BUILDING ENERGY EFFICIENCY R&D Roadmap
TABLE OF CONTENTS

EXECUTIVE SUMMARY ...................................................................................................................... 3

1. INTRODUCTION ............................................................................................................................. 6
   1.1 RATIONALE OF BUILDING EE .................................................................................................. 6
   1.2 CURRENT AND ON-GOING INITIATIVES ............................................................................... 8
   1.3 OBJECTIVES OF ROADMAP ................................................................................................. 9

2. CURRENT AND FUTURE PATHWAYS FOR BUILDING EE AND FOCUSED TECHNOLOGIES .... 11
   2.1 INTEGRATED DESIGN (ID) ...................................................................................................... 11
   2.2 BUILDING ENVELOPE AND FAÇADE SYSTEM ..................................................................... 12
   2.3 AIR CONDITIONING & MECHANICAL VENTILATION ............................................................... 14
   2.4 BUILDING MANAGEMENT & INFORMATION SYSTEM ......................................................... 19
   2.5 PRIORITIZING TECHNOLOGY RESEARCH AND DEVELOPMENT ......................................... 22

3. POTENTIAL FOR ENERGY EFFICIENCY IMPROVEMENTS ..................................................... 25
   3.1 TECHNOLOGY ADOPTION SCENARIOS ............................................................................... 25
   3.2 POTENTIAL ENERGY SAVINGS ............................................................................................... 26
   3.3 POTENTIAL CO₂ EMISSION SAVINGS ................................................................................... 26
   3.4 ECONOMICS OF BUILDING ENERGY EFFICIENCY DEPLOYMENT ..................................... 27

4. CHALLENGES AND OPPORTUNITIES ...................................................................................... 28
   4.1 CHALLENGES ...................................................................................................................... 28
   4.2 OPPORTUNITIES .................................................................................................................... 28

5. CONCLUSION: SUPPORTING DEPLOYMENT .......................................................................... 32

6. APPENDICES .................................................................................................................................. 34

7. MAIN CONTRIBUTORS .................................................................................................................... 43
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.

- **Targets**: 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 (m²) 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>
<thead>
<tr>
<th>Technical Challenges</th>
<th>Non-Technical Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lack of test-bedding opportunities¹</td>
<td>Lack of policies and incentives for developing technologies from R&amp;D to market adoption</td>
</tr>
<tr>
<td>Inefficient Operation, Maintenance and Management (OM&amp;M)</td>
<td>OM&amp;M with short term contracts</td>
</tr>
<tr>
<td>Lack of specific technologies that can holistically address the issues around retrofitting of existing buildings</td>
<td>Lack of right knowledge, awareness and training of facility personnel in OM&amp;M domain</td>
</tr>
<tr>
<td>Lack of in-depth, up-to-date knowledge of actual performance</td>
<td>Risk aversion on taking up of new technologies due to lack of information, awareness, validated data, and incentives</td>
</tr>
<tr>
<td>Over sizing of systems and equipment due to uncertainty of end-user energy profile and over provision to meet regulatory standards</td>
<td>Lack of in-depth knowledge on costs of technologies</td>
</tr>
<tr>
<td>Lack of easy to use software for integrated design, modelling, simulation, and analysis</td>
<td>Lack of accountability of consultants and design team on actual performance of the building</td>
</tr>
<tr>
<td>Lack of data availability and measurement verification</td>
<td></td>
</tr>
<tr>
<td>Lack of accurate integrated design process and execution (building design based on whole life cycle, cost benefit, risk analysis and social impact)</td>
<td></td>
</tr>
</tbody>
</table>

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

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

- **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 CO₂-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](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 (CO₂) are converted to CO₂-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

<table>
<thead>
<tr>
<th>Overview of RD&amp;D incentives/schemes</th>
</tr>
</thead>
<tbody>
<tr>
<td>MND Research Fund (MNDRF)</td>
</tr>
<tr>
<td>MND-A*STAR grant calls</td>
</tr>
<tr>
<td>Energy Innovation Research Programme (EIRP)</td>
</tr>
<tr>
<td>Innovation Grant (iGrant)</td>
</tr>
</tbody>
</table>
### 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**

- **Experts and Collaborators Input**
  - Gather and analyse secondary data
  - Primary data research (interviews, questionnaires, modelling)
  - Conduct roadmapping exercises (workshops, focus group sessions)
  - Integrate roadmaps, set priorities until 2030
  - Consolidate all documentation and materials

- **Roadmap; Recommendations for implementation; R&D outlook**

- **Review Cycle**
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).

