# Built Environment Decarbonisation Technology Roadmap

Building and Construction Authority

SINGAPORE GREEN BUILDING COUNCIL

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# FOREWORD

Over the past 20 years, Singapore has established ourselves as a leader in green buildings for the tropical and sub-tropical climate. As part of our commitments to combat climate change, Singapore has set an ambitious goal for the city-state to achieve net-zero emissions by 2050.  This will require further transformation of our Built Environment (BE).

Building upon our 2018 efforts, this refreshed technology roadmap arrives at a crucial moment, as the BE sector steps up efforts to decarbonise. The roadmap addresses critical challenges, particularly embodied carbon, which is projected to constitute nearly half of all new construction emissions through 2050. This will require innovative solutions and coordinated industry action among the BE stakeholders.

According to World Intellectual Property Organisation (WIPO)[1], 80% of the technologies required to halve global greenhouse emissions of the BE sector by 2030 are already available. Our focus will now shift to effective deployment and implementation. This roadmap provides direction and guidance for stakeholders across the sector to embark on their decarbonisation journey and to advance Singapore's position as a climate-resilient global city.

We invite all industry partners – developers, building owners, architects, engineers, sustainability consultants, builders – to join us in this crucial endeavour. Together, we can create a sustainable BE that sets new standards for tropical urban development and ensures a high-quality living environment for future generations. The transition to a sustainable future requires immediate collective action. We look forward to your partnership in realising this vision.

**Mr Kelvin Wong**
**CEO**
**Building and Construction Authority**

**Mr Lee Ang Seng**
**President (2023 - 2025)**
**Singapore Green Building Council**

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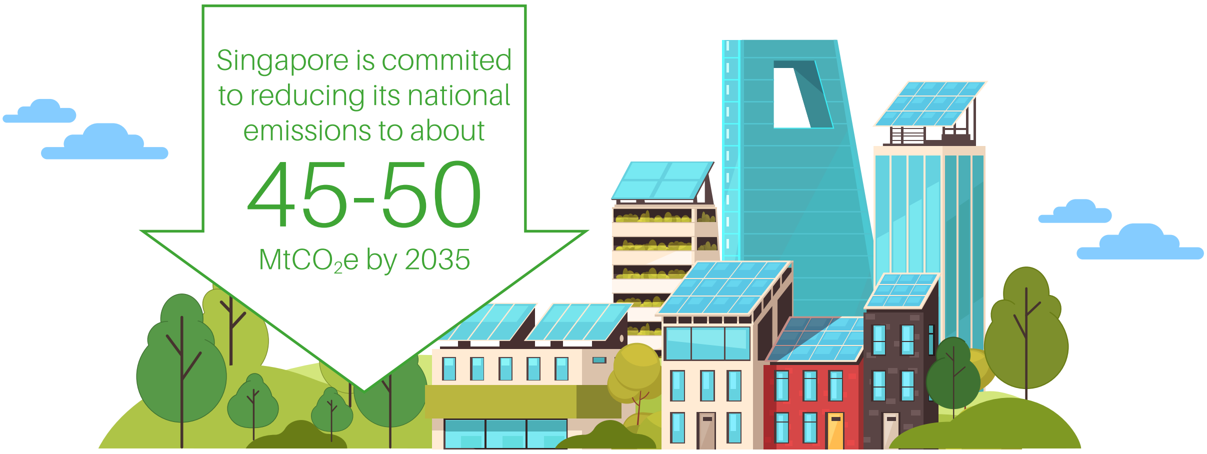
[1] World Intellectual Property Organisation. (2023). WIPO Green Technology Book:  Solutions for Climate Change mitigation. Retrieved from https://www.wipo.int/green-technology-book-mitigation/en/foreword-wipo.html

# EXECUTIVE SUMMARY

Singapore is committed to **reducing its national emissions to about 45 to 50 $MtCO_2e$ by 2035** from the projected 60 $MtCO_2e$ in 2030. These targets are in line with the country's **Long-Term Low-Emissions Development Strategy (LEDS) to achieve net-zero emissions by 2050**.




As the country advances its climate ambitions under the **Singapore Green Plan 2030**, the BE sector must focus on addressing whole life carbon – the total emissions produced by a building throughout its entire life cycle – which includes **operational carbon and embodied carbon**.

Due to our early emphasis on energy efficiency measures since 2005 via the Green Mark scheme and the Singapore Green Building Masterplans, operational carbon is expected to decline with increasing energy efficiency and the adoption of renewable energy.

As operational carbon is reduced, embodied carbon will grow in importance as a proportion of total emissions. Upfront carbon, which refers to carbon emissions during materials production and construction phases of the life cycle before the building or infrastructure begins operating, has the potential to account for up to half of the entire carbon footprint of new construction between now and 2050. Hence, it is important for us to pay more attention to embodied carbon.

Technology will play a key role in this transition to enable the rapid development and deployment of solutions to encourage the switch to low-carbon alternatives and drive forward transformational change.

Developed jointly by the Building and Construction Authority (BCA) and Singapore Green Building Council (SGBC) (with support from Agency for Science, Technology and Research (A*STAR)), this roadmap serves as a guide to help industry stakeholders identify key future-ready solutions and strategies that reduce whole life carbon emissions in buildings to prepare Singapore's built environment and its firms for a low-carbon future. It builds on existing efforts to drive life cycle thinking and material carbon transparency in the built environment sector.

Over a span of seven months, BCA and SGBC engaged about 100 BE Firms, Trade Associations, Institutes of Higher Learning (IHL), material suppliers and technology providers to **identify close to 70 key emerging and existing technology solutions** and strategies to help building owners decarbonise their buildings. A subsequent one-month public consultation at the International Green Building Conference (IGBC) 2025 in August 2025 garnered over 50 responses from the industry.

| Themes | Strategies | Number of solutions | Examples |
|---|---|---|---|
| **Operational Carbon Reduction** | Optimisation across Multiple Buildings in District-Level | 3 | Switch to district cooling system (DCS), urban energy modelling software |
| | Passive Strategies | 9 | Ventilated façades, natural ventilation, vacuum insulation panel, façade enhancement solutions for existing solutions, phase change materials, $CO_2$ absorbing coatings with sequestration capabilities |
| | Active Strategies | 23 | Alternative cooling technologies (ACTs), energy recovery systems, magnetocaloric cooling chillers, advanced solid-state/thermoelectric cooling, dual temperature chiller plant |
| | Smart Energy Management | 8 | Occupant-Centric Optimisation, Smart Operations with Digital Twins, Self-calibration Reference Sensors |
| | Renewable Energy | 5 | Façade Solar, Micro Wind Turbines, Vibration energy harvesting materials |
| **Embodied Carbon Reduction** | Carbon Avoidance Design | (Design Concept) | Build less, light and efficient, Adaptive reuse, Kit-of-Parts |
| | Low-Carbon Materials | 11 | Supplementary Cementitious Materials, $CO_2$ to aggregates, Geopolymer Concrete with $CO_2$ Sequestration, Green Steel, 3D printing using low carbon materials |
| | Low-Carbon Construction | 5 | Site Electrification, Lean Construction Methods, Circularity in Construction, Use of clean energy on-site |
| | Circularity in Construction | 2 | Construction & Demolition (C&D) Waste Material Processing, Material Passports |
| | Digital Carbon Tools | 3 | Whole Life Carbon Calculator, Life Cycle Assessment (LCA) Analysis Tools, ESG-related tools for disclosure and reporting, Agentic Artificial Intelligence (AI) solution for Whole Life Carbon Management |

Across both operational and embodied carbon reduction, the greatest carbon savings potential in the building life cycle lies in the project conception and design stages. Decisions made during these initial phases can either lock in carbon-intensive pathways or enable substantial emissions reductions throughout the building's life cycle. Fundamental choices about building orientation, materials and space utilisation determine immediate embodied carbon lock-in while shaping decades of operational practices and carbon emissions.

Project teams must front-load their carbon reduction efforts and invest more time and resources in early-stage analysis and decision-making. This proactive approach is far more cost-effective than mitigating carbon emissions through retrofits or operational adjustments later in the building's life cycle.

