview
Benny Raphel	National University of Singapore	Interview, Workshop
Lee Siew Eang	National University of Singapore	Interview, Workshop
Chandra Sekhar	National University of Singapore	Interview, Workshop, Focus Group Discussion
Huang Yi Chun	National University of Singapore	Interview, Workshop, Focus Group Discussion
Sekhar Kondepudi	National University of Singapore	Interview, Workshop, Focus Group Discussion
Sanjib Kumar Panda	National University of Singapore	Workshop
Tham Kwok Wai	National University of Singapore	Workshop, Focus Group discussion
Forrest Meggers	National University of Singapore	Interview, Workshop, Focus Group Discussion
Tony Tay	Parsons Brinckerhoff	Interview
Karthikeyan Kamaraj	Parsons Brinckerhoff	Interview, Workshop
Paul Hallacher	Penn State University	Focus Group discussion

William Bahnfleth	Penn State University	Focus Group discussion
Roy Goh	PPG Architectural Glass	Interview
Sin Jia Hau	Schneider Electric	Workshop
Jayaraman Balachandar	Siemens	Workshop, Focus Group Discussion
Costas Spanos	Singapore Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST)	Focus Group discussion
Szu Cheng Chien	Singapore Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST)	Focus Group discussion
Julie Stein	Singapore Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST)	Interview
Khalid Mahmoud Mosalam	Singapore Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST)	Workshop
Gan Geok Chua	Singapore Safety Glass	Workshop
Thomas Schroepfer	Singapore University of Technology and Design	Interview, Focus Group discussion
Marcel Bruelisauer	Singapore-ETH Centre for Global Environmental Sustainability	Interview, Workshop, Focus Group Discussion
Chen Fangzhi	Solar Energy Research Institute of Singapore	Interview, Workshop, Focus Group Discussion
Choo Thian Song	Solar Energy Research Institute of Singapore	Workshop
Serene Lim Xin Hui	SPRING Singapore	Workshop
Joy Gai	Surbana	Interview
Mike Nga	Tacam Steel Pte. Ltd.	Workshop
Maggie Low	Technoform Bautec Asia Pacific Pte Ltd	Workshop
Quek Thian Seong	Technoform Bautec Asia Pacific Pte Ltd	Workshop
Lee Eng Lock	Trane Distribution Pte Ltd	Interview, Workshop
Kevin Weekly	UC Berkley	Interview
Elaine Tan	Urban Redevelopment Authority	Focus Group discussion
Teck Leong Lim	Urban Redevelopment Authority	Focus Group discussion
Melissa Sapuan	Urban Redevelopment Authority	Workshop
Alex Lee	ZEB Technology	Focus Group discussion

APPENDIX IV

List of Roadmap Reviewers:

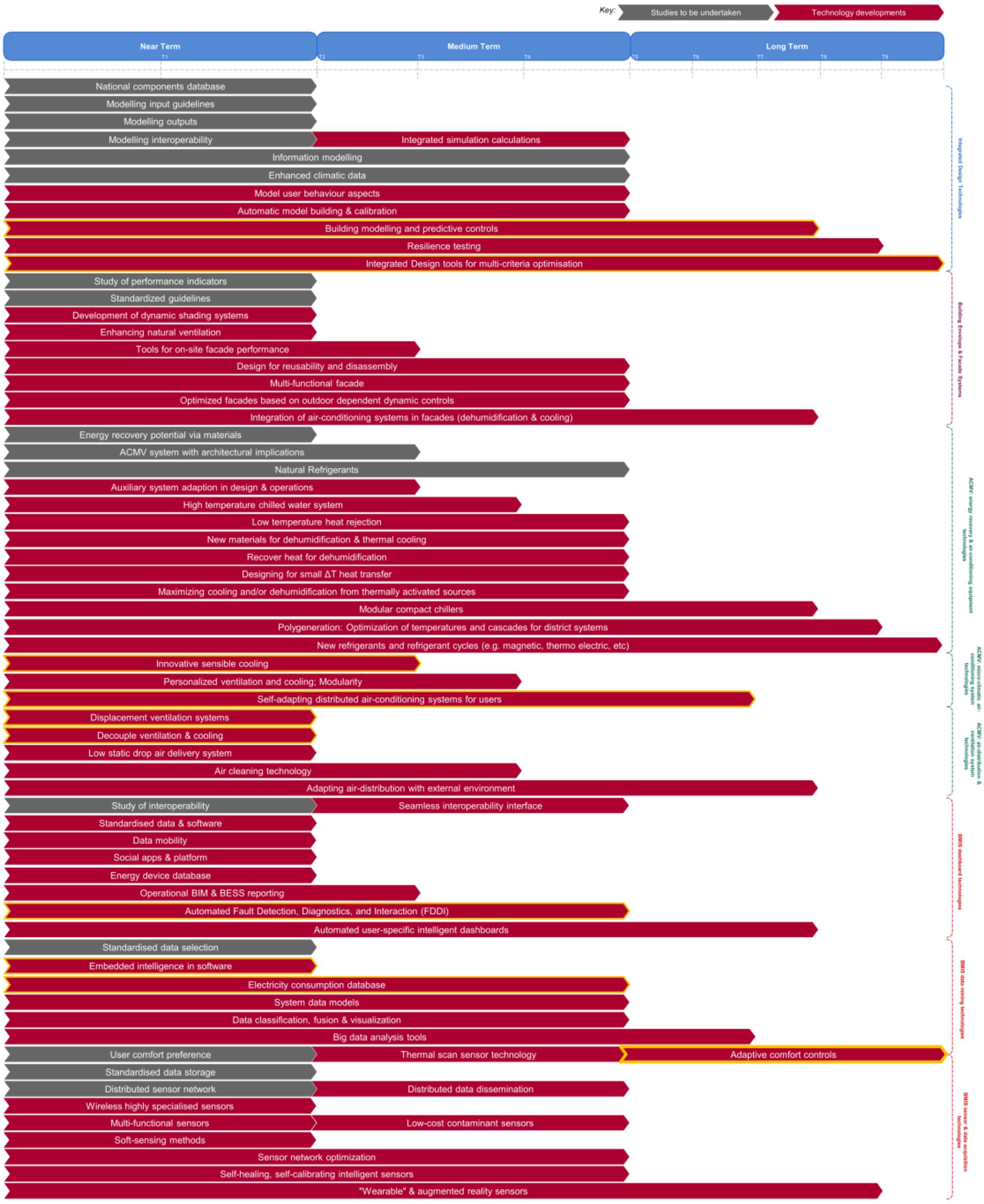
The outcome of the roadmap was shared with a panel of international reviewers. Comments and feedback have been addressed accordingly. We would like to thank the reviewers for their contribution.

	Name	Designation	Organization
1	Lam Khee Poh	Professor, School of Architecture Center for Building Performance & Diagnostics	Carnegie Mellon University, United States
2	Deo Prasad	Professor, Program Director - Sustainable Development	University of New South Wales, Australia
3	James D. Freihaut	Director, DOE Mid Atlantic Clean Energy Application Centre Chief Scientist, DOE Energy Efficient Buildings Hub	Pennsylvania State University
4	Marc LaFrance	Energy Analyst Buildings Sector	International Energy Agency (IEA)

Appendix V

Complete list of 52 technologies and studies

The chart is organized across various time horizons based on projected lengths of time each technology would need to be developed before providing useful results. For example, near term technologies are expected to yield useful results two years after research begins while long term technologies are expected to yield useful results ten years after research begins. The figure is also colour-coded to represent preliminary studies (grey) and expected progress of technology readiness level throughout the research process (red). The top ten technologies are outlined in yellow.



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- Ross Brindle

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Mrs. Leong-Kok Su Ming	Building and Construction Authority
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Mr. Edmund Ooi	National Research Foundation
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