SUPER LOW ENERGY BUILDING
TECHNOLOGY ROADMAP

Contents

EXECUTIVE SUMMARY

Singapore has committed to reducing its emissions intensity by 36% from 2005 levels by 2030. Buildings sector, which is responsible for more than one-third of the country's total electricity consumption, holds a major role in reduction of carbon footprint to mitigate climate change.

To drive the energy efficiency of buildings, Building and Construction Authority (BCA) has been working closely with industry and stakeholders towards the target of greening 80% of the building stock by 2030. Since 2005, BCA has rolled out a suite of initiatives such as Green Building Masterplans, Green Mark schemes and the Green Buildings Innovation Cluster (GBIC) programme. Besides, various government agencies have embarked on several national sustainability programmes such as the Sustainable Singapore Blueprint, Smart Nation initiative and SolarNova, driving a multifaceted approach towards the development and adoption of sustainable technologies and solutions for the built environment.

In the past decade, technological advances and intensified national efforts have been shaping the landscape of Singapore's built environment. Greater opportunities arise in developing, deploying and mainstreaming technological innovations to push the boundaries of building energy efficiency.

These developments have provided a great opportunity and powerful catalyst for realizing BCA's aspirational of achieving Positive Energy, Zero Energy and Super Low Energy Buildings (known as Super Low Energy) that are 60-80% more energy efficient over 2005 levels.

To address challenges and harness opportunities provided by Super Low Energy (SLE), BCA partnered with industry and academia, including the Energy Research Institute @NTU (ERI@N) and Solar Energy Research Institute of Singapore (SERIS), to jointly develop a Technology Roadmap that charts the pathways towards SLE via development, pioneering and adoption of technologies.

The Roadmap examines a wide spectrum of emerging energy technologies, analyses their interaction and integration, and explore their feasibilities in our tropical and urban context. Through technology trending and foresighting, the Roadmap outlines the broad strategies to help the industry design and develop cost-effective SLE buildings.

1. INTRODUCTION

Background

Global commitment for a deep cut on CO_2 emissions has started a worldwide trend toward reducing energy consumption and increasing adoption of renewable energy. Singapore has targeted to reduce emissions intensity by 36% from 2005 levels by 2030.

In Singapore, buildings consume one-third of the nation's total electricity consumption. Building energy efficiency is critical in the national's sustainability agenda in tackling the long term challenges of climate change and global warming.

In this context, BCA has set the national target of achieving 80% Green Gross Floor Area (GFA) by 2030. Since the launch of BCA Green Mark scheme in 2005, more than 3,300 buildings or 36%[1] of the building stocks by GFA has achieved GM standards. BCA has progressively raised the energy performance of buildings through a mix of regulatory, incentive and building research and development (R&D) capabilities. The energy efficiency measures have reaped results where the current best-in-class building has achieved at least 50% energy savings over 2005 levels, and the building stock's overall Energy Use Intensity (EUI) has improved by 9% since year 2008[2].

Building Energy Consumption Landscape

Singapore consumed about 48,626 GWh of electricity in 2016. **Buildings sector which is responsible for more than one-third of the country's total electricity consumption,** holds a major role in reducing carbon footprint to mitigate climate change.

[1] As at July 2018
[2] Building Energy Benchmarking Report (BEBR) 2017

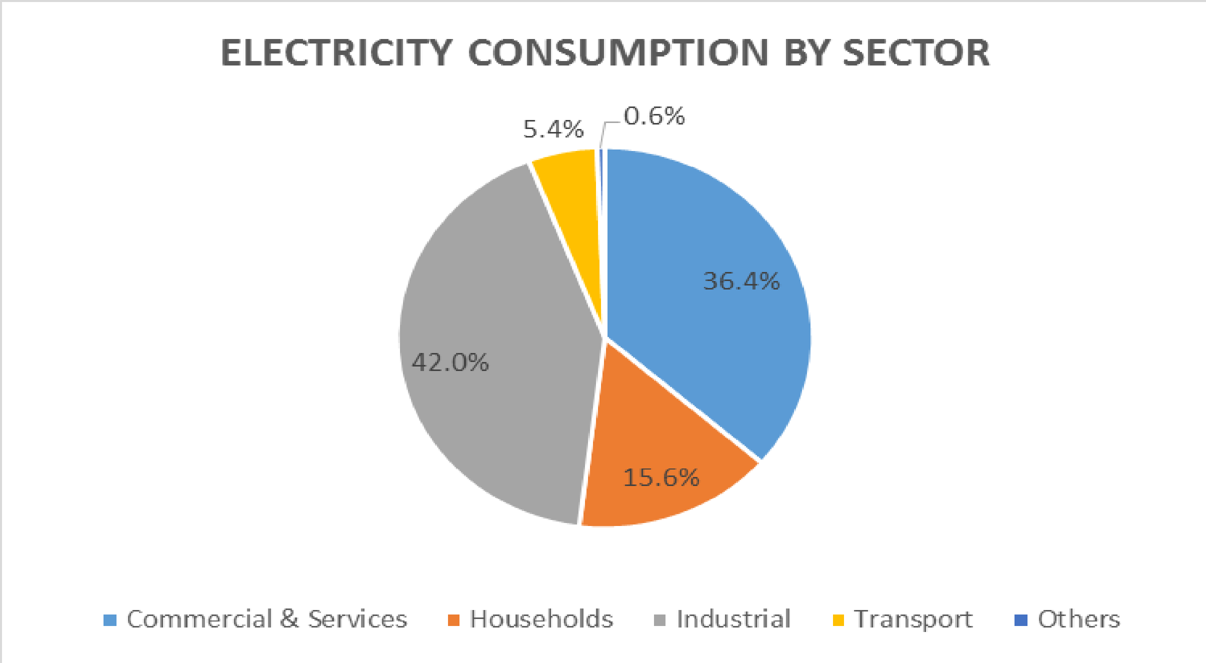

Figure 1: Singapore Electricity Consumption Landscape (source: Energy Market Authority's Singapore Energy Statistics 2017)

<u>Commercial Building Landscape</u>

For the buildings sector, commercial building, which comprises office, retail, hotel and mixed development buildings, constitutes about 74% of the total energy consumption. (See Fig. 2). Office building constitutes close to 45% of the total energy used in the commercial building stock[3].

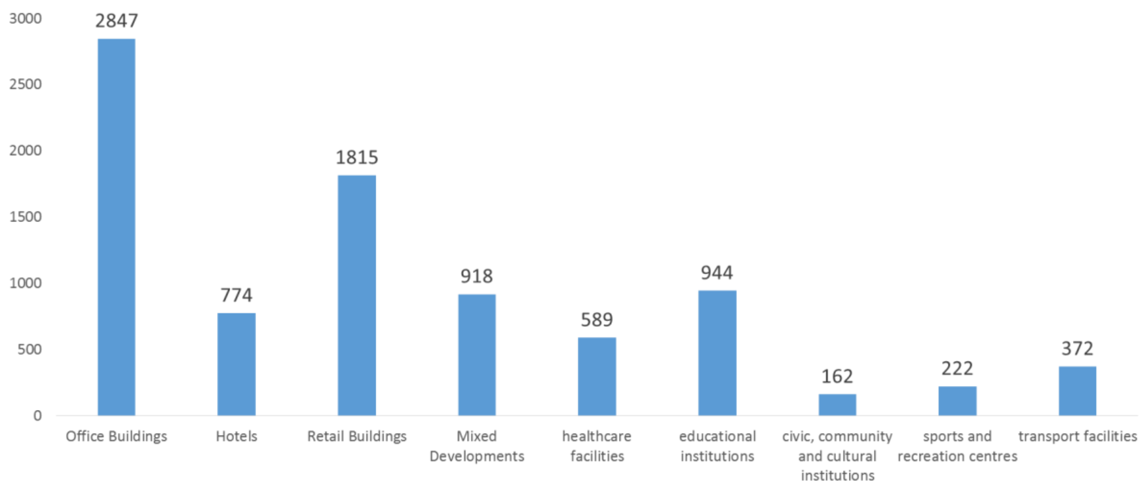

Figure 2: Energy consumption by building type in 2017 (source: BCA BEBR 2018 Report)

[3] Based on analysis of more than 1,000 Buildings (commercial buildings, healthcare facilities Building Energy Benchmarking Report (BEBR) for 2018.

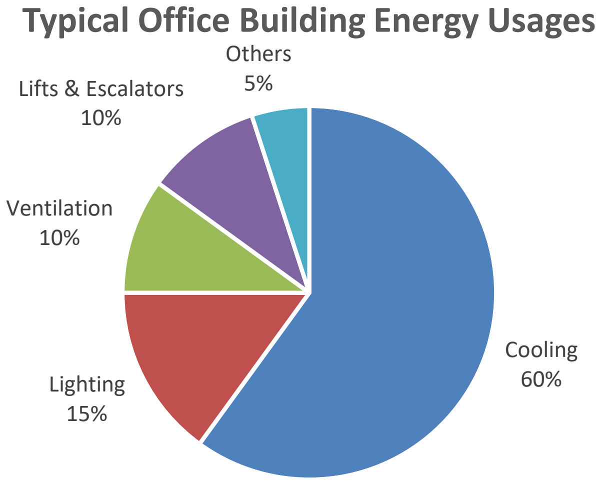

Figure 3: Typical Office Building Energy Usages

For a typical office building electricity consumption, mechanical systems such as air conditioning and mechanical ventilation (ACMV), lighting, vertical transportation, etc are responsible for the bulk of the energy consumption in a building. **Majority of the electrical consumption in a building is attributed to cooling (60%), mechanical ventilation (10%) and lighting (15%).** (Figure 3). Another active source of energy consumption are plug loads, which may **consume up to 25% of the total building energy consumption.** This is attributed to the extensive use of computers, monitors, servers in commercial buildings, and mini refrigerators, televisions and other appliances in guest rooms of hotels.

The average EUI of commercial buildings has improved substantially over the period from 2008 to 2017. This could be due to a mix of regulatory, fiscal policies and building R&D capabilities over the last decade.