# INTRODUCTION

Buildings account for over 20% of Singapore's emissions. Hence, greening our buildings is key to achieving our emissions reduction targets. Since 2006, BCA has launched several editions of Green Building Masterplans comprising a suite of initiatives and policies focused on the Green Mark scheme, such as setting minimum energy efficiency standards, leveraging legislative and incentive instruments and supporting research and innovation (R&I). In 2021, BCA and the SGBC worked together with industry stakeholders and the community to develop and launch the 4th edition of the Singapore Green Building Masterplan (SGBMP). This introduced the '80-80-80 by 2030', which are three key aspirational targets for the BE sector.

**Vision**

"A leading green BE sector mitigating climate change and providing a healthy, liveable and sustainable BE for all"

**80% of buildings to be green by 2030:**

- Raising mandatory Environmental Sustainability Standards
- Publication of building energy performance data
- Green Mark 2021
- Nudging Poor Performers

**Support Scheme:** Green Mark Incentive Scheme for Existing Buildings 2.0 (GMIS-EB 2.0)

**80% of new developments to be Super Low Energy (SLE) building from 2030:**

- GreenGov.SG
- Raise Environmental Sustainability Standard (including EE requirements) for projects under GLS programme
- Develop SLE standards for residential buildings

**Support Scheme:** BE Transformation GFA Incentive Scheme

**80% Energy Efficiency (EE) improvement (from 2005 levels) by 2030:**

- GBIC Research and Development (GBIC R&D)
- GBIC Prototyping
- GBIC Demonstration (GBIC Demo)

**Support Scheme:** Enhanced GBIC funding (GBIC 2.0)

Supported by Integrated FM and Aggregated FM (IFM & AFM) grant for buildings to operate and maintain optimal building performance, to improve buildings' energy efficiency and cultivate a sustainable BE in Singapore.

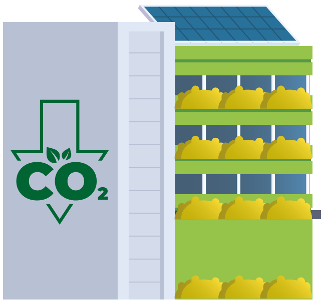
One facet of the SGBMP is to drive green building innovation. With support from the National Research Foundation (NRF), BCA has established initiatives such as the Green Building Innovation Cluster (GBIC) Programme to accelerate the development and deployment of promising energy-efficient technologies in buildings. The Built Environment Innovation Hub (BEIH) brings together innovators and key stakeholders, including progressive firms, IHL and venture capital firms, to collaborate and solve real-world challenges faced by the sector.

As the global landscape evolves, this is a timely opportunity to assess emerging trends, technologies, and innovations to lay the foundation for Singapore's next set of ambitious decarbonisation goals.

# Looking Ahead - Post 2030 Challenges and Global Trends

## Shrinking National Carbon Budgets towards 2050

Beyond 2030, international pressure to decarbonise will continue to intensify as countries strengthen their climate commitments. Many countries have established targets for achieving net-zero carbon emissions, with Uruguay aiming for 2030, Finland for 2035, and most other nations setting their sights on 2050. As national carbon budgets continue to shrink, the BE sector which accounts for approximately 40% of energy-related carbon emissions, will face mounting scrutiny and stricter regulations.




## Emphasis on Embodied Carbon Reduction in the BE Sector

According to the **World Green Building Council (WorldGBC), building and construction contribute 11% of global carbon emissions** from materials and construction processes alone. **Embodied carbon can account for up to 50% of total emissions** over a building's life cycle, especially in highly energy efficient buildings. In net-zero energy buildings, embodied carbon contributes 100% of the building's carbon emissions. The next decade is critical. The WorldGBC urges that all new buildings should reduce **embodied carbon by at least 40%** by 2030.


## Climate Disclosure and GHG Emissions Reporting

Increasingly, preparing for a low-carbon world is an international obligation and economic necessity. Corporate reporting requirements are tightening as regulators and investors demand transparency. The European Union (EU) mandates detailed sustainability reporting for large companies with similar regulations in the US, Hong Kong, Japan and Singapore. Locally, all Singapore Exchange (SGX)-listed companies are required to start Scope 1 and 2 greenhouse gas (GHG) emissions from FY2025, while Straits Times Index (STI) constituents from Scope 3 GHG emissions from FY2026. Globally, accelerating embodied carbon regulation is driven by the EU Carbon Border Adjustment Mechanism (CBAM), which prices carbon in imports. As more countries enforce carbon limits and life cycle assessments, firms slow to decarbonise risk facing escalating penalties.

# Purpose of the Roadmap

Research, development, and innovation in decarbonisation technologies could take up to 10 years from initial concept to wider commercial deployment. Even as we strive to achieve SGBMP's 80-80-80 by 2030, it is important to identify and prioritise technologies to meet future challenges.

BCA and SGBC partnered with A*STAR Consortium Operation & Technology Roadmapping team on a technology roadmapping study for the decarbonisation of the BE sector for two key objectives:

- Gather industry insight on a post-2030 vision for BE sector decarbonisation, identify key emerging technologies and recommend future research and development (R&D) areas to advance SLE buildings in the tropics.
- Support decision-making on key R&I areas in the next decade to ensure the timely availability of technologies essential to address post-2030 decarbonisation challenges.

Importantly, this roadmap highlights key technologies available for decarbonisation in the BE. Rather than an exhaustive list, it is a continuation of efforts built on existing policies, pilot projects, and R&D initiatives. The roadmap aligns with long-term climate goals based on the Pareto Principle, by focusing on 20% of building components causing 80% of emissions. This approach helps policy makers, solution providers and adopters to prioritise innovation activities in the most impactful areas. The list of shortlisted technologies is available in Annexes B to D of the roadmap.

# POST-2030 TECHNOLOGY AMBITIONS

Beyond 2030, Singapore's BE must adopt transformative technologies that enable deep decarbonisation across the full building life cycle. This includes both mature solutions that require scaling up and emerging technologies that need targeted R&D and ecosystem support.

Three technology aspirations were identified as part of the roadmapping process.

| Technology Aspirations | | |
|---|---|---|
| Operational Carbon | | Embodied Carbon |
| Achieve SLE building by 2040 | New Buildings achieve 80% EE by 2040 | 40% embodied carbon by 2040 |
| We want technologies that can enable our diverse existing building stock **to be able** to achieve SLE building by 2040 | We want technologies that can enable new buildings **to be able** to achieve 80% EE by 2040 | We want technologies that can enable new buildings **to be able** to reduce their embodied carbon by 40% by 2040 (w ref GM2021) |

The current roadmap builds on the foundations laid in the 2018 **SLE Building Technology Roadmap**, which primarily addressed operational carbon. This edition of the BE Decarbonisation Technology Roadmap adopts a whole life carbon approach to include embodied carbon reduction.