<table>
<thead>
<tr>
<th>Near Term T0</th>
<th>Medium Term T0+2</th>
<th>Long Term T0+5</th>
<th>Long Term T0+10</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>National components database</td>
<td>Modeling inputs</td>
<td>Modeling guidelines</td>
<td>Integrated simulation calculations</td>
<td>Need to establish a database of building components used in Singapore, including details such as material properties</td>
</tr>
<tr>
<td>Modeling outputs</td>
<td>Information modelling</td>
<td>Enhanced climatic data</td>
<td>Model user behaviour aspects</td>
<td>Define standards for performance metrics reported as outputs</td>
</tr>
<tr>
<td>Modeling interoperability</td>
<td>Automatic model building &amp; calibration</td>
<td>Building modelling and predictive control</td>
<td>Resilience testing</td>
<td>Define standards to be used as modelling inputs in the future, including allowable tolerance and accuracy thresholds</td>
</tr>
<tr>
<td>Integrated Design tools for multi-criteria optimisation</td>
<td>Integrated Design tools for multi-criteria optimisation</td>
<td>Integrated Design tools for multi-criteria optimisation</td>
<td>Integrated Design tools for multi-criteria optimisation</td>
<td>Aggregate data across different modelling tools (GIS, CPS, M&amp;E, etc.) to enhance interoperability and eventually develop a tool that performs all simulations simultaneously</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Localized climate data for accurate energy modelling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ability to model and predict user behaviour within a building</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Create and calibrate model using only geometry and space use</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Examine building’s durability under simulated scenarios</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Optimise for whole building approach to minimize negative impacts and maximize efficiency</td>
</tr>
</tbody>
</table>

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

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.

![Figure 2.2: Technology pathway for BEFS technologies](image)

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

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) 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.

---

### Table 2.2: Top ACMV Technologies from US DOE Report

<table>
<thead>
<tr>
<th>Technology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Thermoelastic Cooling</strong></td>
<td>Thermoelastic cooling systems utilise shape-memory metal alloy that alternately absorbs or creates heat through its thermoelastic characteristics.</td>
</tr>
<tr>
<td><strong>2. Aerosol Duct Sealing</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>3. Dedicated Outdoor Air System</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>4. Permanent Magnet Motors</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>5. Switched Reluctance Motors</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>6. Bernoulli Cooling Cycle</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>7. Thermoelectric Cooling Cycle</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>8. Duct Leakage Diagnostics</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>9. Zephyr Ceiling Tiles</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>10. Ductwork in the Conditioned Space</strong></td>
<td>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.</td>
</tr>
</tbody>
</table>

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.\footnote{Note: For controls, refer to focus area “Building Management and Information Systems”}

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

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

---

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

<table>
<thead>
<tr>
<th>Near Term T0</th>
<th>Medium Term T0+5</th>
<th>Long Term T0+10</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Innovative sensible cooling</td>
<td>Personalized ventilation and cooling: Modularity</td>
<td>Self-adapting distributed air-conditioning systems for users</td>
<td>Improve energy efficiency and occupant comfort via reduction in air flow and enhanced control</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Devise accurate ventilation strategies for every individual with intelligent controls</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Flexibility of air distribution systems that dynamically adjusts with space and time</td>
</tr>
</tbody>
</table>
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.
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

<table>
<thead>
<tr>
<th>Near Term (T0)</th>
<th>Medium Term (T0+5)</th>
<th>Long Term (T0+10)</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Study of interoperability</strong></td>
<td><strong>Seamless interoperability interface</strong></td>
<td></td>
<td>Determine appropriate protocol to allow components from different vendors to communicate and function, implement such protocol to be industry standard</td>
</tr>
<tr>
<td><strong>Standardised data &amp; software</strong></td>
<td></td>
<td></td>
<td>Standardised performance indicators as simulation output</td>
</tr>
<tr>
<td><strong>Data mobility</strong></td>
<td></td>
<td></td>
<td>Interaction of dashboards with mobile devices</td>
</tr>
<tr>
<td><strong>Social apps &amp; platform</strong></td>
<td></td>
<td></td>
<td>Encourage social environmental awareness via competition</td>
</tr>
<tr>
<td><strong>Energy Device Database</strong></td>
<td></td>
<td></td>
<td>Facility manager can locate faulty equipment within building</td>
</tr>
<tr>
<td><strong>Operational BIM &amp; BESS reporting</strong></td>
<td></td>
<td></td>
<td>Dashboard can support dynamic built environment</td>
</tr>
<tr>
<td><strong>Automated FDDI</strong></td>
<td></td>
<td></td>
<td>Alert facility manager and instantly provide sequential instructions to resolve operational problems</td>
</tr>
<tr>
<td><strong>Automated user-specific intelligent dashboards</strong></td>
<td></td>
<td></td>
<td>Dashboard automatically changes interface dependent on user</td>
</tr>
</tbody>
</table>