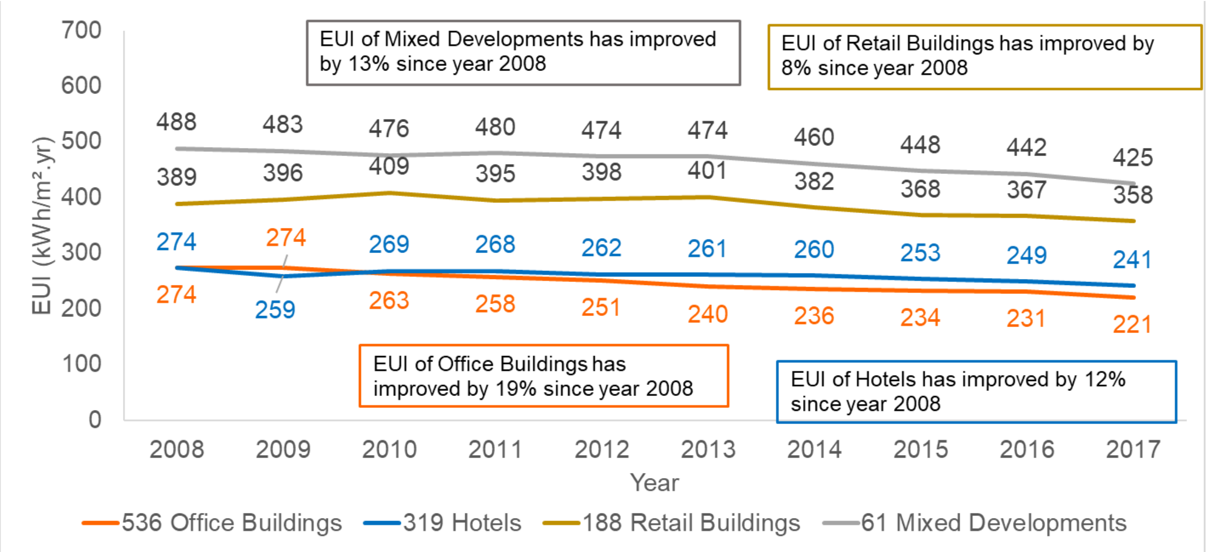

Figure 4: EUI trends for commercial buildings (source: BCA BEBR 2018 Report)

Educational Building Landscape

Educational building, which includes institutes of higher learning (IHLs) and Ministry of Education's public schools, is the next highest consumption with **about 11% of the total energy consumption.**

a) Institute of high learning (IHL) and private colleges/schools

Over the eight-year period from 2008 to 2016, the annual electricity consumption of IHLs and private colleges/schools had increased at a lower rate of 36%, as compared to the growth of the corresponding GFA at 57%. The average EUI for universities was 358 kWh/m^2.yr and 124 kWh/m^2.yr for polytechnics in 2017.

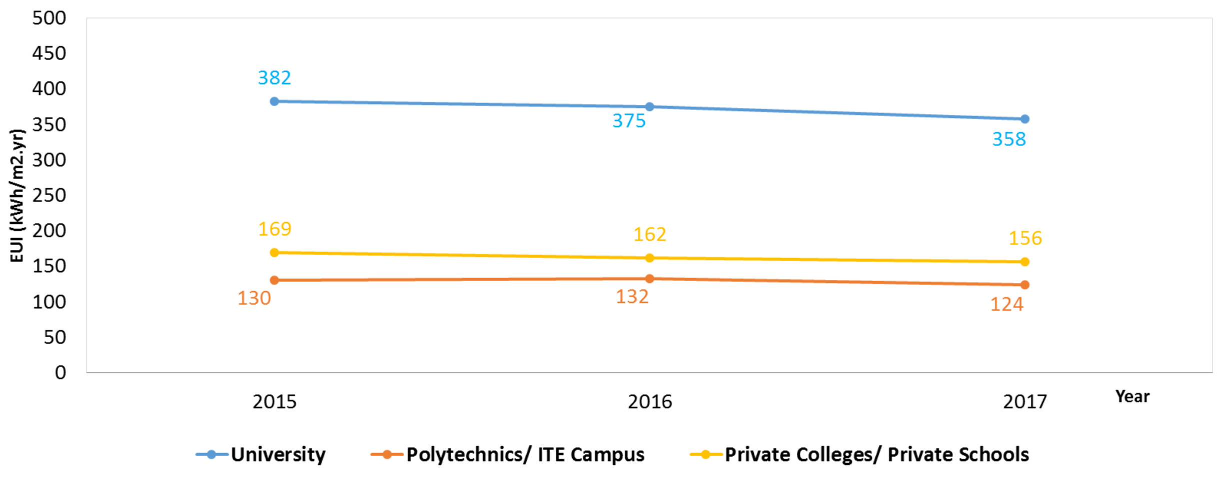

Figure 5: EUI trends for IHL buildings (source: BCA BEBR 2018 Report)

Some of the universities and polytechnics have plan to green their campus with a target to lower energy consumption significantly. For instance, Nanyang Technological University (NTU)'s EcoCampus aims to achieve 35% reduction in energy, water and waste intensity for their campus by 2020 (using year 2011 as baseline).

b) <u>Public Schools</u>

Singapore has about 360 public schools, providing learning environment for more than 400,000 students. Each school typically comprises low-medium rise (i.e. 3 – 6 storeys) buildings with around 80% of floor areas that are naturally ventilated. On average, energy consumption in schools is relatively low (i.e. 20 – 40 kWh/m^2.yr). Public schools which are in phases of installing solar panels under the SolarNova programme, have shown the most potential to achieve Positive or Zero Energy School status with further energy improvement measures.

<u>Healthcare Facilities</u>

Over the eight-year period from 2008 to 2016, the annual electricity consumption of healthcare facilities has increased at a faster rate of 55%. **In general, healthcare facilities have an overall increasing EUI trend since 2008.** It was observed that the EUI has increased by 10% over the eight-year period. With the growing demand for sophisticated healthcare services, there will be a need for hospitals, specialist centres and polyclinics to place greater emphasis on energy efficiency.

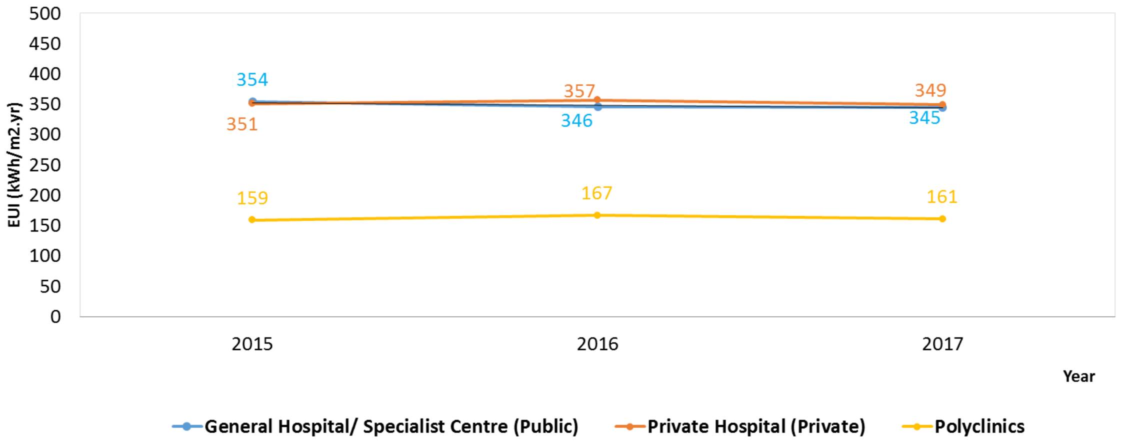

Figure 6: EUI trends for healthcare facilities (source: BCA BEBR 2018 Report)

Current Research, Development, Demonstration (RD&D) Initiatives

RD&D is a key enabler to accelerate knowledge application and capability building in Singapore's drive to promote energy efficiency and green buildings.

Since 2007, BCA has worked with various agencies to set up research and innovation programmes to support the national target of greening 80% of the building stock. One such key programme is the $52 million **Green Buildings Innovation Cluster (GBIC)**[4] funding support from National Research Foundation (NRF), established as a one-stop hub to experiment, exhibit, and exchange knowledge of promising building energy efficient solutions with industry stakeholders.

A stock take of existing R&D efforts shows that approximately S$45 million of funding has gone into supporting close to 70 green building R&D projects to push the energy efficiency boundaries further (See Fig. 7).

[4] GBIC is a one-stop hub to experiment, exhibit, and exchange knowledge of promising building energy efficient solutions with industry stakeholders. It comprises three major activities, i.e. R&D, Demonstration and Repository.

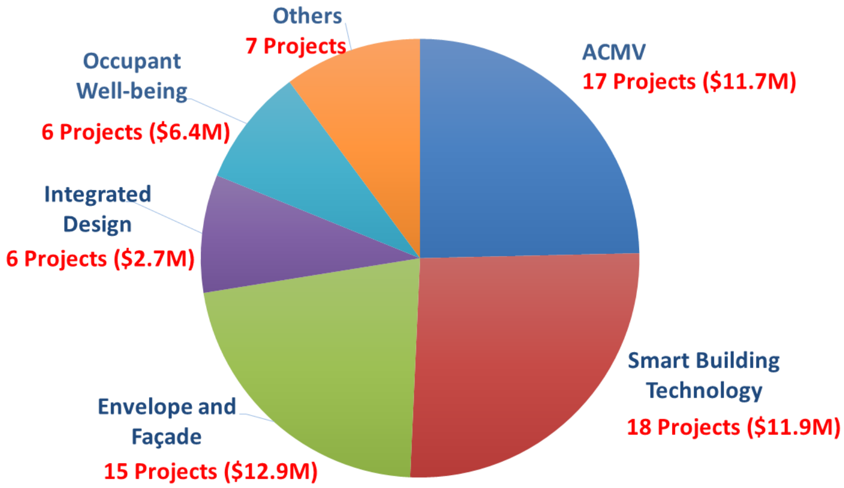

Figure 7: Green Building R&D funding distribution

Research funding has supported several disruptive technologies such as reinventing air conditioning to cool buildings in the tropics. For instances, separate dehumidification and cooling functions; develop highly effective desiccant membrane to remove humidity in air-conditioning with less energy; develop high efficient alternative cooling systems such as passive displacement ventilation. These innovations could achieve more than 40% of energy savings on air-conditioning.

The other key areas of R&D focus is on developing cost effective smart building technologies to make the buildings smarter, greener and healthier, using optimisation, machine learning, big data analytics and smart controls.

Test-bedding and Demonstration

Besides applied R&D, piloting/demonstration projects that help translate R&D outcomes to adoption are also emphasised. Piloting project provides an actual building environment to demonstrate the impact and to realise energy efficiency opportunities of various emerging technologies at the systems level. A positive and impactful demonstration will give confidence and enable stronger buy-in from industry in adopting new technologies and practices.

Zero Energy Building @ BCA Academy, a living lab, was built in 2009. It is South-East Asia's first retrofitted ZEB, equipped with solar photovoltaic (PV) together with more than 30 technologies. Over the past 8 years, this building has generated more energy than it consumed on an annual basis. As a demonstration and educational platform, the ZEB has played an important role to testbed and introduce new technologies to the industry.

Figure 8: ZEB@ BCA Academy

The launch of the **BCA SkyLab** in 2016, the world's first high-rise rotatable lab for the tropics, placed BCA at the helm of green building technology R&D arena. The ground-breaking laboratory provides a platform to support technology test-bedding under real-world building conditions to determine the integrated technology performance. This will help minimise risks to building owners when a new technology is deployed to actual buildings.

Figure 9: BCA SkyLab

Moving forward, BCA is partnering with the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST), a research entity under the National Research Foundation CREATE Programme, to embark on a major research collaboration to significantly transform BCA's Zero Energy Building (ZEB) into a positive energy building**, ZEB Plus**, which serves as a unique living laboratory for smart building technologies, or an "Office of the Future". The current ZEB, which has already been recognised as one of the most energy efficient buildings in Singapore with stellar energy efficiency50% better than a code-compliant building, will push its boundaries further. The energy efficiency of ZEB will be enhanced to achieve a further 20% improvement over the current level. Together with the upgrading of the existing solar PV system, the building will be able to achieve an overall energy surplus of at least 40%.