# WHAT IS THE WHOLE LIFE CARBON APPROACH?

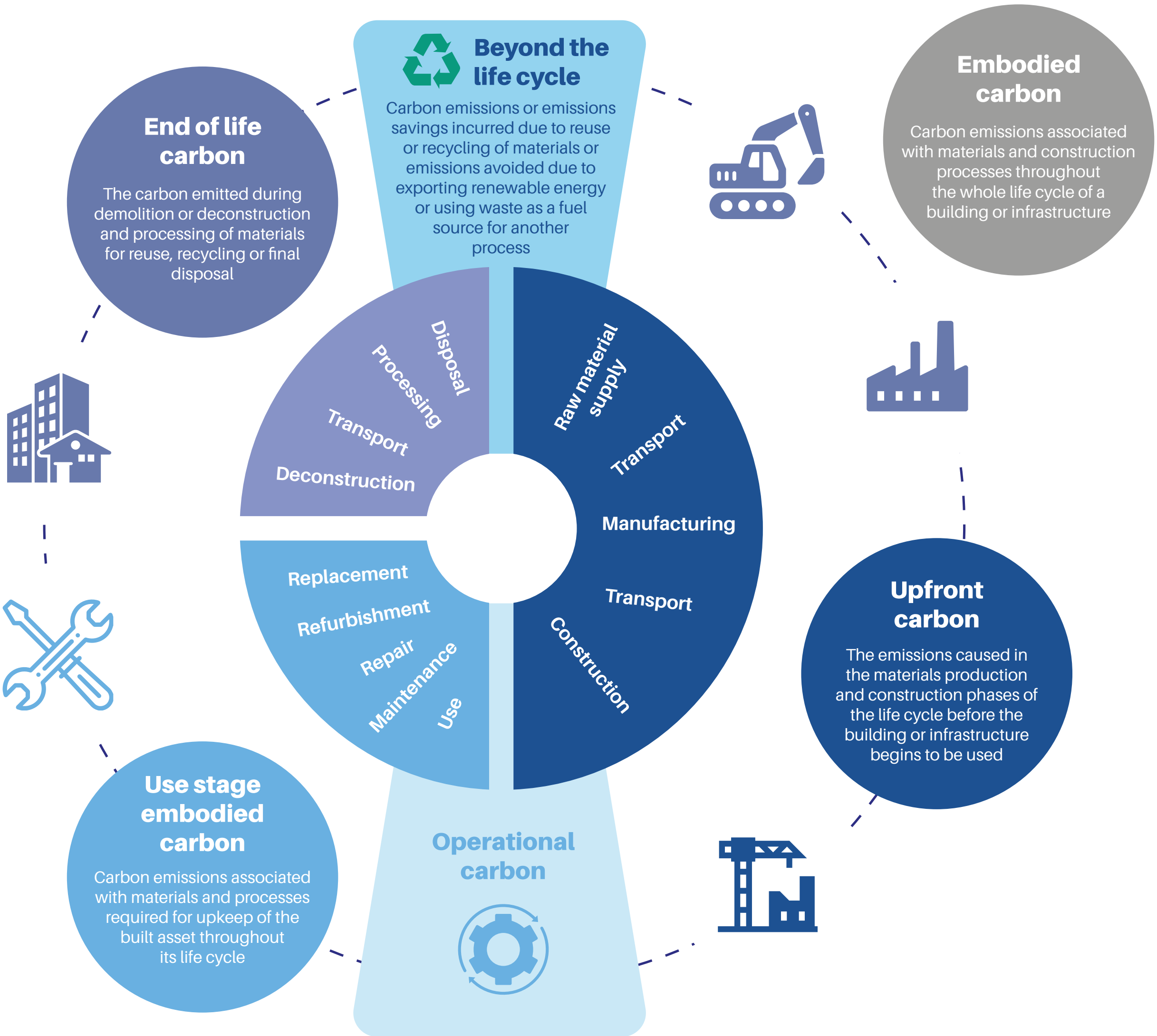



Figure 1: Project life cycle showing both the scope of the definition and need for whole life consideration.
Source: World Green Building Council

The whole life carbon approach is a comprehensive method for assessing a building's total carbon emissions across its entire life cycle, from construction through operation to end-of-life.

### Operational Carbon

- Accounts for all carbon emissions associated with the energy used to operate and run a building throughout its lifetime (e.g. ACMV systems for space cooling, lighting, other common building services like elevators and plug loads)
- These emissions are typically calculated based on annual energy consumption and the relevant carbon emission factors for different energy sources (electricity, gas, etc.).

### Embodied Carbon

- Accounts for all carbon emissions associated with materials and construction processes throughout the building's entire life cycle.
- While the make-up of carbon emission will differ between building typologies, it is estimated that as much as half of the total carbon emissions from new building construction may be due to upfront emissions. Once the building is completed, the majority of these upfront carbon emissions will be locked in.

### The need for a Balanced Approach

Today, operational carbon remains the biggest contributor over a building's lifetime. Ongoing efforts under the SGBMP to increase building energy efficiency and enhance renewable energy are expected to reduce these emissions.

Embodied carbon has typically been overlooked but as buildings become more energy-efficient, the proportion of operational carbon emissions will decrease. This increases the relative significance of embodied carbon in the building's total carbon footprint.

There is a need for a balanced approach. While reducing upfront carbon in construction is vital, it is crucial to also consider operational and whole life carbon impacts. Material choices and design decisions must consider long-term impacts to avoid poor operational outcomes that lead to financial, environmental, and social costs.

### Updated Reduction Pathway

Building on the reduction pathway established in the 2018 SLE Building Technology Roadmap, the following has been updated and categorised to reflect both operational carbon and embodied carbon strategies, in alignment with a whole life carbon approach.

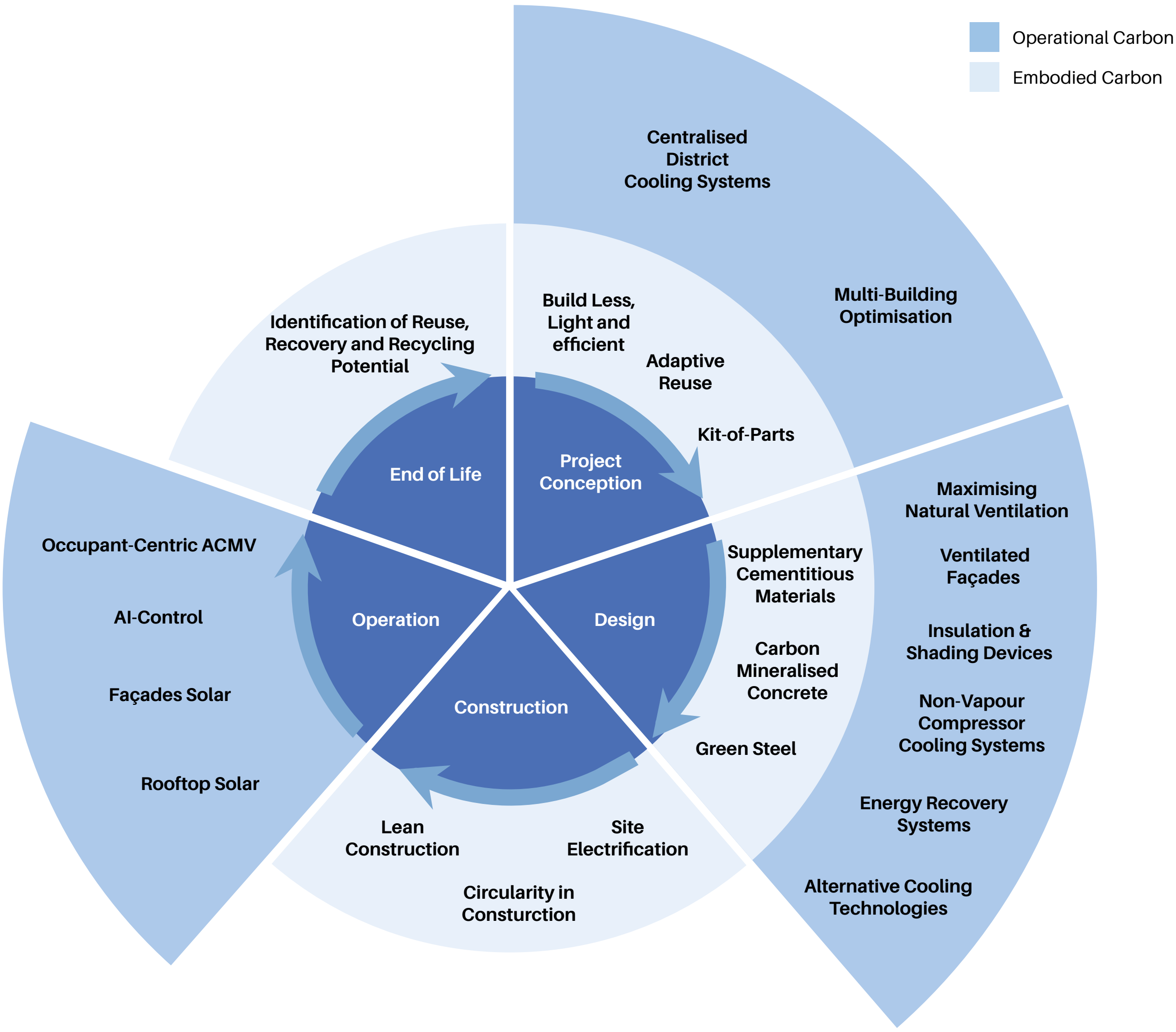



Figure 2: Embodied/Operational Carbon Strategies

### Technology Prioritisation

The identified technologies and solutions are grouped into categories based on technology readiness level (TRL) and potential energy reduction impact and carbon reduction impact, to guide differentiated strategies:

- **Areas of Research and Innovation**
  These are lower TRL (4-6) solutions but have higher potential impact in carbon reduction (more than 30%[2] energy reduction). These solutions will require research, prototyping and validation.