### Figure 2.10: Technology pathways for data mining technologies

<table>
<thead>
<tr>
<th>Near Term (T0)</th>
<th>Medium Term (T0+5)</th>
<th>Long Term (T0+10)</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standardised data selection</strong></td>
<td></td>
<td></td>
<td>Devise framework for categorizing data across building profiles</td>
</tr>
<tr>
<td><strong>Embedded software intelligence</strong></td>
<td></td>
<td></td>
<td>Software detects sensor output anomalies during operation to enable faster and more effective decision-making for facility managers</td>
</tr>
<tr>
<td><strong>Electricity consumption database</strong></td>
<td></td>
<td></td>
<td>Organized data set used for enhanced operational efficiency and benchmarking performance</td>
</tr>
<tr>
<td><strong>System data models</strong></td>
<td></td>
<td></td>
<td>Determine system synergies for operation optimization</td>
</tr>
<tr>
<td><strong>Data classification, fusion &amp; visualization</strong></td>
<td></td>
<td></td>
<td>Data is organized &amp; displayed in manner that is easy for stakeholder to visualise</td>
</tr>
<tr>
<td><strong>Big data analysis tools</strong></td>
<td></td>
<td></td>
<td>Software and hardware capable of collecting, organizing, and analysing “big data” expected in the future</td>
</tr>
</tbody>
</table>
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

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

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

<table>
<thead>
<tr>
<th>Label</th>
<th>Bottom 10 Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACMV-3</td>
<td>Use of recovered heat for dehumidification</td>
</tr>
<tr>
<td>ACMV-1</td>
<td>Auxiliary system adaption</td>
</tr>
<tr>
<td>BEFS-3</td>
<td>Tools for measuring on-site façade performance</td>
</tr>
<tr>
<td>ID-1</td>
<td>Model user behaviour aspects</td>
</tr>
<tr>
<td>ACMV-15</td>
<td>Air delivery system with low static drop</td>
</tr>
<tr>
<td>BEFS-5</td>
<td>Multifunctional facades</td>
</tr>
<tr>
<td>ACMV-4</td>
<td>Low temperature heat rejection</td>
</tr>
<tr>
<td>ACMV-17</td>
<td>Adapting air distribution with external environment users</td>
</tr>
<tr>
<td>ACMV-16</td>
<td>Air cleaning technologies</td>
</tr>
<tr>
<td>ACMV-5</td>
<td>Designing for small DT heat transfer</td>
</tr>
</tbody>
</table>
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/m²/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)

<table>
<thead>
<tr>
<th>Adoption Level</th>
<th>Time Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate</td>
<td>8%</td>
</tr>
<tr>
<td>Aggressive</td>
<td>15%</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Adoption Level</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Business as Usual</td>
<td>Assumes baseline energy use does not change, matches current GM statistics as of 2013</td>
</tr>
<tr>
<td>2</td>
<td>Mandatory GM Certification for New Construction</td>
<td>All new construction in Singapore must meet GM Certification standards</td>
</tr>
<tr>
<td>3</td>
<td>Scenario 2 + Retrofit for GM Certification</td>
<td>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</td>
</tr>
<tr>
<td>4</td>
<td>Scenario 3 + Moderate Technology Improvement</td>
<td>Technology improves with conservative Energy Efficiency targets</td>
</tr>
<tr>
<td>5</td>
<td>Scenario 3 + Aggressive Technology Improvement</td>
<td>Technology improves with aggressive Energy Efficiency targets</td>
</tr>
</tbody>
</table>
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>
<thead>
<tr>
<th>Scenario</th>
<th>Cumulative Savings (GWh)</th>
<th>% Cumulative Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>13,498</td>
<td>4.6%</td>
</tr>
<tr>
<td>3</td>
<td>17,050</td>
<td>5.8%</td>
</tr>
<tr>
<td>4</td>
<td>66,009</td>
<td>22.3%</td>
</tr>
<tr>
<td>5</td>
<td>84,027</td>
<td>28.4%</td>
</tr>
</tbody>
</table>