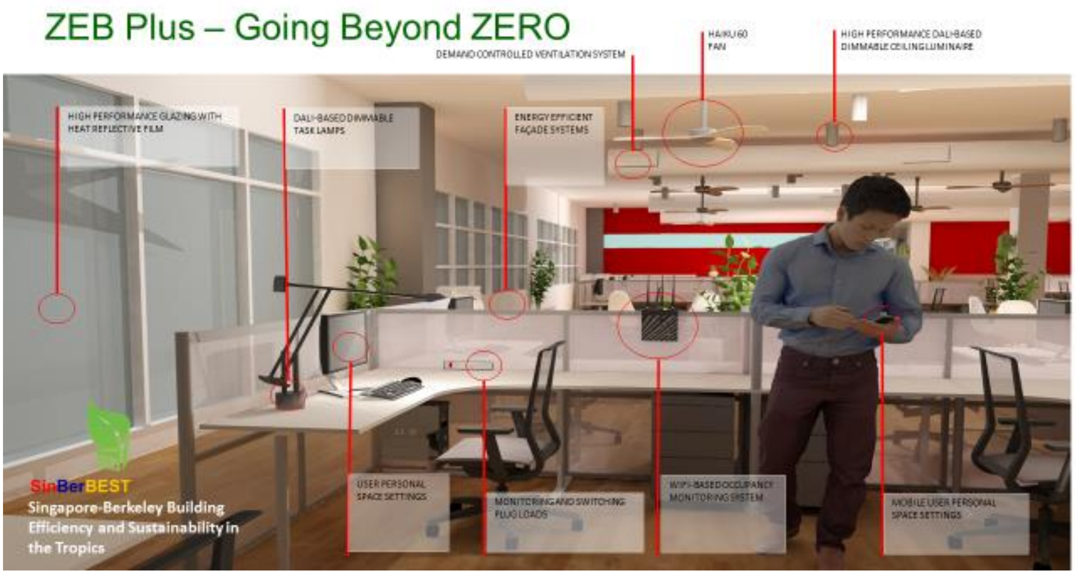

Figure 10: Proposed ZEB Plus (source: SinBerBEST)

Upcoming Zero Energy Buildings

Zero energy buildings are gaining traction in Singapore. Besides the ZEB@BCA Academy, there are several ZEB developments in the pipeline.

National University of Singapore (NUS)'s first Net Zero Energy Building (NZEB@SDE)

Conceptualised by the NUS School of Design and Environment, the ZEB@SDE[5] is designed to be climate responsive with net zero energy consumption. The six storey building will feature a range of green building designs, such as harnessing solar energy, hybrid cooling approach, natural ventilation and lighting.

[5] The project is expected to be completed by 2019.

One key aspect of the NZEB@SDE is its contemporary architecture design which demonstrates a deep understanding of the tropical climate of Singapore.

NZEB@SDE is also designed to consume only as much energy as it produces. This is made possible by harvesting solar energy using solar PV panels installed on the roof.

Figure11: Net Zero Energy Building (NZEB@SDE) (Source: NUS)

Integral to the concept of net zero energy consumption for NZEB@SDE is the need to rethink air conditioning. This resulted in the design of an innovative hybrid cooling system which ensures that rooms would not be overly cooled.

Rooms will be supplied with cool air at higher temperatures and humidity levels than a conventional system, and this is augmented with elevated air speeds from ceiling fans. Coupled with NZEB@SDE's tropical architecture design, this creates a highly comfortable environment that is also significantly more energy efficient.

Singapore Management University Net Zero Energy SMU-X

Another example is the SMU-X, which has obtained funding support from GBIC programme, to design and construct a new 5-storey teaching and learning facility[6]. SMU-X targets to achieve net zero energy building through the use of passive design to reduce air-conditioning requirements, and to reduce energy demands by adopting novel energy efficient technologies and experimenting with cutting-edge research work.

To achieve the Net-Zero Energy target, SMU-X adopted the following approaches:

a) Adoption of Mass Engineered Timber (MET) for its building facades and roofing design to effectively reduce solar heat gain, and to improve productivity through time and manpower savings;

b) Tap on highly efficient chiller plant coupled with hybrid cooling system using Passive Displacement Cooling System;

c) Integrate innovative technologies on a smart building solution platform to improve the overall building energy performance

In addition, SMU-X will also see the widespread use of highly efficient solar PV on its roof and veranda to generate sufficient electricity to offset the energy consumption.

Figure 12: Singapore Management University Net Zero Energy SMU-X (Source: SMU)

[6] The project is currently in construction phase and is expected to be completed by 2020/21.

2. DEVELOPMENT OF SLE TECHNOLOGY ROADMAP

Objectives of Technology Roadmap

BCA has set a long term aspiration goal for positive (PE), zero (ZE) and super-low (SLE) energy for low, mid and high-rise typical buildings in Singapore.

To support realisation of the goal, BCA embarked on a technology roadmap study of the SLE for the Tropics, with the objectives of evaluating the technological feasibility of SLE in the current and near future scenarios and to identify key emerging technologies and recommend future R&D areas to advance SLE in the Tropics.

BCA partnered Energy Research Institute at Nanyang Technological University (ERI@N) and Solar Energy Research Institute of Singapore (SERIS) on the Technology Roadmap study.

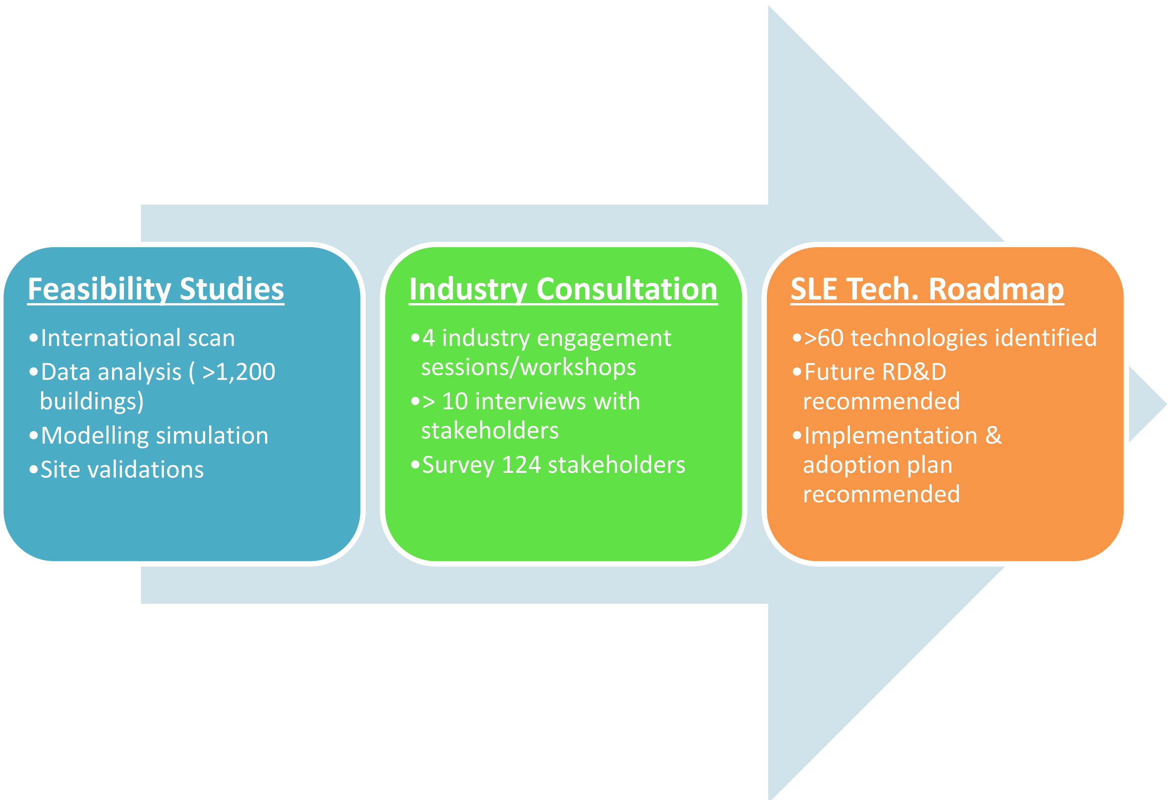

Figure 13: Development of SLE Roadmap

The study started by reviewing two existing technology roadmaps developed in 2014, i.e. Building Energy Efficiency (BEE) R&D Roadmap and Solar PV Technology Roadmap. The BEE roadmap set normalised Energy Efficiency Index (EEI) targets to achieve improvements in the EEI by 40% (moderate adoption) to 60% (aggressive adoption) over 2013 best-in-class buildings (GM Platinum as a proxy) by year 2030. The corresponding EEI for office building is as shown in Table 1 below.

	EEI (kWh/m²/year)						
Year	2005 Levels	2013 GM Platinum Building	2016	2020	2030	Improvement over 2013 GM Platinum by 2030	Improvement over 2005 levels by 2030
Moderate	244	143	131	114	86	40%	65%
Aggressive	244	143	122	101	57	60%	77%

Table 1: Targets setting BEE Roadmap by 2030

SLE Technology Roadmap recommends stretched R&D targets to achieve improvements in the EEI by 60% over 2005 industry levels by 2018 and 80% by year 2030. The corresponding EEI for office building is as shown in Table 2 below.

	EEI (kWh/m²/year)					
Year	2005 Levels	2018	2020	2025	2030	Improvement over 2005 by 2030
SLE Roadmap Target	244	100	85	60	50	80%

Table 2: R&D Targets setting for SLE Technology Roadmap by 2030

International Case Studies

A scan of global international zero energy building initiatives and case studies were carried out to review emerging technologies suitable for the topic. The findings of this review aimed at broadening the understanding of existing high performance buildings and serve to corroborate the possibility of technology integration and energy-efficiency that can be achieved in Singapore's context.

Industry Consultation

Since the beginning of the roadmap development, strong emphasis was placed on the stakeholder engagement through a consultative process. Four thematic workshops were conducted with focus group discussions for different types of buildings, i.e.

schools, medium rise and high rise office buildings. More than 10 interviews and engagement sessions with agencies and companies.

Survey was conducted with over 120 respondents from the industry, academia and stakeholders. Over 80% of the participants gave positive responses to the SLE aspiration and support developing a SLE initiative in Singapore.

Energy Modelling of Integrated Solutions

Energy-modelling studies were carried out on different typologies of buildings, with focus on office and school buildings, to assess the energy-savings potential of an integrated energy-efficient design. Design iterations were carried out on the energy models, introducing advanced technologies in lighting, envelope, plug load management, ACMV systems, controls and renewable energy using market-available solutions. This progressive approach led to final energy models, representative of the current and future (2030) technical potential of each building typology.