- **Quick Wins**
  These are higher TRL (7-9) and higher impact solutions that are ready to be deployed.

- **Ready for Adoption**
  These are higher TRL (7-9) solutions but have lower impact in carbon reduction. These technologies have the potential for R&I to further push the boundaries of carbon reduction impact.

- **Future Opportunities**
  These are solutions that are currently have a lower TRL (4-6) solutions with limited current impact in carbon reduction. These solutions would be monitored for their future development.

### Matrix for Categorisation of Solutions

| Technology Readiness Level (TRL) | Description |
|---|---|
| TRL 1-3 | Basic research and concept proofing phase. |
| TRL 4-6 | Validation and demonstration phase. |
| TRL 7-9 | Deployment phase (solutions in the market). |

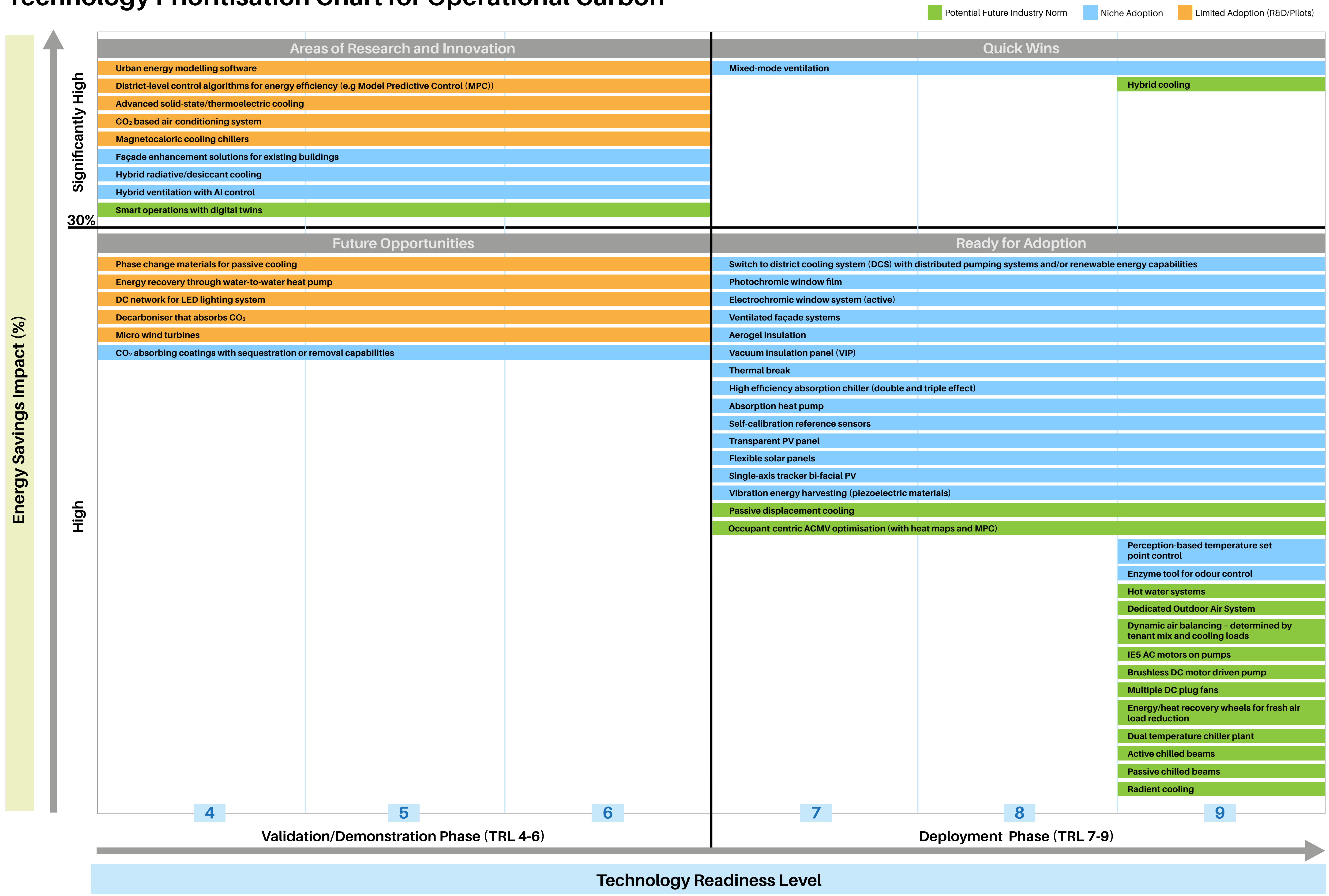
| Impact | Operational Carbon | Embodied Carbon[3] |
|---|---|---|
| High | Up to 30% energy reduction over comparable existing best-in-class solutions. | Up to 30% reduction in embodied carbon emissions comparable to conventional system. |
| Significantly High | >30% energy reduction over comparable existing best-in-class solutions. | >30% reduction in embodied carbon emissions comparable to conventional system. |

| Market Adoption | Description |
|---|---|
| Limited Adoption (R&D/Pilots) | Solution not adopted in the market or still undergoing pilot testing/demonstration phase. |
| Niche Adoption | Solution has some market adoption locally but confined to specific typologies or use cases. |
| Potential Future Industry Norm | Solution is slowly gaining wider adoption or could become an industry norm. |

[2] For operational carbon, energy reduction is measured over comparable existing best-in-class solutions. For embodied carbon, carbon reduction is measured against comparable conventional systems.

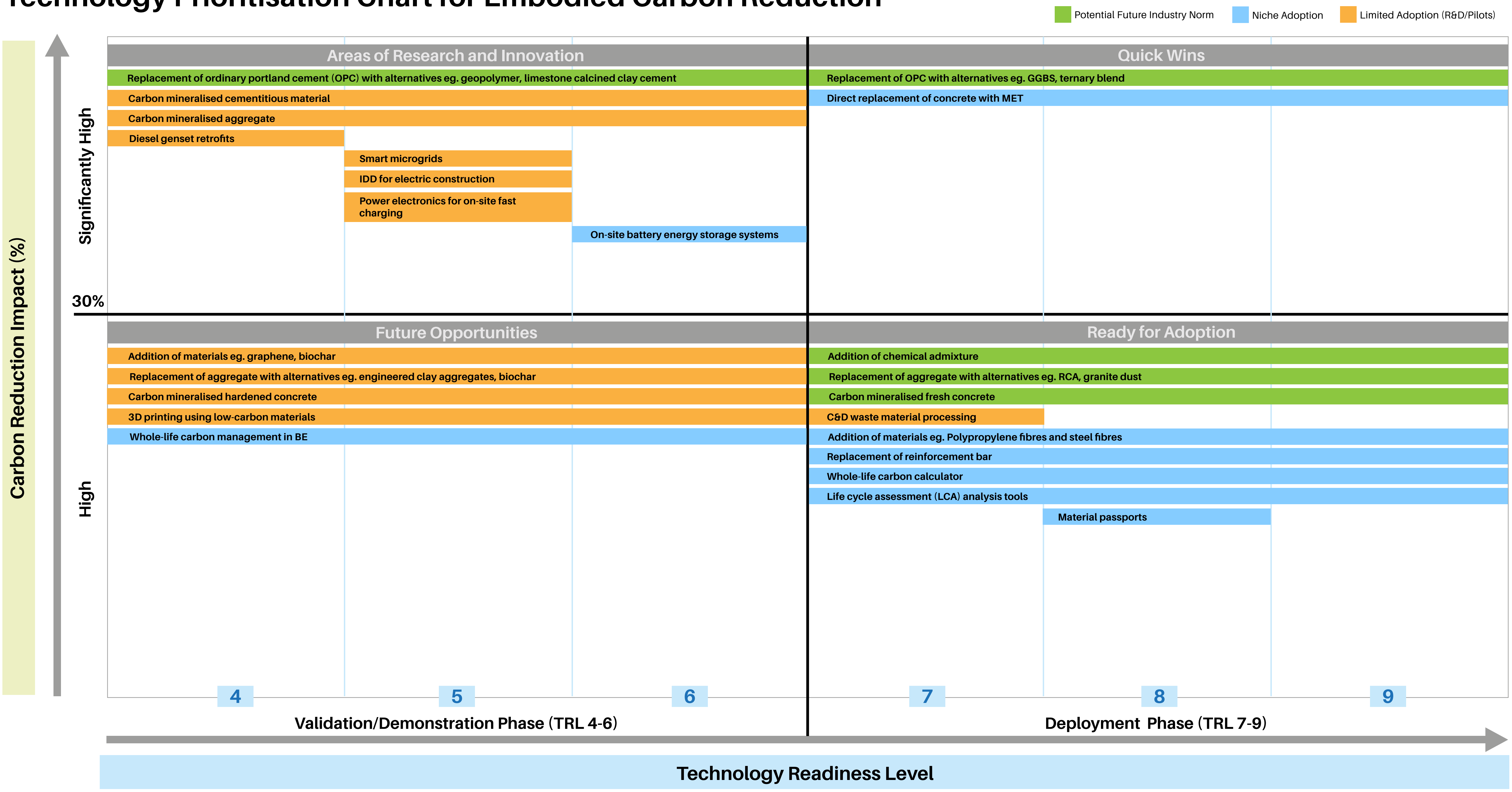
[3] Potential Impact at system level* (*the impact to the overall carbon footprint of the concrete when the material replaces conventional materials)