3.3 POTENTIAL CO₂ EMISSION SAVINGS

To calculate potential CO₂ 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 CO₂ is emitted when electricity is generated in Singapore. According to latest Energy Market Authority data from 2012 (EMA, 2013), 0.4977 kg of CO₂ 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>
<thead>
<tr>
<th>Scenario</th>
<th>Cumulative Savings (Million tonnes)</th>
<th>% Cumulative Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>6.7</td>
<td>4.6%</td>
</tr>
<tr>
<td>3</td>
<td>8.5</td>
<td>5.8%</td>
</tr>
<tr>
<td>4</td>
<td>32.9</td>
<td>22.3%</td>
</tr>
<tr>
<td>5</td>
<td>41.8</td>
<td>28.4%</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cumulative Net Cost (Million SGD)</th>
<th>Cumulative Net Carbon Abatement Cost (SGD/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-334</td>
<td>-50</td>
</tr>
<tr>
<td>3</td>
<td>-1,021</td>
<td>-120</td>
</tr>
<tr>
<td>4</td>
<td>-558</td>
<td>-16</td>
</tr>
<tr>
<td>5</td>
<td>8,195</td>
<td>171</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Technical Challenges</th>
<th>Non-Technical Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lack of test-bedding opportunities⁵</td>
<td>Lack of policies and incentives for developing technologies from R&amp;D to market adoption</td>
</tr>
<tr>
<td>Inefficient Operation, Maintenance and Management (OM&amp;M)</td>
<td>OM&amp;M with short term contracts</td>
</tr>
<tr>
<td>Lack of specific technologies that can holistically address the issues around retrofitting of existing buildings</td>
<td>Lack of right knowledge, awareness and training of facility personnel in OM&amp;M domain</td>
</tr>
<tr>
<td>Lack of in-depth, up-to-date knowledge of actual performance</td>
<td>Risk aversion on taking up of new technologies due to lack of information, awareness, validated data, and incentives</td>
</tr>
<tr>
<td>Over sizing of systems and equipment due to uncertainty of end-user energy profile and over provision to meet regulatory standards</td>
<td>Lack of in-depth knowledge on costs of technologies</td>
</tr>
<tr>
<td>Lack of easy to use software for integrated design, modelling, simulation, and analysis</td>
<td>Lack of accountability of consultants and design team on actual performance of the building</td>
</tr>
<tr>
<td>Lack of data availability and measurement verification</td>
<td></td>
</tr>
<tr>
<td>Lack of accurate integrated design process and execution (building design based on whole life cycle, cost benefit, risk analysis and social impact)</td>
<td></td>
</tr>
</tbody>
</table>

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, 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

References


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:

<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
<th>Participation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yusof Bin Kassim</td>
<td>3M</td>
<td>Workshop</td>
</tr>
<tr>
<td>Lim Say Leong</td>
<td>ABB Industry Pte Ltd</td>
<td>Workshop</td>
</tr>
<tr>
<td>Russell Cole</td>
<td>Arup</td>
<td>Interview, Workshop</td>
</tr>
<tr>
<td>Richard Tai</td>
<td>Arup</td>
<td>Workshop, Focus Group discussion</td>
</tr>
<tr>
<td>Michael Chin</td>
<td>Arup / Aurecon</td>
<td>Interview</td>
</tr>
<tr>
<td>Scott Munro</td>
<td>Arup</td>
<td>Workshop</td>
</tr>
<tr>
<td>Doris Oesterreicher</td>
<td>Austrian Institute of Technology</td>
<td>Interview</td>
</tr>
<tr>
<td>Sunil Moongadi Kunjayyappan</td>
<td>Autodesk Inc</td>
<td>Workshop</td>
</tr>
<tr>
<td>Sharelle Low Shu Qing</td>
<td>Building and Construction Authority</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Wong Ngian Chung</td>
<td>Building and Construction Authority</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Zhou Xu</td>
<td>Building and Construction Authority</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Lam Siew Wah</td>
<td>Building and Construction Authority</td>
<td>Interview</td>
</tr>
<tr>
<td>Choo Whatt Bin</td>
<td>Building and Construction Authority</td>
<td>Workshop</td>
</tr>
<tr>
<td>Leong-Kok Su Ming</td>
<td>Building and Construction Authority</td>
<td>Workshop</td>
</tr>
<tr>
<td>Ang Kian Seng</td>
<td>Building and Construction Authority</td>
<td>Workshop, Focus Group Discussion</td>
</tr>
<tr>
<td>Jeffery Neng Kwei Sung</td>
<td>Building and Construction Authority</td>
<td>Workshop, Focus Group Discussion</td>
</tr>
<tr>
<td>Gao Chun Ping</td>
<td>Building and Construction Authority</td>
<td>Workshop</td>
</tr>
<tr>
<td>Yong Ping Quen</td>
<td>Building System and Diagnostics Pte Ltd</td>
<td>Interview</td>
</tr>
<tr>
<td>Tan Boon Kuan</td>
<td>Carrier Singapore</td>
<td>Interview</td>
</tr>
<tr>
<td>Loh Rathman</td>
<td>Carrier Singapore</td>
<td>Interview, Workshop</td>
</tr>
<tr>
<td>Wang See Chenn</td>
<td>Carrier Singapore</td>
<td>Workshop</td>
</tr>
<tr>
<td>Gayle Tan</td>
<td>Cyclect Electrical Engineering Pte Ltd</td>
<td>Workshop</td>
</tr>
<tr>
<td>Kazuhide Motegi</td>
<td>Dai Nippon Paint Asia Pacific Pte Ltd</td>
<td>Workshop</td>
</tr>
<tr>
<td>Raymond Tan</td>
<td>Daikin</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Lee Boon Woei</td>
<td>DP Architects</td>
<td>Interview, Workshop</td>
</tr>
<tr>
<td>Joelle Chen</td>
<td>Economic Development Board</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Goh Chee Kiong</td>
<td>Economic Development Board</td>
<td>Interview, Focus Group Discussion</td>
</tr>
<tr>
<td>Name</td>
<td>Organisation</td>
<td>Event Type</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>---------------------------------------------------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td>Tan Xin Yi</td>
<td>Economic Development Board</td>
<td>Workshop</td>
</tr>
<tr>
<td>William Loh</td>
<td>Energeia Glass</td>
<td>Interview</td>
</tr>
<tr>
<td>Andrew Seah Boon Yong</td>
<td>Energy Market Authority</td>
<td>Workshop</td>
</tr>
<tr>
<td>Majid Bin Haji Sapar</td>
<td>Energy Research Institute @ NTU</td>
<td>Interview, Workshop, Focus Group Discussion</td>
</tr>
<tr>
<td>Choo Fook Hoong</td>
<td>Energy Research Institute at NTU</td>
<td>Workshop</td>
</tr>
<tr>
<td>Gerhard Schmitt</td>
<td>Future Cities Laboratory</td>
<td>Interview</td>
</tr>
<tr>
<td>Low Loke Kiong Vincent</td>
<td>G-Energy Global PL</td>
<td>Workshop</td>
</tr>
<tr>
<td>Lui Wing Sin</td>
<td>GETC Asia Pte Ltd / Metro GT</td>
<td>Interview</td>
</tr>
<tr>
<td>Kamitani Matsuo</td>
<td>Hitachi Plant Technologies (Asia) Pte Ltd.</td>
<td>Workshop</td>
</tr>
<tr>
<td>Yukio Fukushima</td>
<td>Hitachi Plant Technologies (Asia) Pte Ltd.</td>
<td>Workshop</td>
</tr>
<tr>
<td>Lester Chia</td>
<td>Housing Development Board</td>
<td>Workshop</td>
</tr>
<tr>
<td>Lim Ah Hee</td>
<td>Housing Development Board</td>
<td>Workshop</td>
</tr>
<tr>
<td>Ching-Hua Chen-Ritzo</td>
<td>IBM</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Zhili Zhou</td>
<td>IBM</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Poh Hee Joo</td>
<td>Institute of High Performance Computing, A-STAR</td>
<td>Workshop, Focus Group discussion</td>
</tr>
<tr>
<td>Soong Sau Khong</td>