Building Data Analysis and Site Measurement

The study analyzed more than 1,200 building data from BCA Building Energy Benchmarking Report (BEBR) 2016 and Ministry of Education (MOE)'s school data to explore the feasibility of these building stocks to achieve Positive, Zero and Super-Low energy using **moderate and aggressive assumption scenarios.**

In this study, 12 schools were selected for site investigation on their energy consumption pattern, indoor environmental quality, and potential areas for improvements with existing or emerging technologies.

Expert Peer Reviews

Peer reviews by international experts and local industry and academia experts were carried out to seek comments on the efforts required to strengthen Singapore's position as a global leader in green buildings in the tropics, and comments on the emerging technologies and future RD&D to achieve SLE.

3. DEFINITIONS OF POSITIVE ENERGY, ZERO ENERGY, SUPER LOW ENERGY BUILDING

The important first step is to create a common definition of a Super Low Energy suitable for Singapore's context. Over the globe, there are many different definitions of ZEB, mainly to suit the local context and address the practicality of achieving ZEB in these countries. In Singapore's context, the Zero Energy Building is defined as **"The best-in-class energy performing Green Mark building with all of its energy consumption, including plug load, supplied from renewable sources (both on-site and off-site)".**

Under the challenges and constraints of Singapore's dense and urbanised landscape, a balanced approach in spurring renewables adoption, in particular solar technology to achieve zero energy, is recommended. Nonetheless, building development should maximise the on-site renewable sources first before exploring off-site renewable sources.

The approach of attaining a ZEB is by first achieving low energy consumption through passive and active energy efficiency measures, followed by the use of renewable energy to supplement the remaining load. In this respect, the pre-requisite for ZEB should **achieve at least 60% energy savings from 2005 levels**.

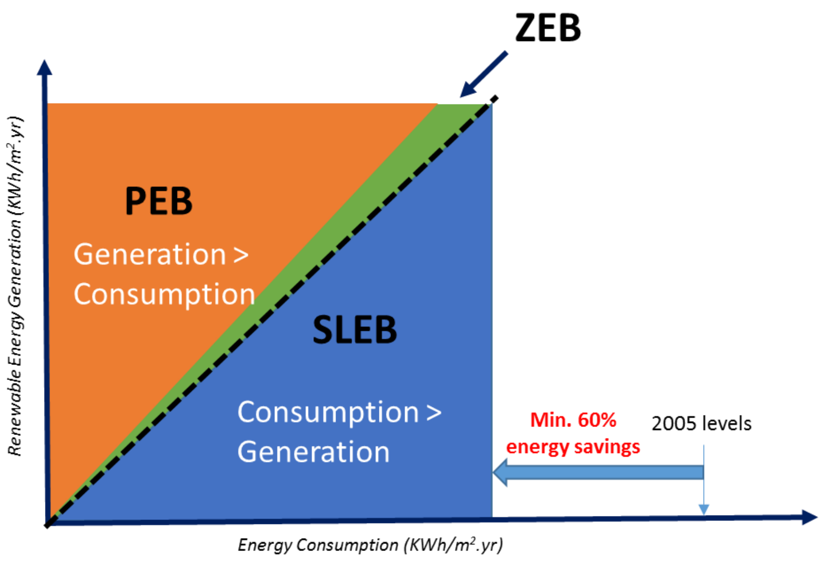

Figure 14: Graphical representation of PEB, ZEB & SLEB definitions

A structured and expanded definition for ZEB, i.e. Positive Energy, Zero Energy, Super Low Energy Building that is applicable to specific building types was defined as shown below.

Category	**Energy Efficiency[7] (Beyond GM Platinum)**	**Renewable Energy (RE) vs Energy Consumption (EC)**	**Examples**
Positive Energy	60% Energy Savings over 2005 level	RE >= 110% EC	Public schools; Camps; Landed Houses, etc.
Zero Energy		RE >= 100% EC	Mid-size office buildings and IHL buildings, etc
Super Low Energy		-	High-rise commercial buildings, etc

Figure 15: PEB, ZEB and SLEB definitions

[7] Current best in class GM Platinum building is able to achieve 50% energy savings over 2005 level

4. KEY TECHNOLOGIES TO ACHIEVE SUPER LOW ENERGY

In order to prioritize technologies and strategies to cut energy-consumption in buildings, a number of key-action areas have been identified within the four broad areas: Passive Strategies, Active Strategies, Smart Energy Management and Renewable Energy.

Besides, user behaviour is critical in reducing a building's plug loads consume about 25% of the total building energy consumption.

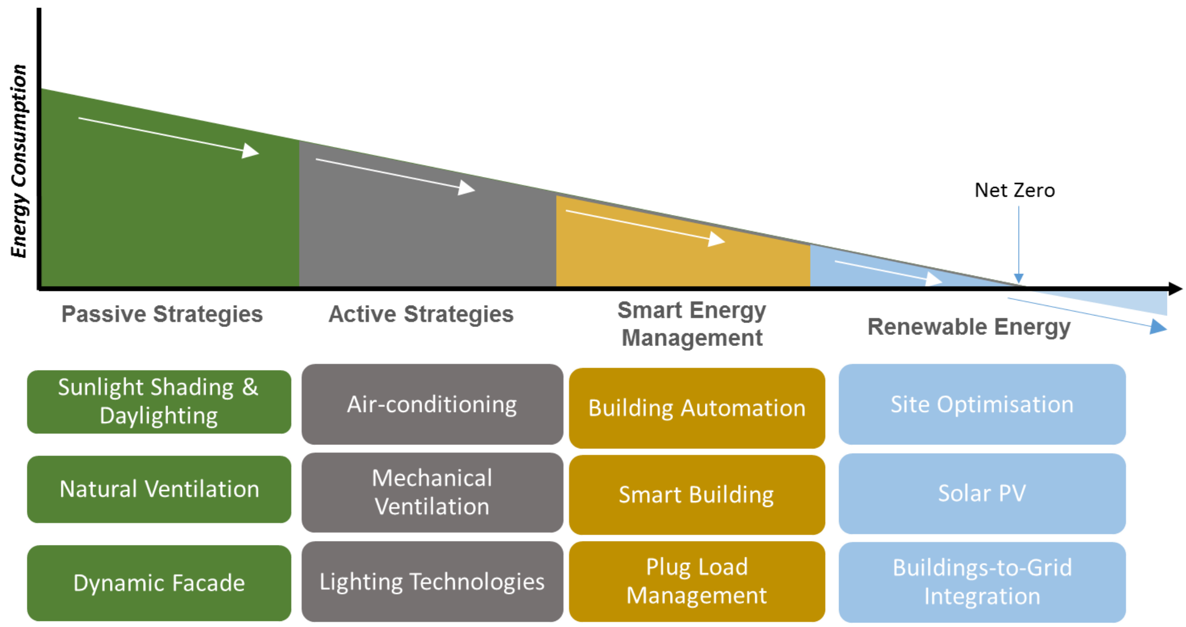

Figure 16: Energy reduction strategies towards SLE

<u>Passive Strategies</u>

Passive strategies are a fundamental prerequisite in the design of energy-efficient buildings, as these integrate energy efficiency and project-specific parameters (as microclimate, material proprieties and functionality) into the skin and bones of the building. Most of the passive solutions belong to standard good building and design practices, and must be attentively tailored to each specific context. In the context of retrofitting an existing building, the possibility of implementing passive solutions might be limited and complicated, requiring in some cases consistent structural and architectural changes to correct the physical features of a building, and must therefore be assessed case by case.

Active Technologies

Active systems, typically mechanical systems such as air conditioning, mechanical ventilation, lighting, vertical transportation, etc, are responsible for the bulk of the energy consumption in a building.

In the commercial office building, the majority of the building electrical consumption is attributed to cooling (60%), mechanical ventilation (10%) and lighting (15%). Another active source of energy consumption is plug loads. These loads may consume about 25% of the total building energy consumption due to an extensive use of computers, monitors, servers in commercial buildings and mini refrigerators, televisions and other appliances in guest rooms of hotels.

Smart Energy Management System

Building management system (BMS) is a control system that can be used to monitor and manage the mechanical, electrical and electromechanical services in a given facility. Such services can control, among other appliances, power, ventilation, air-conditioning, physical access control, pumps, elevators and lights. These systems improve energy-efficiency by allowing a usage of the appliances tailored to the real needs, saving on operation and maintenance costs, and improve occupancy comfort.

One of the most fast-growing and dynamic technologies towards net zero is the smart building technologies. Through tapping on Internet of Things (IoT), advanced sensors, big data analytics, smart technologies have shown a potential of saving an estimated 8-18% of total building energy consumption and providing a host of non- energy benefits[8]. Through R&D, substantial progress has been made in areas such as data-driven optimisation, model predictive control of multiple systems, etc.

Renewable Energy Technologies

Solar energy is currently the most feasible source of renewable energy for buildings to offset their energy consumption in Singapore. Singapore receives an annual average

[8] Smart Buildings: A Deeper Dive into Market Segments, American Council for an Energy-Efficient Economy (ACEEE), 2017

irradiance of 1,636 kWh/m^2 per year, which can be utilised through photovoltaic (PV), by converting sunlight into electricity, and solar thermal, producing hot water. This report will focus mainly on solar PV.

To achieve PE- ZE- status, the energy budget is strongly determined by the solar PV output of the building. Hence it is in the building owner's best interest to maximise the PV output. Fig 17 illustrates the efficiencies of commercially available PV modules. Fig 18 shows the current achievable and future projected energy factor for PV.

Technology	**Efficiency (%)**	**Manufacturers (examples)**
High-efficiency Si	19 – 22	Panasonic, SunPower
Mono-Si	17 – 19	Jinko Solar, Trina Solar, Kyocera, Hanwha-SolarOne, Canadian Solar, Hanwha-Q-Cells, LG
Multi-Si	16 – 18	REC Solar, Jinko Solar, Trina Solar, Soltech, Mitsubishi, Sunrise Solartec, Motech, Mission Solar, MegaCell, JA Solar, Yingli, Gintech, Suniva, Hyundai, Suntech, LG
Thin film	14 – 16	Solar Frontier (CIGS), First Solar (CdTe)

Figure 17: Efficiencies of commercially available PV modules, tested at standard test conditions (1000 W/m^2 and a cell temperature of 25°C)[9]

Year	**Energy factor (BAS) (MWh/m^2)**	**Energy factor (ACC) (MWh/m^2)**
2017[10]	0.18	0.18
2025	0.28	0.32
2030	0.29	0.36

Figure 18: Energy factor for 2017, 2025, and 2030.

Strategies to Impact User Behaviour

Plug loads are generally referred as an electrical energy consumption due to the use of equipment plugged into an outlet, categorized as electronics, plug loads within traditional end uses, and miscellaneous loads. Equipment commonly contributing to plug-load energy comprises Audio/Video equipment, Computers and Monitors, Gym

9 SERIS Research and Fraunhofer Institute for Solar Energy Systems, Photovoltaics Report, 12 July 2017.

10 2017 values based on actual values[10] rather than predicted values.

and Training Equipment, Laundry Equipment, Office Occupant Comfort (desk lamps, AC units, fans), Printers and Scanners, Kitchen and Breakroom equipment, Lab Equipment, etc. (NBI 2012).