# Technology Prioritisation Chart for Operational Carbon




The Technology Prioritisation Chart for Operational Carbon Reduction provides an overview of the assessed technologies based on their potential energy reduction impact, technology readiness level, and market adoption potential. For more details on the technology descriptions and prioritisation assessment, please refer to **Annex B**.

# Technology Prioritisation Chart for Embodied Carbon Reduction




The Technology Prioritisation Chart for Embodied Carbon Reduction provides an overview of the assessed technologies based on their potential embodied carbon emissions reduction impact, technology readiness level, and market adoption potential. For more details on the technology descriptions and prioritisation assessment, please refer to **Annex C**.

# OPERATIONAL CARBON REDUCTION

Since the launch of the 2018 SLE BuildingTechnology Roadmap and the SLE Challenge, SLE projects have begun to gain traction locally with over 180 projects[4] involving over 190 developers, architects and consultants. Through funding support under the GBIC Programme, several progressive building owners have come forward to provide an actual building environment to pilot innovative technologies and practices to push the energy boundaries further. **As of early 2025, our best-in-class SLE buildings have achieved 72% savings over 2005 levels**. Along with this, the ecosystem for SLE-enabling technologies has evolved since 2018 with several technologies and strategies from the earlier roadmap reaching greater maturity or wider industry acceptance. A Full list of established operational carbon and embodied carbon solutions can be found under Annex D.

## Best-In-Class Super Low Energy Buildings

### Keppel Bay Tower

Keppel Bay Tower's implementation of emerging technologies such as a **high-efficiency air distribution system, an innovative cooling tower water management system, smart LED lighting solutions and an intelligent building control system** helped transform the 20-year-old development. Keppel Bay Tower became the first commercial building that is fully powered by renewables, to be certified under the BCA Green Mark Platinum SLE/Zero Energy (ZE) rating scheme.  These initiatives boosted a further energy efficiency reduction by about 30% and cut over 800 tonnes of carbon emissions per year, from its initial Green Mark Platinum level.

Source: BCA's Best-in-Class Super Low Energy Building Series on Keppel Bay Tower

[4] Data correct as of June 2025.

## Singapore Management University (SMU) Connexion

SMU Connexion is a Green Mark Platinum-certified ZE (on-site) building that exemplifies sustainability and innovation. Constructed predominantly with eco-friendly, durable, and renewable mass engineered timber (MET), it stands as one of Singapore's pioneering on-site net-zero energy (NZE) buildings. By adopting an unconventional design strategy and incorporating advanced smart building technologies, the building exemplifies the feasibility of achieving on-site net ZE performance within a highly urbanised city centre context. Its key design features include:

- Responsive architectural design for optimised shading and natural ventilation.
- Enhanced passive displacement cooling (PDC)
- Dimmable LED lighting with networked sensors
- On-site solar photovoltaic panels
- Predictive and responsive smart building control systems

SMU Connexion champions new construction initiatives, showcasing MET technology to support the BCA push for higher productivity through Design for Manufacturing and Assembly (DfMA), and the development of more sustainable built environments.


Source: BCA's Best-in-Class Super Low Energy Building Series on SMU Connexion

## Samwoh Smart Hub (SWSH)

SWSH was designed to achieve minimal energy consumption while simultaneously reducing its operational carbon footprint. Key considerations included innovative building shapes, sizes and orientations.

The development incorporates cutting-edge technologies across various domains to achieve its goal of being a positive energy building that produces 25% more energy than it consumes:

- Uses passive design elements to optimise natural resources to minimise energy demand. These include the thoughtful placement of windows, insulation and shading.
- Employs an innovative air-conditioning system to enhance energy efficiency and occupant comfort. These includes Solar Driven Digitally Controlled Chiller, Open Circuit Cooling Tower with EC Technology, Run-Around AHU Coil and Smart Fan Coil Unit.
- Adopts a smart energy management system acts as a data repository, allowing continuous analysis and troubleshooting to ensure optimal performance and occupant well-being.
- Deploys on-site solar PV to generate its own energy from renewable sources, contributing to its positive energy status.

SWSH has attained Energy Use Intensity (EUI) of 46 kWh/sqm/year, making it 84% more energy efficient compared to 2005 levels. In recognition of its achievements, SWSH was honoured with the BCA Green Mark Platinum Award (Positive Energy).


Source: BCA's Best-in-Class Super Low Energy Building Series on Samwoh Smart Hub

Beyond advancing energy efficiencies for our best-in-class buildings, significant opportunities exist for technology to tackle the operational challenges of the existing building stock and elevate their performance to SLE standards.

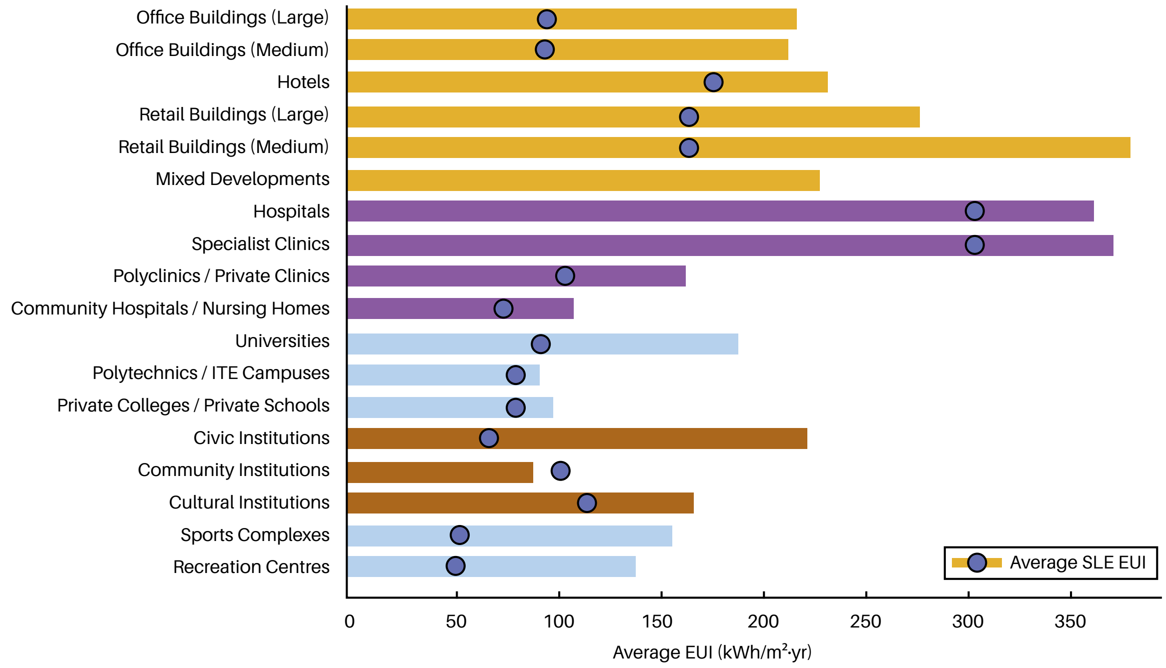



Figure 3: Average EUI by Building Typologies.