<td>Johnson Controls (S) Pte Ltd</td>
<td>Interview, Workshop</td>
</tr>
<tr>
<td>Terence Tan</td>
<td>Johnson Controls (S) Pte Ltd</td>
<td>Interview, Workshop, Focus Group Discussion</td>
</tr>
<tr>
<td>Koh Chwee</td>
<td>JTC Corporation</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>David Tan</td>
<td>JTC Corporation</td>
<td>Interview</td>
</tr>
<tr>
<td>Tang Pei Luen</td>
<td>JTC Corporation</td>
<td>Workshop</td>
</tr>
<tr>
<td>Loh Wai Soong</td>
<td>JTC Corporation</td>
<td>Workshop</td>
</tr>
<tr>
<td>Uma Maheshwaran</td>
<td>Jurong Consultants Pte Ltd</td>
<td>Interview, Focus Group Discussion</td>
</tr>
<tr>
<td>Reshma Singh</td>
<td>Lawrence Berkeley National Laboratory</td>
<td>Interview, Focus Group Discussion</td>
</tr>
<tr>
<td>Stephen Selkowitz</td>
<td>Lawrence Berkeley National Laboratory</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Les Norford</td>
<td>Massachusetts Institute of Technology</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Steven Kang</td>
<td>Measurement and Verification Pte Ltd</td>
<td>Workshop</td>
</tr>
<tr>
<td>Mathieu Meur</td>
<td>Meinhardt</td>
<td>Workshop</td>
</tr>
<tr>
<td>Martin Lim</td>
<td>Metro GT</td>
<td>Interview</td>
</tr>
<tr>
<td>Jack Huang</td>
<td>Ministry of National Development</td>
<td>Workshop</td>
</tr>
<tr>
<td>Loy Liang Xian</td>
<td>Ministry of Trade and Industry</td>
<td>Workshop</td>
</tr>
<tr>
<td>Chris Ho</td>
<td>Mitsubishi</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Pang See Kin</td>
<td>Munters</td>
<td>Interview, Workshop</td>
</tr>
<tr>
<td>CHANG Wei-Chung, Victor</td>
<td>Nanyang Technological University</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Name</td>
<td>Institution</td>
<td>Activity</td>
</tr>
<tr>
<td>---------------------------</td>
<td>--------------------------------------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Anutosh Chakraborty</td>
<td>Nanyang Technological University</td>
<td>Interview, Focus Group Discussion</td>
</tr>
<tr>
<td>Tseng King Jet</td>
<td>Nanyang Technological University</td>
<td>Workshop</td>
</tr>
<tr>
<td>Wong Yew Wah</td>
<td>Nanyang Technological University</td>
<td>Workshop, Focus Group Discussion</td>
</tr>
<tr>
<td>Yu Hao</td>
<td>Nanyang Technological University</td>
<td>Workshop, Focus Group discussion</td>
</tr>
<tr>
<td>Toh Kok Chuan</td>
<td>Nanyang Technological University</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Zhao Jiyun</td>
<td>Nanyang Technological University</td>
<td>Workshop</td>
</tr>
<tr>
<td>Tay Cher Seng</td>
<td>Natflow Pte Ltd</td>
<td>Workshop, Focus Group Discussion</td>
</tr>
<tr>
<td>Ho Hiang Kwee</td>
<td>National Climate Change Secretariat</td>
<td>Interview, Workshop, Focus Group Discussion</td>
</tr>
<tr>
<td>Lou Xian Fang</td>
<td>National Climate Change Secretariat</td>
<td>Workshop</td>
</tr>
<tr>
<td>Tang Tuck Weng</td>
<td>National Climate Change Secretariat</td>
<td>Workshop</td>
</tr>
<tr>
<td>Benedict Chia</td>
<td>National Climate Change Secretariat</td>
<td>Workshop, Focus Group Discussion</td>
</tr>
<tr>
<td>Ananda Ram Bhaskar</td>
<td>National Environment Agency</td>
<td>Interview, Workshop, Focus Group Discussion</td>
</tr>
<tr>
<td>Edmund Koh</td>
<td>National Parks</td>
<td>Workshop</td>
</tr>
<tr>
<td>Jonathan Cheng</td>
<td>National Research Foundation</td>
<td>Workshop</td>
</tr>
<tr>
<td>Tsoi Mun Heng</td>
<td>National Research Foundation</td>
<td>Interview, Workshop</td>
</tr>
<tr>
<td>Cheong Kok Wai</td>
<td>National University of Singapore</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Wong Nyuk Hien</td>
<td>National University of Singapore</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Chou Siaw Kiang</td>
<td>National University of Singapore</td>
<td>Interview</td>
</tr>
<tr>
<td>Nirmal Kishnani</td>
<td>National University of Singapore</td>
<td>Interview</td>
</tr>
<tr>
<td>Benny Raphael</td>
<td>National University of Singapore</td>
<td>Interview, Workshop</td>
</tr>
<tr>
<td>Lee Siew Eang</td>
<td>National University of Singapore</td>
<td>Interview, Workshop</td>
</tr>
<tr>
<td>Chandra Sekhar</td>
<td>National University of Singapore</td>
<td>Interview, Workshop, Focus Group Discussion</td>
</tr>
<tr>
<td>Huang Yi Chun</td>
<td>National University of Singapore</td>
<td>Interview, Workshop, Focus Group Discussion</td>