Plug load is a substantial energy end-use in office buildings in its own right, but also significantly contributes to internal heat gains.

BCA Building Energy Benchmarking Report (BEBR) shows that the **tenants' electricity consumption, including plug loads, is half of the total buildings' electricity consumption** for office and retail buildings. There is scope for building owners and tenants to work together more closely to reduce their energy footprint. Technologies to **influence user behaviour** need to be explored as well, to reduce plug load energy consumption.

Details of the current technologies to achieve SLE are shown in Annex A.

5. FEASIBILITY STUDIES

The roadmap studied potential impacts, technical feasibilities, and implementing pathways towards SLE using today and future technologies. Based on stocktaking and technology foresighting, it identified more than 60 solutions from existing technologies and emerging R&D innovations under four broad strategies (i.e. Passive Design, Active Systems, Smart Energy Management and Renewable Energy), to be supported over the next 5 - 10 years in order to develop and deploy the SLE solutions.

Feasibility Study of SLE with Current Technologies

Positive Energy for Low-rise Building

One of the key focus areas in this study is Singapore's public schools buildings. Singapore has about 360 public schools, providing learning environment for more than 400,000 students. Each school typically comprises mainly low-medium rise (i.e.3 – 6 storeys) buildings with around 80% of the floor areas that are naturally ventilated. On average, energy consumption intensity in schools is relatively low (i.e. 20 – 40 $kWh/m^2.yr$).

The feasibility study shows that achieving a positive or zero energy school is possible with the incorporation of currently available technologies. These include LED lighting, cool paint, energy efficient ceiling fan, lighting dimming system etc. as well as renewable energy from the solar PV system.

The study concludes that over 60% of the 360 existing schools in Singapore has the potential of achieving Positive energy or Zero energy status, by deploying solar PV and adopting a series of energy efficiency improvement measures, as shown in Fig 19. It also shows there are tremendous benefits to carry out the ZEB upgrading together with the improvement of indoor environmental quality for a more conducive learning environment, as well as using the ZEB as an opportunity for a national environmental sustainability education for the future generation.

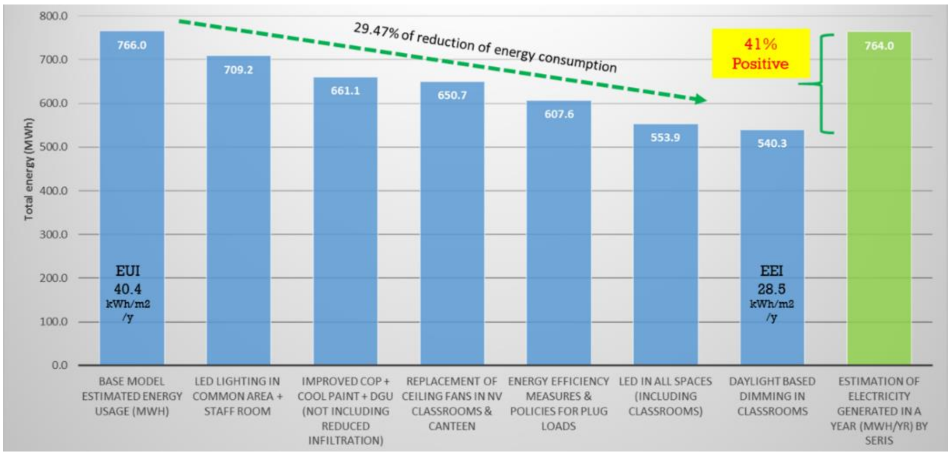

Figure 20: Total Energy Consumption breakdown for low-rise school building (in MWh)

Zero Energy for Medium-rise Building

The main challenges for medium to high rise buildings to achieve ZEB status are constraints of rooftop space, and high air-conditioning area which accounts for 70% to 90% of the total gross floor area for a typical office building.

Study has shown that to achieve ZEB in medium-rise (6 to 7 storeys) office buildings, a paradigm shift of building design would be required. For example, greater adoption natural ventilation or hybrid system of ventilation in office spaces would have to be considered.

Different strategies were simulated for office buildings as shown in Figure 21. In this simulation, the approach is to reduce energy consumption by having good passive designs, follows by adopting high efficient AC, smart lighting system and plug load reduction strategies. The balance of energy is then fully covered by the PV installation on the roof top, covered walkways/ link ways/ carparks and extension of roof as a cantilevered structure, to achieve ZEB status. The list of possible strategies to achieve ZEB is as shown below:

- Natural ventilation (NV) in all ancillary spaces like corridor, toilet, staircase
- Improved Glass/Wall construction & shading
- Ambient-Task Lighting
- Reduced Plug loads

- Hybrid AC System
- High Temperature CHWS
- High efficiency VVVF-Regen lifts
- Reduce% AC space (57% AC)
- Increase PV generation beyond the building footprint (i.e. roof extension, covered linkways, carparks, etc)

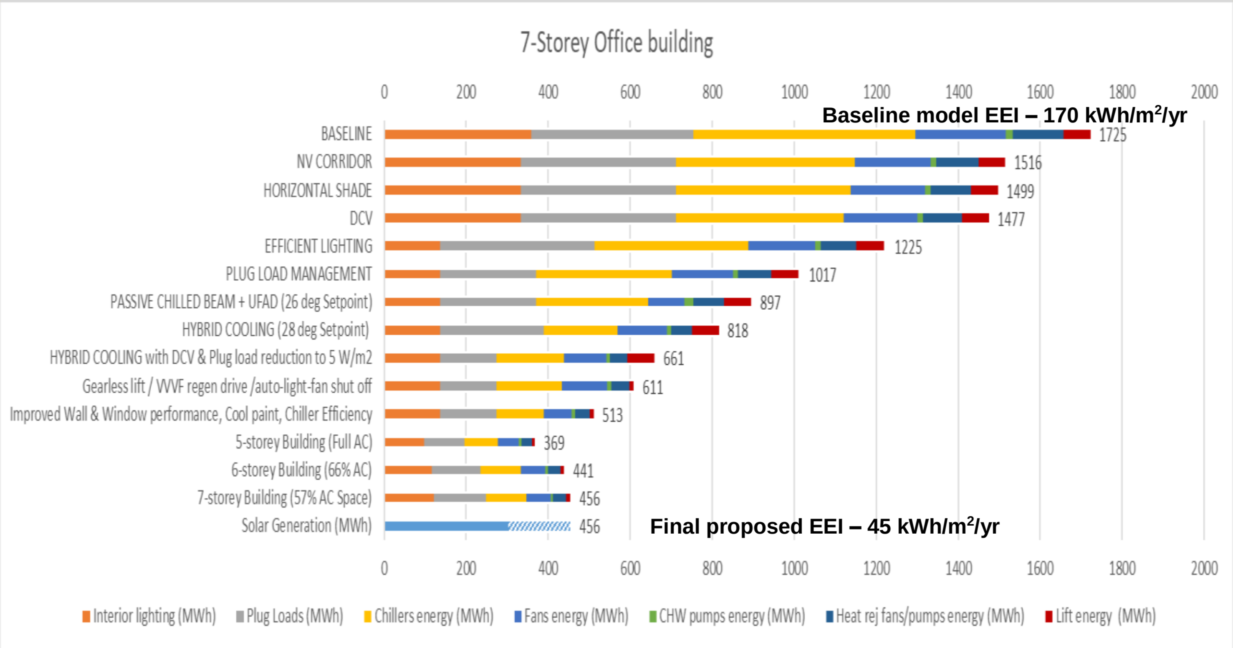

Figure 21: Total Energy Consumption breakdown for 7-storey office building (in MWh)

Super-Low Energy for High-rise Building

Different strategies using current cutting edge solutions were simulated as shown in Figure 22 to bring down the corresponding reduction in energy use below 100kWh/m^2/yr, to make it possible to be super-low energy with 60% energy savings over 2005 levels.[11] The list of possible strategies to achieve SLEB is as shown below:

- NV in all ancillary spaces like corridor, toilet, staircase
- Improved Glass/Wall construction & shading
- Ambient-Task Lighting
- Reduced Plug loads

[11] EEI for office building using the standards and codes from 2005 was seen to be 244 kWh/m^2/yr. Current BCA Green Mark Platinum office buildings can achieve about 120-140 kWh/m^2/yr.

- Hybrid AC System
- High Temperature CHWS
- High efficiency VVVF-Regen lifts

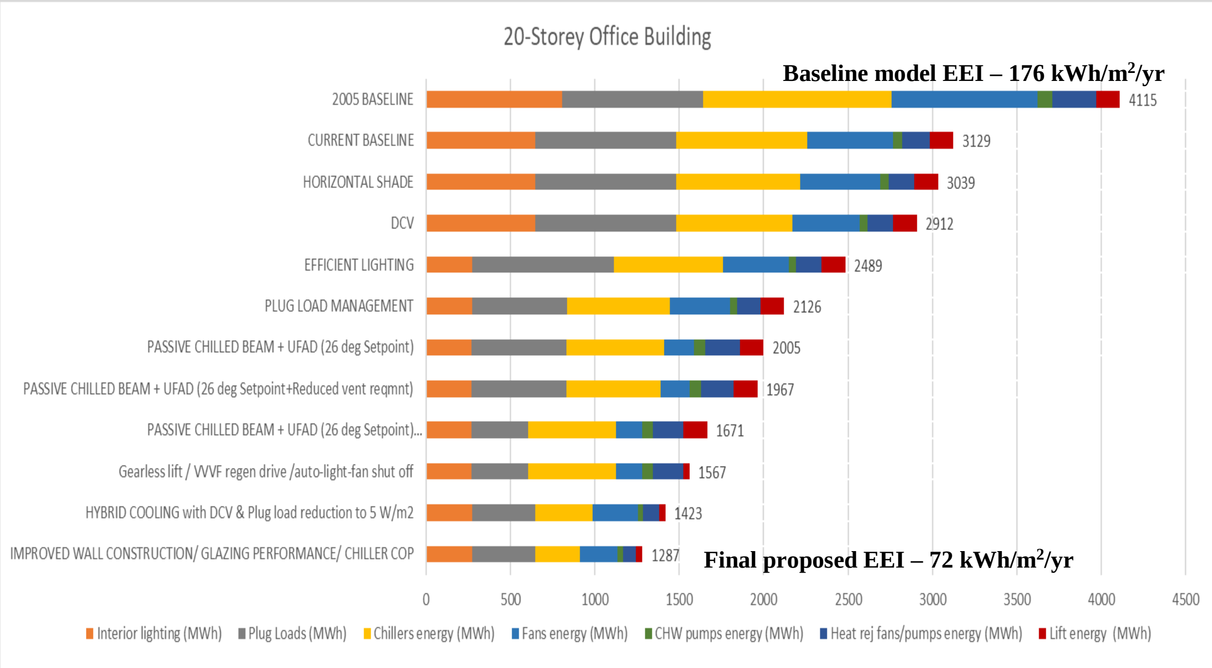

Figure 22: Total Energy Consumption breakdown for 20-storey office building (in MWh)

Feasibility Study of SLE with Future Technologies

In order to assess the potential of achieving SLE in the medium (2025) to long term (2030), further studies and simulation were carried out based on the projected technology improvement.