Looking ahead, the roadmap identifies the following technologies as key needle movers to push building energy efficiency further.

## Operational Carbon Reduction Strategies

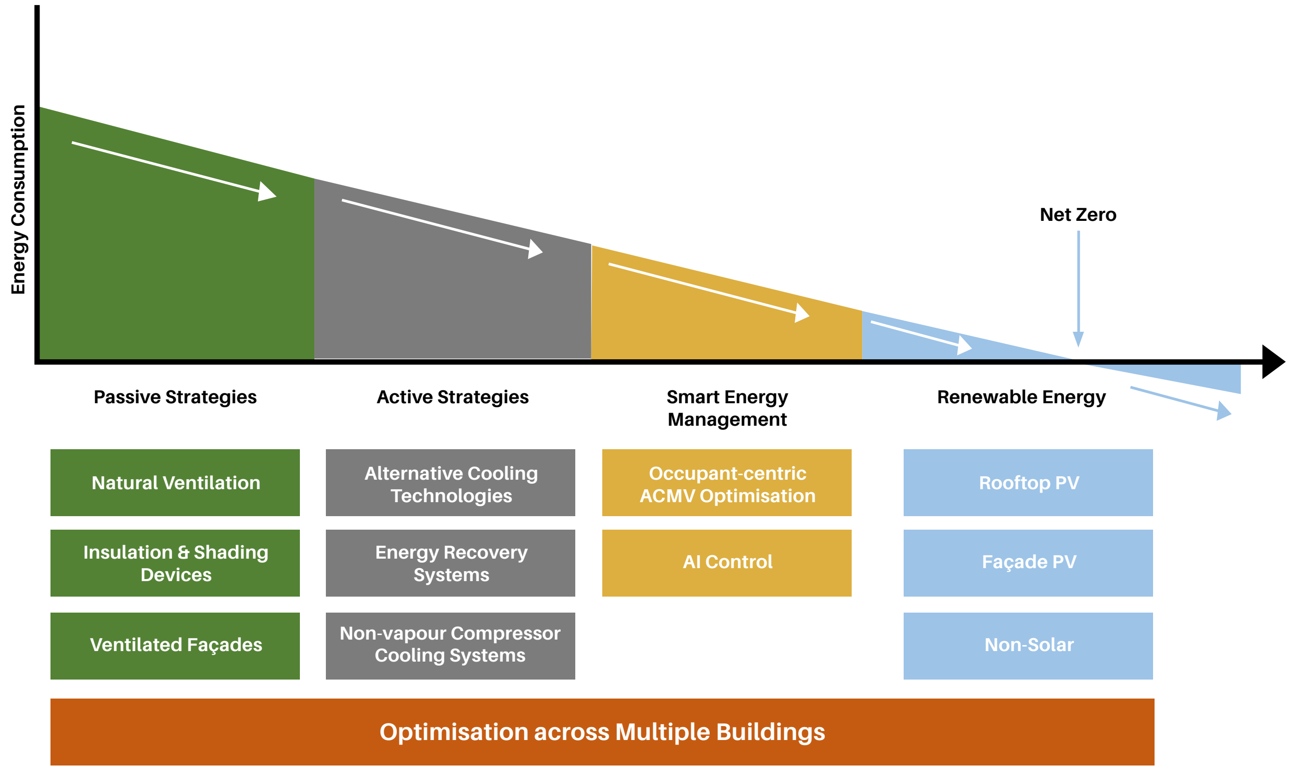



Figure 4: Operational Carbon Reduction Strategies

Key Area #1:

## Reducing Cooling Demand by Maximising Natural Ventilation

Air-conditioning and mechanical ventilation (ACMV) systems for space cooling constitute the largest energy demand in Singapore's buildings, consuming 40-60% of a building's total energy. This significant energy burden is set to intensify with the increasing frequency of hot spells due to climate change. While ACMV systems are more efficient now, with systems claiming to achieve up to 0.55 kW/tonne for best-in-class chiller efficiency, unlocking the next bound of energy savings will require limiting cooling demand from the onset. By incorporating upstream design considerations (e.g., electrical, mechanical, and structural) to maximise the zoning of more naturally ventilated spaces and leveraging natural airflow, buildings can reduce reliance on mechanical cooling systems. Increasingly, this can be done for both transient and occupied spaces (see case study).

### Case Study on DBS Newton Green

#### Façade Shading & Natural Ventilation

To address Singapore's tropical climate, a passive design strategy was implemented to reduce energy use by limiting solar heat gain and enhancing the existing building's performance. The building features a façade of vertical bamboo strips, which allow the plantation to climb vertically, giving a look that support climbing plants, forming a living wall irrigated with that enhances indoor air quality (IAQ) through phytoremediation, utilising cool condensate water from the air-conditioning system. This not only improves IAQ through phytoremediation but also enhances thermal comfort and saves energy as naturally ventilated spaces do not need air-conditioning.

In collaboration with the Nature Society of Singapore, native plant species were selected to attract and support local bird and butterfly species such as the magpie robin, bulbul, and flowerpecker. Today, over 50% of the building's perimeter is covered in greenery, serving both to lower internal temperatures and to promote urban biodiversity.

**10%** of the floor area that was previously air-conditioned has been converted to naturally ventilated spaces that do not need air-conditioning


Source: DBS Bank

Key Area #2:

## Shifting Away from Traditional ACMV Design to Alternative Cooling Technologies (ACTs) or Non-Compressor/Non-Refrigerant Cooling Cycles

Where cooling needs cannot be avoided, designs should adopt ACTs such as radiant cooling or PDC, that mimic the natural flow of heat/convective processes over a traditional ACMV design. Most of the ACTs identified in the 2018 SLE Building Technology Roadmap have reached maturity with commercial solutions readily available locally. Many ACTs reap energy-saving benefits by operating at higher set points (e.g., 24°C to 25°C). Building user acceptance of this change will be key for wider adoption.

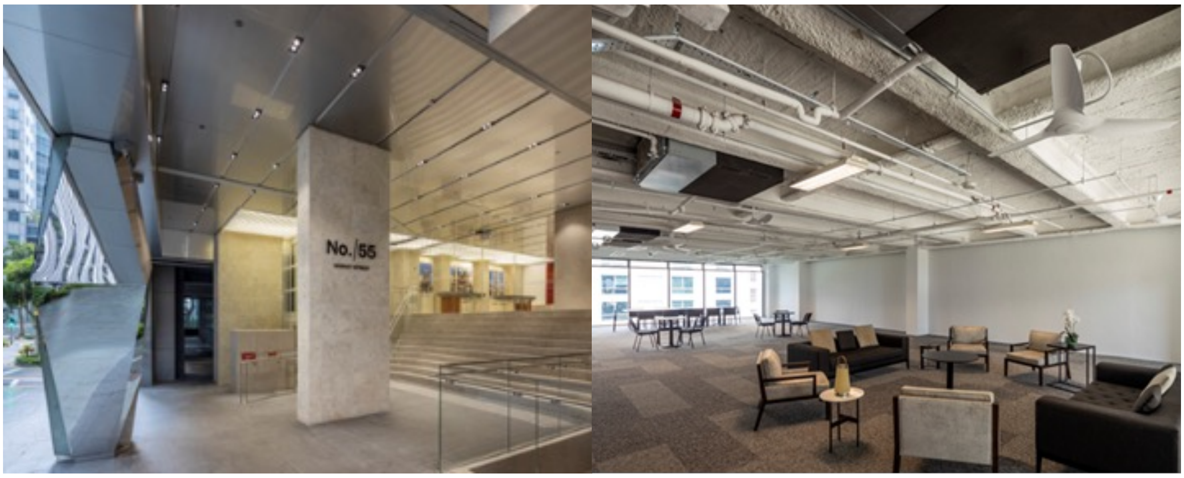
Looking further ahead, instead of making incremental efficiency improvements in conventional vapour-compression systems, switching to new solutions that do not need compressor cycles could offer better efficiency gains. Technologies like magnetocaloric cooling, absorption chillers and thermoelectric cooling eliminate the energy-intensive compression process, using more direct energy conversion methods that minimise energy wastage. These systems achieve higher coefficients of performance and work better, particularly in part-load conditions. These systems also eliminate harmful refrigerants, significantly reducing their carbon footprint and environmental impact.