</tr>
<tr>
<td>Sekhar Kondepudi</td>
<td>National University of Singapore</td>
<td>Interview, Workshop, Focus Group Discussion</td>
</tr>
<tr>
<td>Sanjib Kumar Panda</td>
<td>National University of Singapore</td>
<td>Workshop</td>
</tr>
<tr>
<td>Tham Kwok Wai</td>
<td>National University of Singapore</td>
<td>Workshop, Focus Group discussion</td>
</tr>
<tr>
<td>Forrest Meggers</td>
<td>National University of Singapore</td>
<td>Interview, Workshop, Focus Group Discussion</td>
</tr>
<tr>
<td>Tony Tay</td>
<td>Parsons Brinckerhoff</td>
<td>Interview</td>
</tr>
<tr>
<td>Karthikeyan Kamaraj</td>
<td>Parsons Brinckerhoff</td>
<td>Interview, Workshop</td>
</tr>
<tr>
<td>Paul Hallacher</td>
<td>Penn State University</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Name</td>
<td>Organization</td>
<td>Role</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>---------------------------------------------------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td>William Bahnfleth</td>
<td>Penn State University</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Roy Goh</td>
<td>PPG Architectural Glass</td>
<td>Interview</td>
</tr>
<tr>
<td>Sin Jia Hau</td>
<td>Schneider Electric</td>
<td>Workshop</td>
</tr>
<tr>
<td>Jayaraman Balachandar</td>
<td>Siemens</td>
<td>Workshop, Focus Group Discussion</td>
</tr>
<tr>
<td>Costas Spanos</td>
<td>Singapore Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST)</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Szu Cheng Chien</td>
<td>Singapore Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST)</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Julie Stein</td>
<td>Singapore Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST)</td>
<td>Interview</td>
</tr>
<tr>
<td>Khalid Mahmoud Mosalam</td>
<td>Singapore Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST)</td>
<td>Workshop</td>
</tr>
<tr>
<td>Gan Geok Chua</td>
<td>Singapore Safety Glass</td>
<td>Workshop</td>
</tr>
<tr>
<td>Thomas Schroepfer</td>
<td>Singapore University of Technology and Design</td>
<td>Interview, Focus Group discussion</td>
</tr>
<tr>
<td>Marcel Bruelisauer</td>
<td>Singapore-ETH Centre for Global Environmental Sustainability</td>
<td>Interview, Workshop, Focus Group Discussion</td>
</tr>
<tr>
<td>Chen Fangzhi</td>
<td>Solar Energy Research Institute of Singapore</td>
<td>Interview, Workshop, Focus Group Discussion</td>
</tr>
<tr>
<td>Choo Thian Song</td>
<td>Solar Energy Research Institute of Singapore</td>
<td>Workshop</td>
</tr>
<tr>
<td>Serene Lim Xin Hui</td>
<td>SPRING Singapore</td>
<td>Workshop</td>
</tr>
<tr>
<td>Joy Gai</td>
<td>Surbana</td>
<td>Interview</td>
</tr>
<tr>
<td>Mike Nga</td>
<td>Tacam Steel Pte. Ltd.</td>
<td>Workshop</td>
</tr>
<tr>
<td>Maggie Low</td>
<td>Technoform Bautec Asia Pacific Pte Ltd</td>
<td>Workshop</td>
</tr>
<tr>
<td>Quek Thian Seong</td>
<td>Technoform Bautec Asia Pacific Pte Ltd</td>
<td>Workshop</td>
</tr>
<tr>
<td>Lee Eng Lock</td>
<td>Trane Distribution Pte Ltd</td>
<td>Interview, Workshop</td>
</tr>
<tr>
<td>Kevin Weekly</td>
<td>UC Berkley</td>
<td>Interview</td>
</tr>
<tr>
<td>Elaine Tan</td>
<td>Urban Redevelopment Authority</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Teck Leong Lim</td>
<td>Urban Redevelopment Authority</td>
<td>Focus Group discussion</td>
</tr>
<tr>
<td>Melissa Sapuan</td>
<td>Urban Redevelopment Authority</td>
<td>Workshop</td>
</tr>
<tr>
<td>Alex Lee</td>
<td>ZEB Technology</td>
<td>Focus Group discussion</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Name</th>
<th>Designation</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lam Khee Poh</td>
<td>Professor, School of Architecture Center for Building Performance &amp; Diagnostics</td>
<td>Carnegie Mellon University, United States</td>
</tr>
<tr>
<td>Deo Prasad</td>
<td>Professor, Program Director - Sustainable Development</td>
<td>University of New South Wales, Australia</td>
</tr>
<tr>
<td>James D. Freihaut</td>
<td>Director, DOE Mid Atlantic Clean Energy Application Centre Chief Scientist, DOE Energy Efficient Buildings Hub</td>
<td>Pennsylvania State University</td>
</tr>
<tr>
<td>Marc LaFrance</td>
<td>Energy Analyst Buildings Sector</td>
<td>International Energy Agency (IEA)</td>
</tr>
</tbody>
</table>
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.
7. MAIN CONTRIBUTORS