The study shows that with further technological developments and R&D, it would be viable for a typical medium rise office building to achieve ZE by 2025 and PE by 2030. High-rise office building could attain EEI of 50 kWh/m^2/yr or below, making it possible for super-low energy with 80% energy improvement over 2005 levels.

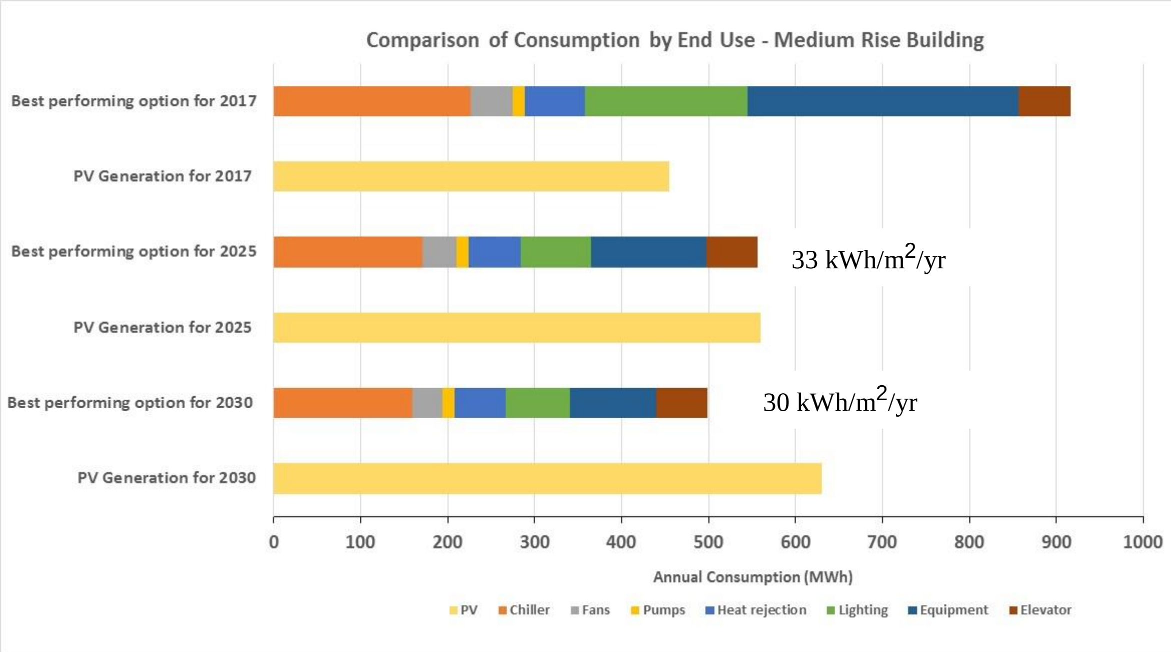

Figure 23: Breakdown for Medium-Rise Building

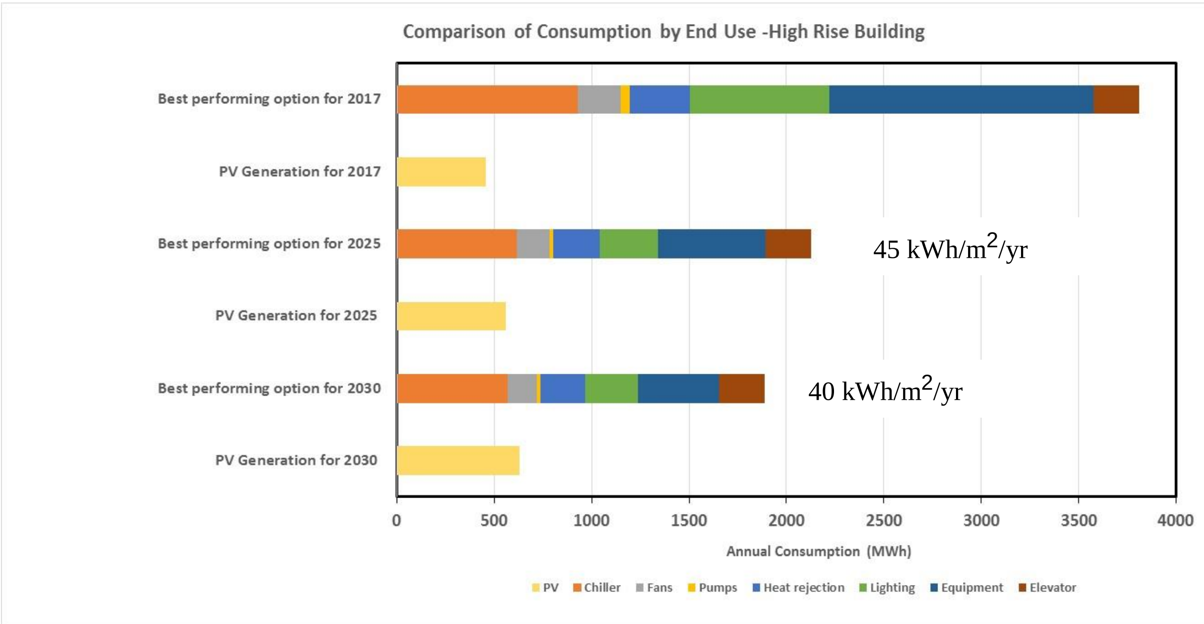

Figure 24: Breakdown for High-Rise Building

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6. CHALLENGES

Workshops were held to provide a platform from which a multi-disciplinary working group of experts and key stakeholders could create a repository of information for best building design processes, practices and technologies to increase the energy efficiency of low-rise school buildings, medium rise and high rise office buildings in Singapore.

More than 450 experts from the industry, developers, government agencies and academia participated in four workshops.

Several challenges for achieving goals and targets for SLE were identified during the roadmapping process. The key challenges and possible follow up actions are listed in Table 3.

Challenges and Barriers	**Possible Follow-up Actions**
Lack of knowledge about the concept of ZEB, its benefits, fear of failure, and reluctance to change to new technology	Proper education and capability building for users
Difficult to set up the baseline of human comfort Difficult to change the occupants' habit	Influencing users' behaviors
Challenge for all stakeholders to align with the objective of achieving a ZEB for it to come to fruition	Integrative design approach
Limited space for PV on roof top	Consider beyond building concepts
Spaces tend to be over designed in terms of plug loads	Designers, building owners and tenants to be on board before actual design to ensure optimization
Complication in implementing certain green measures due to having multiple tenants at the same office building	Sustainability awareness programmes in offices
Low perceived value of ZEB / High perceived cost of ZEB	In-depth cost benefit study for ZEB and SLEB in Singapore context.

Lack of demonstration and test-bedding opportunities / Lack of incentive schemes	Enhance existing funding and incentive schemes
Regulation barriers	Engage and have regular dialogues with relevant authorities to resolve potential barriers

Table 3: Challenges and Possible Follow up Actions

7. FUTURE RD&D

An SLE building with 60% energy efficiency improvement is technically feasible with best-in-class technologies today, but more research, development and demonstration (RD&D) is needed to push the boundaries to **80% energy efficiency improvement**, and to do so in a cost effective way.

To address SLE challenges, **disruptive technologies should be developed**. Cost reduction research should be emphazised to significantly reduce the cost of the emerging technologies to be cost-effective for mass adoption in the market.

Due to the hot tropical climate of Singapore, there is a high demand for cooling and dehumidification in order to maintain occupant comfort. As air-conditioning is the largest contributor of energy consumption in buildings, it is logically the most impactful area for technology development of energy efficiency improvements.

One area worth focusing for further research is to reinvent the ways to cool buildings. For examples, to further explore non-compressor air-conditioning - using water as a refrigerant in combination of membrane and evaporative cooling techniques; to develop advanced and cost effective desiccant membrane air conditioning system to address dehumidification in our tropical environment using lesser energy. The other example is to investigate the opportunities brought by hybrid cooling with higher indoor temperatures to deliver cooling to occupants with lesser energy and good thermal comfort.

Another fast-growing and dynamic technologies towards net zero is the **smart building technologies.** Through tapping on Internet of Things (IoT), advanced sensors, data analytics, smart technologies have shown a potential of saving an estimated 8-18% of total building energy consumption and providing a host of non-energy benefits[12].

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[12] Smart Buildings: A Deeper Dive into Market Segments, American Council for an Energy-Efficient Economy (ACEEE), 2017

To continue driving R&D towards innovative solutions with tangible outcomes, it is essential to focus on development of smart technologies that are connected to building systems and are able to achieve significant energy savings.

Some of the possible smart technology areas in smart sensor and control technologies, advanced data analytics, and artificial intelligence for building systems are:

- Integrated information and communication technology (ICT)/Internet of things (IoT) solutions to improve building energy management;
- Accurate, low cost, multi-functional smart sensor network systems for indoor environment monitoring and control;
- Advanced data analytics and artificial intelligence techniques for optimising building operations;
- Open and universal data management platforms/applications that allow communication and integration of multiple building systems;
- Smart solutions that can capture individual users' preference, deliver solutions, and influence occupant's behaviours;
- Adaptive and smart controls for innovative cooling, lighting and process load control systems.

The list of the RD&D and deployment pathway is shown in Annex B.

8. CONCLUSION

The primary focus of the roadmap was to identify technologies for RD&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 a **60 - 80% improvement on energy efficiency over 2005 levels by 2030.** These EE improvements would contribute to an overall reduction of electricity consumption and emissions due to Singapore's building stock.

The key findings from the Technology Roadmap are summarized as below:

1) More than 60 potential solutions from enhanced existing technologies and emerging R&D innovations have been identified and grouped under four broad categories, namely Passive Strategies, Active Strategies, Smart Energy Management and Renewable Energy.

2) Achieving SLE with 60% energy efficiency improvement (over 2005 codes) is technically feasible with best-in-class technologies today.

3) Further technological advancements and R&D will be needed to reach 80% energy efficiency improvement, to make SLE both technically feasible and economically viable for mainstream adoption by 2030.

4) Lower rise institutional buildings and schools have the potential to achieve zero or positive energy target first.

The Roadmap makes recommendations for future research and technology development directions to maximise the benefits of innovations, including greater focus on technology translation and co-innovation. It also provides insights into cost-effective solutioning for implementation, and recommends driving wide adoption of SLE through the BCA Green Mark scheme.