Globally, cooling R&D remains dominated by traditional compressor-based cycles. Systems with non-compressor cycles have yet to be demonstrated effectively in tropical climates, which offers significant potential for further R&D in Singapore.

### Case Study on Kajima Office at 55 Market Street

#### Hybrid Cooling

Kajima adopted a cooling system that combines two or more different cooling technologies to achieve optimal energy efficiency and performance. This approach often involves integrating fans with traditional mechanical cooling methods. The elevated air temperature (cooling temperature setpoint from 24°C to 27°C) with increased air flow leads to reduction in cooling demand and improvement in thermal comfort and IAQ. By adopting hybrid cooling, 36% energy reduction was observed in daily ACMV energy consumption.



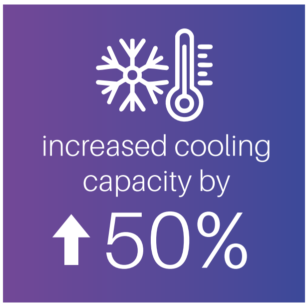

Source: Kajima Corporation

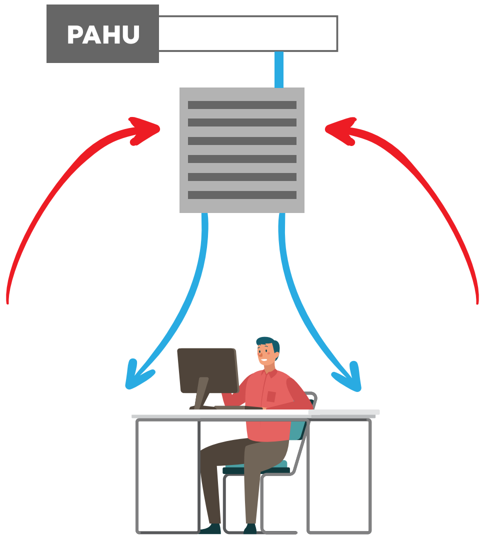
Technical Reference on Hybrid Cooling System for Air-Conditioning (TR 141:2025) is available on Singapore Standards website.

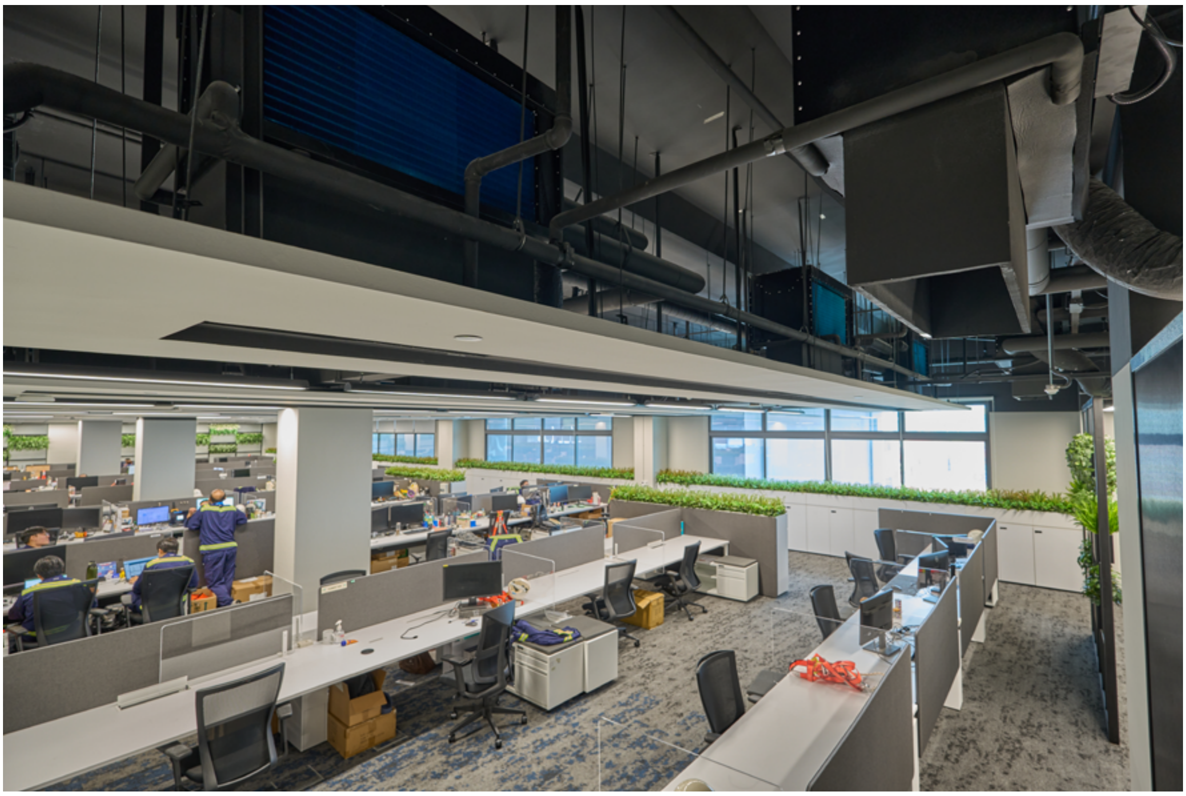
## Case Study on PSA Tuas Maintenance Base

### Passive Displacement Cooling (PDC)

PDC is a method of cooling where airflow is generated through natural convection, eliminating the need for energy to power a fan. The thermosiphon beam is used to increase cooling capacity by 50% in occupied spaces such as the pantry and open office areas. This innovation generates a thermosiphon cycle that starts with an initial injection of air by the primary air handling unit (PAHU), which creates a change in pressure that draws air from the room towards the cooling coils. Airflow increases as the cycle repeats, speeding up the cooling process.