**NTU (AUTHORS)**
- Aaron Patrick Boranian
- Dr. Betka Zakirova
- Jatin Narotam Sarvaiya
- Nilesh Y. Jadhav
- Priya Pawar
- Zhang Zhe

**Nexight Group**
- Ross Brindle

**Technology Roadmap for Building Energy Efficiency Working Committee 2013**

<table>
<thead>
<tr>
<th>Working Committee Members</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mr. Ang Kian Seng</td>
<td>Building and Construction Authority</td>
</tr>
<tr>
<td>Mr. Jeffery, Neng Kwei Sung</td>
<td>Building and Construction Authority</td>
</tr>
<tr>
<td>Mrs. Leong-Kok Su Ming</td>
<td>Building and Construction Authority</td>
</tr>
<tr>
<td>Mr. Toh Eng Shyan</td>
<td>Building and Construction Authority</td>
</tr>
<tr>
<td>Mr. Lim Ah Hee</td>
<td>Housing Development Board</td>
</tr>
<tr>
<td>Mr. Tang Pei Luen</td>
<td>JTC Corporation</td>
</tr>
<tr>
<td>Ms. Tan Li Yen</td>
<td>National Environment Agency</td>
</tr>
<tr>
<td>Mr. Jonathan Cheng</td>
<td>National Research Foundation</td>
</tr>
<tr>
<td>Mr. Edmund Ooi</td>
<td>National Research Foundation</td>
</tr>
<tr>
<td>Ms. Melissa Sapuan</td>
<td>Urban Redevelopment Authority</td>
</tr>
<tr>
<td>Ms. Elaine Tan</td>
<td>Urban Redevelopment Authority</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Working Committee Observers</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mr. Jason Tang</td>
<td>Economic Development Board</td>
</tr>
<tr>
<td>Mr. Ngin Hoon Tong</td>
<td>Energy Market Authority</td>
</tr>
<tr>
<td>Mr. Jack Huang</td>
<td>Ministry of National Development</td>
</tr>
<tr>
<td>Dr. Yang Yanli</td>
<td>Ministry of National Development</td>
</tr>
<tr>
<td>Mr. Loy Liang Xian</td>
<td>Ministry of Trade and Industry</td>
</tr>
<tr>
<td>Dr. Chen Hsiao Wei</td>
<td>National Climate Change Secretariat</td>
</tr>
<tr>
<td>Dr. Lou Xian Fang</td>
<td>National Climate Change Secretariat</td>
</tr>
</tbody>
</table>
Disclaimer, Limitation of Liability

This report represents the personal opinions of the contributors. The contributors, the Nanyang Technological University, Singapore (NTU), Nexight Group, Building and Construction Authority, Housing Development Board, JTC Corporation, National Environment Agency, National Research Foundation, Urban Redevelopment Authority, Economic Development Board, Ministry of National Development, Ministry of Trade and Industry and National Climate Change Secretariat exclude any legal liability for any statement made in the report. In no event shall the contributors, the Nanyang Technological University, Singapore (NTU), Nexight Group, Building and Construction Authority, Housing Development Board, JTC Corporation, National Environment Agency, National Research Foundation, Urban Redevelopment Authority, Economic Development Board, Ministry of National Development, Ministry of Trade and Industry and National Climate Change Secretariat, of any tier be liable in contract, tort, strict liability, warranty or otherwise, for any special, incidental or consequential damages, such as, but not limited to, delay, disruption, loss of product, loss of anticipated profits or revenue, loss of use of equipment or system, non-operation or increased expense of operation of other equipment or systems, cost of capital, or cost of purchase or replacement equipment systems or power.
Lead Agency

Building and Construction Authority

Commissioning Agencies

NCCS
NATIONAL CLIMATE CHANGE SECRETARIAT
PRIME MINISTER’S OFFICE SINGAPORE

NATIONAL RESEARCH FOUNDATION
PRIME MINISTER’S OFFICE