Annex A: Emerging Technologies and Strategies

Passive Strategies

Strategies	Technologies	Description	Potential Energy Performance[13]
Temperature control through Insulation	Thermal insulation	Reduction of the conductive heat transfer components of external loads, contributing to lower use of air-conditioning.	L-M
	Insulated glazing	Reduction of conductive heat transfer through glazing, contributing to lower use of air-conditioning.	L-M
Temperature control through Shading	Double skin façade	Reduction of the cooling load, contributing to lower use of air-conditioning.	M
	Façade greenery	Shades the surfaces and cools the air through evapotranspiration.	M
	Cool paints	Reflect solar IR, reducing heat absorption reducing the cooling load.	M
Temperature control through Ventilation	Wind-driven natural ventilation	Linked to the architectural features of new building, though can be difficult to incorporate successfully for refurbishment for existing buildings.	M-H
Daylight redirecting technologies	Light shelves	Increases the depth of penetration of useful daylight into the building, and reduces the use of artificial lighting. In hotels, most of the lighting load is consumed by the clients during night-time.	L-M
	Tubular Daylight	Application is design-specific. Can bring daylight to unlit spaces like corridors, bathrooms. Complicated and expensive implementation in refurbishment, in new projects good design should achieve similar or better lighting conditions.	L-M
Building Envelope	Insulation materials	A light weight (200 ~ 300 kg/m^3) construction material that improves building's thermal properties (U-	M

[13] *Impact on Building EEI: Low (L) : < 5 kWh/m^2/year; Medium (M) : 5 - 10 kWh/m^2/year; High (H) : >10 kWh/m^2/year*

Black refers to enhanced existing technologies;
Blue refers to emerging technologies (ie. newer concepts from local R&D or overseas technologies that are not widely adopted in Singapore)

		value 0,149 ~ 0,183 W/m^{2}K) and water insulations.	
	Heat Reflective Coating	Optimize current epoxy-based coating formulation to be applied on bare as well as powder coated aluminium window frames in order to obtain a glossy surface finish without any dripping effect and develop polyurethane and acrylic-based coatings which are more resistant to weathering.	M
	Cool Paint Incorporating Phase Change Material (PCM)	An innovative cool paint through the incorporation of multi-functional Phase Change Material (PCM) capsules with high solar reflectance (>0.8), self-cleaning capability and PCM thermal buffering.	M-H
	Photochromic glass	Enhance home-based photocatalytic coating product for different substrates with supply price less than half of its imported one.	M
	Electrochromic glass	Enable to change the visible and thermal transmittance characteristics to be able to obtain a desired level of lighting or heating from solar energy.	M
	Energy harvesting clear glass	Reduce the solar heat whilst producing renewable energy. Clear glass with high daylight transmittance level	M
	Solar heat shielding film	Effective in both UV and IR blocking without affecting visible light transmittance too much, thus to lower indoor cooling demand and associated cooling energy use. May reduce light transmittance which makes the indoor environment darker.	M

Active Technologies

Strategies	Technologies	Description	Potential Energy Performance
Air Conditioning and Mechanical Ventilation	Demand-controlled ventilation	Automatic adjustment of ventilation equipment according to occupant choice.	H
	Dedicated outdoor air system	Specifically used to treat outdoor air which is delivered into a building for ventilation purposes.	H
	Radiant Cooling Panels	Cools the space by a combination of natural convection and radiation.	H

	Active Chilled Beam (ACB)	Similar to radiant cooling panels except that the ACB has an integral air supply.	H
	Displacement Ventilation	A room air distribution system where conditioned outdoor air is supplied at higher temperatures and low velocity.	H
	Hybrid system: elevated temp. + increased air movement	By allowing higher indoor temperatures in buildings coupled with fans to increase the air movement, one can achieve substantial energy savings while keeping the occupant comfort at an acceptable level.	H
	Automatic air balancing system	Automatic air balancing system is a technology that can provide accurate air distribution for every zone. The flow rate of each terminal is independent of the neighbouring terminals, allowing smooth control of room temperature, humidity and ventilation. Research work is currently ongoing.	M-H
	Non-compressor air-conditioning system	Non-compressor air-conditioning - using water as a refrigerant in combination of membrane and evaporative cooling techniques to achieve more than 30% energy savings, compared to conventional vapour-compression refrigeration	H
	Hybrid two-stage Dehumidification System	A novel desiccant/membrane air dehumidification comprising composite desiccant and membrane to remove humidity with less energy.	H
	Liquid Desiccant AC System	Membrane based liquid desiccant dehumidifier using desiccant salt to store solar thermal energy and low grade waste heat energy.	H
	Advanced Direct Expansion Type AC System	New technologies i.e. Refrigerant Management System (RMS) and Compressor Refrigerant Treatment (CRT) as additional features for the Variable Refrigerant Flow (VRF) air-conditioning system to determine real time COP and enthalpy on site.	H
	VAV Fan Speed's Optimisation System	Eliminates the use of static pressure as control and combines the use of terminal box damper positions, precision airflow measurement and a custom controller with unique algorithm to reduce the fan speed of	M

		an operating VAV system, and thus the duct static pressure.	
	Energy efficient, oil less chiller, e.g. magnetic bearing centrifugal chiller, gas bearing chiller	Eliminates the use of static pressure as control and combines the use of terminal box damper positions, precision airflow measurement and a custom controller with unique algorithm to reduce the fan speed of an operating VAV system, and thus the duct static pressure.	H
	Evaporative cooler	The cooler has a "cold water core" that produces chilled water for a two-stage cooling process: First, warm air is drawn into the unit and cooled by the chilled water; next, the air is passed through an evaporative panel to produce "super-cooled" air.	M-H
	Energy valve	A pressure independent valve that measures and manages coil energy by using an embedded electromagnetic flow meter, along with supply and return water temperature sensors. It measures energy, controls power and manages Delta T.	M
	Solar air conditioner	The hybrid air con can accept both DC power generated by photovoltaic and AC power from normal grid.	M
	High volume low speed (HVLS) fan	The fan can move huge columns of air efficiently at low speed.	M
Lighting Technologies	Direct DC LED Lighting with smart control	Complete integration of LED lighting fixtures.	H
	Ambient + Task lighting	The ambient lighting levels are kept at a lower illuminance level, while higher lighting levels are provided where locally needed. For offices and focus-work spaces.	L-M
	DALI Smart Lighting Control System	Hypothetic savings between 50 – 80% on lighting energy. For offices and spaces with high change in usage patterns, with access to daylight and potential for individual user-addressable controls.	H
	IoT based occupancy-driven lighting control system	Occupancy-driven lighting control system (involving individual/ zonal lighting control, occupancy-positioned system) has potential of 20% improvement in energy saving compared to normal LED lighting	M-H

Smart Energy Management System

Strategies	Technologies	Description	Potential Energy Performance
Smart Energy Management System	ACMV Optimization	Holistically optimize the sequence control and set points control of each equipment of ACMV system to minimize the system energy consumption.	H
	Continuous commissioning	An ongoing process to resolve operating problems, improve comfort, and optimize energy use.	M
	Retro-commissioning	A systematic process to improve an existing building's performance. Using a whole-building systems approach, retro-commissioning seeks to identify operational improvements that will increase occupant comfort and save energy.	M
	Building Energy Management System (BEMS)	An integrated building energy management system that helps measure, monitor and manage the building performance and empower stakeholders to drive energy smart behaviour.	H
	Fault detection and diagnosis system (FDD)	A measurement science that enables automatic detection and diagnosis of equipment faults, sensor failures, and control errors in the ACMV systems of buildings. The resulting fault detection and diagnosis (FDD) software ("FDD tools") will utilize existing sensors and controller hardware, and will employ artificial intelligence, deductive modeling, and statistical methods to automatically detect and diagnose deviations between actual and optimal ACMV system performance.	H
	Demand ventilation controls	An integral part of a building’s ventilation design. It adjusts outside ventilation air based on the number of occupants from the occupancy sensors, and the ventilation demands that those occupants create.	M
	Weather sensing and adaptive controls	An integral part of an ACMV Optimization. It enables the system to take predictive or proactive action necessary to properly adapt to the variable volatility in weather to reset the operation set points to save energy consumption.	L-M

	Model-Predictive Control	An intelligent control system that can analyse a building's energy efficiency so that developers can optimise the building's energy performance and its occupants can enjoy a better indoor air quality.	M
	IoT integration with BMS	A system that collects real-time information on a building's energy and water consumption, and analyses it with patterns of human activities so that energy consumption from its fixtures and appliances can be optimised.	H
	Personality-based EMS	An energy management system for a building that takes into consideration its occupants/users' behaviours and personalities. The results of the analysis will determine the pattern of energy use and optimise energy savings.	M
	BIM Integration with Energy MM&V	This system will "merge" or "integrate" a virtual three-dimensional model of a building with a model of its energy consumption using a series of measuring tools. By putting both models together, building professionals can analyse the measurements as well as patterns of energy consumption and create simulations that attempt to reduce the energy consumption to a minimum	H
	Data-Driven Modelling and Real-Time Optimisation for Chiller Plant	A model that optimises the energy performance / consumption of an air-con chiller plant by tracking and analysing real-time data, and then identifying the patterns of human usage for optimal energy performance	H
	Machine Learning Model	A system that tracks building occupants' thermal comfort with wearable devices (e.g., wristband and smart watches) to sense their vital signs (e.g., heart rate and skin temperature). With the collected data, the system can then adjust the building's air-condition system and room temperature for better energy efficiency without compromising its occupants' comfort.	M

Renewable Energy Technologies

Strategy	Technology	Description	Potential Energy Performance
Solar PV	High efficiency PV	Higher performance PV for better yield per m^2.	H
	Perovskite PV technologies	Perovskite solar cells are flexible and easy to produce. They can be painted or sprayed on a surface from an ink solution or churned out of a printer like a newspaper. That flexibility means they can be attached to virtually anywhere.	M-H
	Integrate PV into architectural	Raise awareness about the availability of more aesthetically pleasing PV modules. With the buy-in from architects and developers, the push towards SLE would experience more support, thus allowing building owners to consider BIPV as a potential source of renewable energy	H
	Co-location of solar PV and greenery	Use of both greenery and solar PV on the same roof space. (PV output increase of 3% due to the extra cooling from the green roof).	H
	Innovative lightweight structures	Innovative structures that possibly can be folded or at least be deployed easily on rooftops. Lightweight flexible PV modules could be developed.	M
	Anti-degradation system	Degradation mechanism to slow down degradation of PV panel over time and make it more durable and efficient.	H

Plug Load Reduction Technologies & Strategies

For Office Building

Strategies	Technologies	Description	Potential Energy Performance
Technologies impacting user behaviour	Individual technological control	Examples of such include: Individual control of appliances, Task lighting and Remote control	M
	Centralized control systems	Examples of such include: BMS systems Power sockets	M
Reduce energy waste	Smart power strips	Address energy use due to phantom loads from many devices through a centralized control of the switch.	L-M
	Timers	Saving on standby modes and idle loads.	L-M
	Computing and Printing Equipment	More efficient low power modes, managing computers being left turned on to enable remote work	M

	Eliminate redundant equipment	Less personal equipment (refrigerators, personal printers, and fax machines)	M
Plug Load Reduction - Change user behaviour	Smart WiFi Timer Plug with Remote control	Off the standby power of the equipment and appliance, web-based or mobile app based dashboard shows the electricity consumption and the operation status of the plug load, allow user remotely off the appliance power through internet. The standby power of the appliance, additional 7% savings of plug load due to the energy consumption visualization and remote control.	M
	Personal electricity consumption monitoring and benchmarking	Monitor and benchmark individual's electricity consumptions, this will give peer pressure to the individual who has not excise good energy saving behaviour.	L-M

For Data Centre

Strategy	Technology	Description	Potential Energy Performance
IT Opportunities	Server Virtualization	Server virtualization offers a way to consolidate servers by allowing data centre operator to run multiple different workloads on one physical host server.	L-M
	Decommissioning of Unused Servers	Decommissioning allows data centre operator to retire aged servers with no use still running, and/or defer purchases of new servers, thus decreasing electricity consumption and cooling load.	H
	Consolidation of Lightly Utilized Servers	Server consolidation reduces total number of servers by putting more applications on fewer machines.	M
	Better Management of Data Storage	Use less storage to use less energy can result from the better data storage best practices available today through storage resource management tools. In addition, there are certain storage hardware devices that use much less energy.	H
	Purchasing More Energy-Efficient Servers, UPSs, and PDUs	New servers use more energy-efficient technology. New efficient UPSs generally range from 92% to 95% efficient. The Eaton Energy Saver System claims to reach 99% efficiency across a wide range of loads. New PDUs use high-efficiency transformers that are 2% to 3% more	H

		efficient overall compared to a generic lower-efficiency transformer.	
Airflow Management Strategies	Hot Aisle/Cold Aisle Layout	The rows of server racks should be oriented so that the fronts of the servers face each other. In addition, the backs of the server racks should also face each other. This orientation creates alternating "hot aisle/cold aisle" rows. Such a layout, if properly organized, greatly reduces energy losses and also prolongs the life of the servers.	L-M
	Containment/Enclosures	Containment refers to the various physical barriers used in addition to a hot aisle/cold aisle arrangement that further eliminate the mixing of cold ("supply") air and hot exhaust air.	L-M
	Variable Speed Fan Drives	CRAC (computer room air conditioning) unit fans vary their fan speeds with the data centre server load, which tends to fluctuate.	M
	Properly Deployed Airflow Management Devices	All airflow management strategies strive to either maximize cooling by supplying cooling ("supply") air directly to equipment, or by eliminating the mixing and recirculation of hot equipment exhaust air.	H
ACMV Adjustments	Server Inlet Temperature and Humidity Adjustments	Add a centralized control system to reduce or stop dueling CRAC units. Change the humidity set points to a range of 30% to 70% relative humidity. Install a series of temperature, humidity, power and pressure sensors throughout the data centre. Use them for monitoring while adjusting temperature and humidity. Utilize communication gateway devices to pull data points into a building management system software interface.	H
	Air-Side Economizer	An air-side economizer is integrated into a central air handling system with ducting for both intake and exhaust. It brings outside air into a building and distributes it to the servers. Instead of being re-circulated and cooled, the exhaust air from the servers is simply directed outside.	M
Innovative cooling technologies	Immersion cooling technology	Immersion cooling in single-phase and two-phase operation, helps improve thermal design by directly immersing IT hardware in a non-conductive liquid.	H

		Heat generated by the electronic components is directly and efficiently transferred to the fluid, thereby reducing otherwise needed active cooling components, such as interface materials, heat sinks and fans.	

For Supermarket

Strategy	Technology	Description	Potential Energy Performance
Energy efficient refrigeration system and controls	Energy efficient refrigeration system	The energy saving refrigeration system that is composed of an energy efficient outdoor condensing unit and the refrigerated display cases	H
	Energy efficient refrigeration controls	Adaptive controls (continuously monitor and adjust system parameters such as superheat or evaporator pressure) Speed controllers for evaporator and condenser fans Timers and dimmers for display-case lighting On-demand defrost Night-time set back Pulsing of anti-sweat heaters Refrigerant leak detection Wireless communication for centralized monitoring and control	H
	Electronically commutated (EC) fans	Fan with a high efficiency, brushless DC motor for commercial fridges & freezers	L-M
Reduce energy waste	Refrigerated display cases fitted with glass door	Glass doors on the Refrigerated display cases keep the cold air inside the fridges, preventing it from mixing with the warm air of the supermarket.	H
	Energy-saving airfoil for the front edge of open-air fridges	Airfoils act as barriers that push cold air back into open fridges, preventing it from mixing with the warm air of the supermarket.	H

Annex B: RD&D and Deployment Pathway

1) Reduce energy consumption

Energy consumption in buildings must be aggressively reduced by all means available *before* any alternative energy-sources are considered and researched.

Target	Key Actions	Areas for Future R&D	Near Term (2020)	Medium Term (2025)	Long Term (2030)
Cut Cooling consumption	Building envelope and façade	Technologies for solar insulation (films)			
		Technologies for shading (films, cool paints)			
		Enhancing natural ventilation such as using simulation-based decision-making tools and thermal comfort studies			
		Tools for on-site façade performance			
		Multi-functional façade for energy storage/power/food generating devices			
		Optimized facades based on outdoor-dependent dynamic controls			
		Integration of air-conditioning systems in facades (dehumidification and cooling)			
	ACMV	Natural Refrigerant			
		ACMV system with architectural implications			
		High temperature chilled water system combined with decoupled sensible cooling and dehumidification.			

		Personalized ventilation and cooling	
		Displacement ventilation systems	
		Innovative sensible cooling	
		Hybrid-cooling with higher indoor temperatures	
		Chilled beam and radiant cooling	
		New materials for dehumidification and thermal cooling	
		Maximizing cooling and/or dehumidification from thermally activated sources	
		Modular compact chillers	
		Self-adapting distributed air-conditioning system for users	
		Polygeneration: optimisation of temperature and cascades for district systems	
Cut Lighting consumption	Daylight	Technologies for daylight (such as Dynamic Shading Strategies: Design of active blinds, roller shades and control systems to meet visual comfort goals while maintaining daylighting levels.)	
	Artificial light	Smart Lighting Systems	
		LED Lighting Systems: • Component level: Driver and power supply efficiency	

		• System level: source efficacy, controls, Lumen maintenance • Human physiological impacts	
Cut Plug loads consumption	Reduce energy waste	Standards for max plug loads in buildings	
		Drive the involvement of users	
		Study the effects of user behaviour	
		Technologies to reduce plug loads	
		User-specific smart dashboards	
Smart Building management	Interface and optimised performance of buildings systems	Seamless interoperability interface	
		Electric consumption database	
		Data classification, fusion and visualization	
		Operational BIM & BESS reporting	
		Distributed data dissemination	
		Multi-functional low-cost sensors	
		Automated FDDI	
		Adaptive comfort controls	
		Building modelling & predictive control	
		System data models	

		Self-healing, self-calibrating intelligent sensors	
		Sensor network optimization	
		Big data analysis tools	
		Wearable sensors	

2) Maximize renewable energy production

Buildings must maximize their on-site clean energy production.

Target	Key-actions	Areas for Future R&D	Near Term (2020)	Medium Term (2025)	Long Term (2030)
Maximize PV generation capacity	**Type of PV technology**	Diffuse more efficient PV technologies			
		Improve the design of existing technologies			
		Durable and long-lasting bonding technologies for fast & easy fixing of PV			
		Study degradation in PV modules in the tropics			
	Conversion efficiency	Regulations for DC/DC networks in buildings			
		Improve the efficiency of the conversion			
	Max radiation	Minimize shaded areas on roof spaces			
		Anti-shading PV system			
	Maximizing roof area	Prioritize building design with maximized roof areas for PV collection			
		Design lightweight structure for roof installations			
		PV integration with greenery			
	Maximize usage areas	Address limitations for fire safety to achieve larger PV roof areas			
		Customize the size of PV panels to maximize the covering of the available roof areas			
		Promote PV integration in building aesthetics			

R&D | Test-bedding, Demo | Deployment, Market

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Belmacs Pte Ltd	Private Sector
CapitaLand Limited	Private Sector
Changi Airport Group	Private Sector
CHIJ St Nicholas Secondary School	School
CIAP Architects Pte Ltd	Private Sector
Corporation Primary School	School
CPG Consultant Pte Ltd	Private Sector
Defence Science and Technology Agency (DSTA)	Public Agency
Dragages Singapore Pte Ltd (DSPL)	Private Sector
Energy Market Authority (EMA)	Public Agency
Engineers Alliance Pte Ltd	Private Sector
Enlighted Sales and Service Pte Ltd	Private Sector
FMC Technologies Singapore Pte Ltd	Private Sector
GreenA Consultants Pte Ltd	Private Sector
I3 Solutions Group (i3)	Private Sector
Infocomm Media Development Authority (IMDA)	Public Agency
JTC Corporation (JTC)	Public Agency

Jurong Secondary School	School
Kajima Corporation	Private Sector
Keppel Data Centres Pte Ltd	Private Sector
Keppel Land Limited	Private Sector
Kimly Construction Pte Ltd	Private Sector
KLA-Tencor (Singapore) Pte Ltd	Private Sector
Kuo Chuan Presbyterian School	School
Lendlease Group	Private Sector
Mandai Park Development Pte Ltd	Private Sector
Marsiling Secondary School	School
Ministry of Culture, Community & Youth (MCCY)	Public Agency
Meinhardt (Singapore) Pte Ltd	Private Sector
Morrow Architects & Planners Pte Ltd	Private Sector
Mott Macdonald Singapore Pte Ltd	Private Sector
Nanyang Technological University (NTU)	Institute of Higher Learning (IHL)
National Climate Change Secretariat (NCCS)	Public Agency
National Parks Board (NParks)	Public Agency
National Research Foundation (NRF)	Public Agency
National University of Singapore (NUS)	Institute of Higher Learning (IHL)
Ngee Ann Polytechnic (NP)	Institute of Higher Learning (IHL)
Palm View Primary School	School
Parsons Brinckerhoff Pte Ltd	Private Sector
RDC Architects Pte Ltd	Private Sector
RightViz Solutions Pte Ltd	Private Sector
SAA Architects Pte Ltd	Private Sector
Samwoh Pte Ltd	Private Sector
Siemens Pte Ltd	Private Sector
Singapore Institute of Technology (SIT)	Institute of Higher Learning (IHL)
Singapore Technologies Electronics Pte Ltd	Private Sector
Squire Mech Pte Ltd	Private Sector
St Andrew’s Community Hospital (SACH)	Private Sector
Surbana Jurong	Private Sector
Teale Pte Ltd	Private Sector
The Ascott Limited	Private Sector
Tiong Seng Contractors Pte Ltd	Private Sector
Trane Distribution Pte Ltd	Private Sector
United World College-South East Asia (UWCSEA)	Institute of Higher Learning (IHL)
Urban Redevelopment Authority (URA)	Public Agency
Webearth Pte Ltd	Private Sector
William Ng Consultants Pte Ltd	Private Sector
Yishun Junior College	School
ZEB-Technology Pte Ltd	Private Sector

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