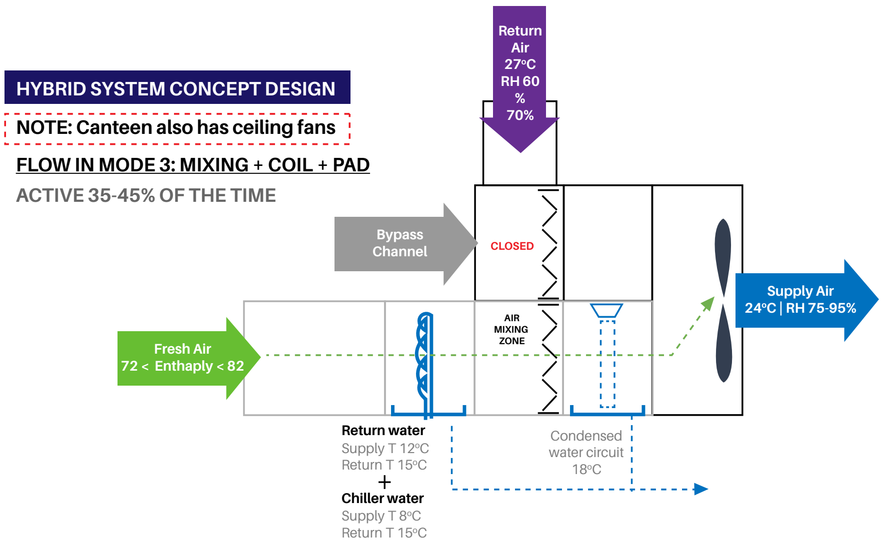



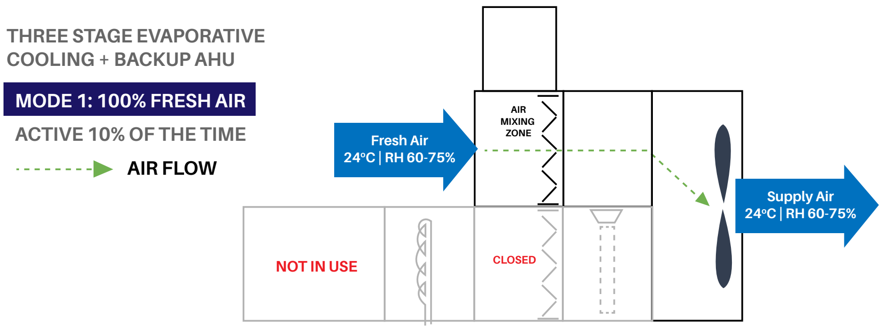
Source: PSA Tuas Maintenance Base

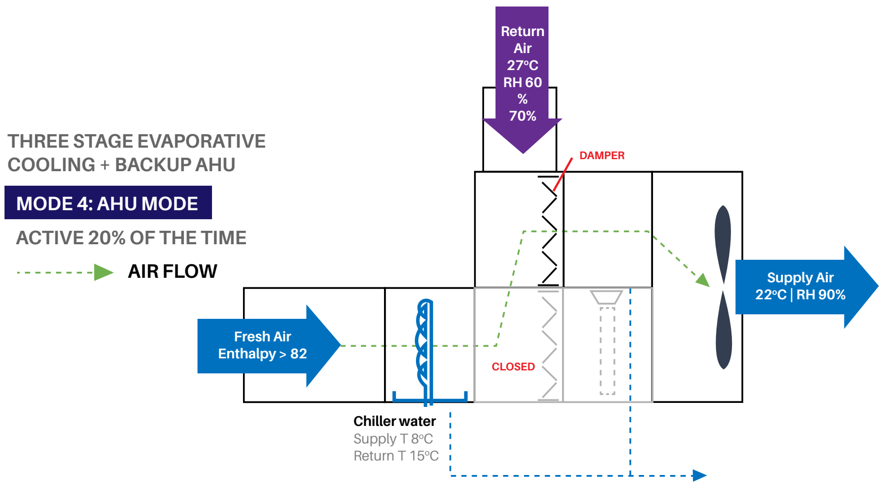
## Case Study on PSA Tuas Maintenance Base

### Hybrid Evaporative Cooling (HEC) System

The HEC replaces conventional PAHU units with an advanced system that operates in three modes: free cooling, evaporative cooling and air handling unit (AHU) mode to provide cooling for its canteen. This optimises energy efficiency by automatically switching between modes, creating a dynamic system that cools efficiently based on external conditions. For additional energy savings, the system reuses return chilled water – cool water that is already circulating in the system – instead of having to maintain a constant supply of chilled water.




Source: BCA's Best-in-Class Super Low Energy Building Series on PSA Tuas Maintenance Base

## Key Area #3:

### Offsetting Energy demand through Energy Recovery Systems

Increasingly, energy recovery technologies capture and reuse heat/cooling energy from exhaust air streams that would otherwise be vented out into the atmosphere to pre-heat/pre-cool incoming fresh air or water. Some examples include:

- In commercial kitchens, hot exhaust air can be passed through a heat recovery system, where its thermal energy is transferred to pre-heat incoming fresh water for hot water systems.
- In buildings, cooling energy from conditioned indoor air that is cooler than outdoor air is reused to pre-cool the fresh air intake.

The technology can be implemented through various methods including air-to-air heat exchangers, enthalpy wheels, or run-around coils, each suited to different applications and building types. Such solutions will increasingly form an important component in energy-efficient building design by reusing heat or cool air that would otherwise be wasted.

### Case Study on DBS Newton Green

#### Energy Recovery Ventilator (ERV)

DBS Newton Green, being an existing building, inherits some constraints over selecting new efficient technologies for retrofit. ERV was considered for this specific project as it has flexibility in unit size as well as unit mounting options within the building. The ERV system is a graphene heat exchanger with high heat exchange efficiency of more than 75% coupled with High-Efficiency Particulate Air (HEPA) filters and Electronically Commutated Motor (ECM) fans with low noise levels. The product recovers the total energy from the return air and has high heat exchange rate when the return and supply air are passed through the Graphene heat exchangers. This reduces the cooling and dehumidification load of fresh air ventilation by more than 75%, as the system can recover both sensible and latent heat by the same efficiency.


Source: DBS Bank

**Key Area #4:**

## Building Optimisation Systems with AI Control

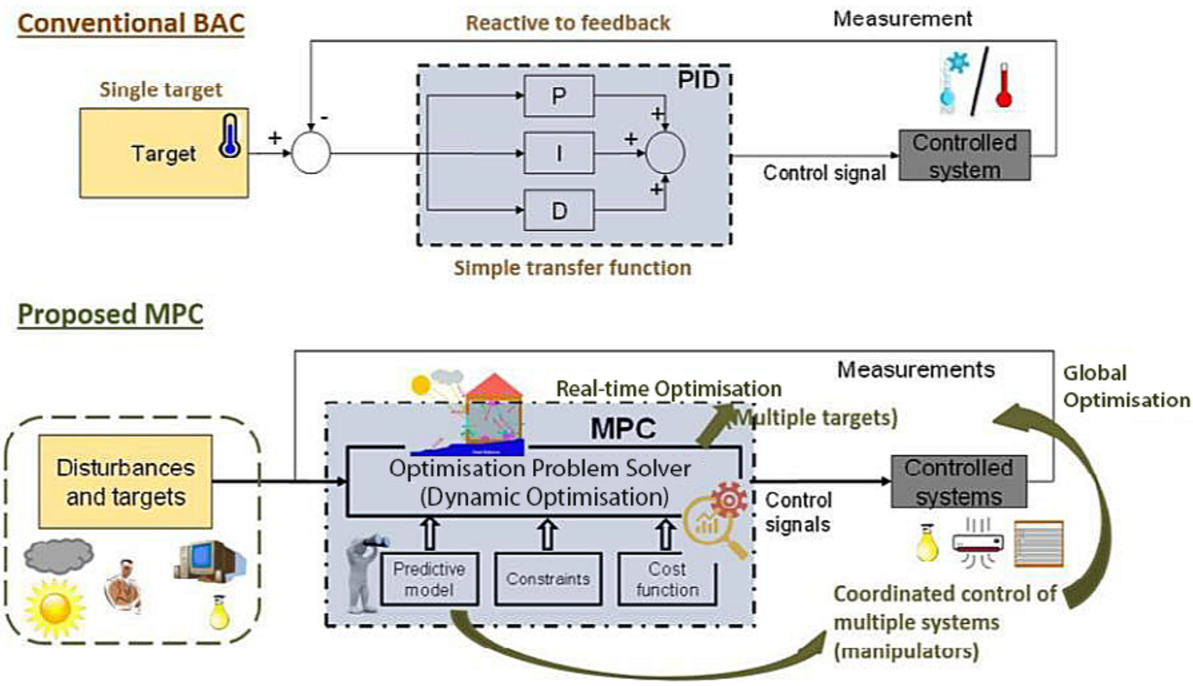
Most large buildings use Building Energy Management Systems (BEMS) for basic monitoring and control of building systems such as air-conditioning, lighting, and security systems. With the rapid proliferation of AI, machine learning (ML), sensors, and data-driven building control solutions, there is potential to yield higher building energy savings through seamless integration and optimisation of building systems. By leveraging these advanced technologies and strategies, buildings can become more integrated, intelligent, efficient, and responsive to both occupant needs and energy constraints.

### Case Study on PSA Tuas Terminal Maintenance Base / Jurong Town Hall

#### Model Predictive Control (MPC)

MPC employs a building model to perform optimal, predictive and coordinated control of various building service systems such as air-conditioning and mechanical ventilation, lighting (automated dimming) and shading (automated blinds and electrochromic windows), etc. MPC technology can be applied to various types of buildings (offices, shopping malls, hotels, institutional, etc.) with centralised building management systems (BMS). It could work as a plug-in module to the existing BMS as a supervisory control layer or as a standalone BMS to the building. The technology also equips buildings with the level of intelligence necessary for cluster/district level control with demand side management (DSM) capabilities for future adaptation of building digitalisation and building-grid integration.

This technology could deliver more than 20% energy savings as compared to conventional building automation and control systems while providing improved human comfort. NRGSense Technologies Pte Ltd, a start-up from NTU, was set up to bring the innovation to market. Some of the buildings adopted are Jurong Town Hall, PSA Tuas Terminal Maintenance Base, Ng Teng Fong General Hospital, Changi T1 and Beibu Gulf Port HQ, Nanning, China.




Source: BCA's Translating Research & Innovation in the Built Environment publication

Key Area #5:

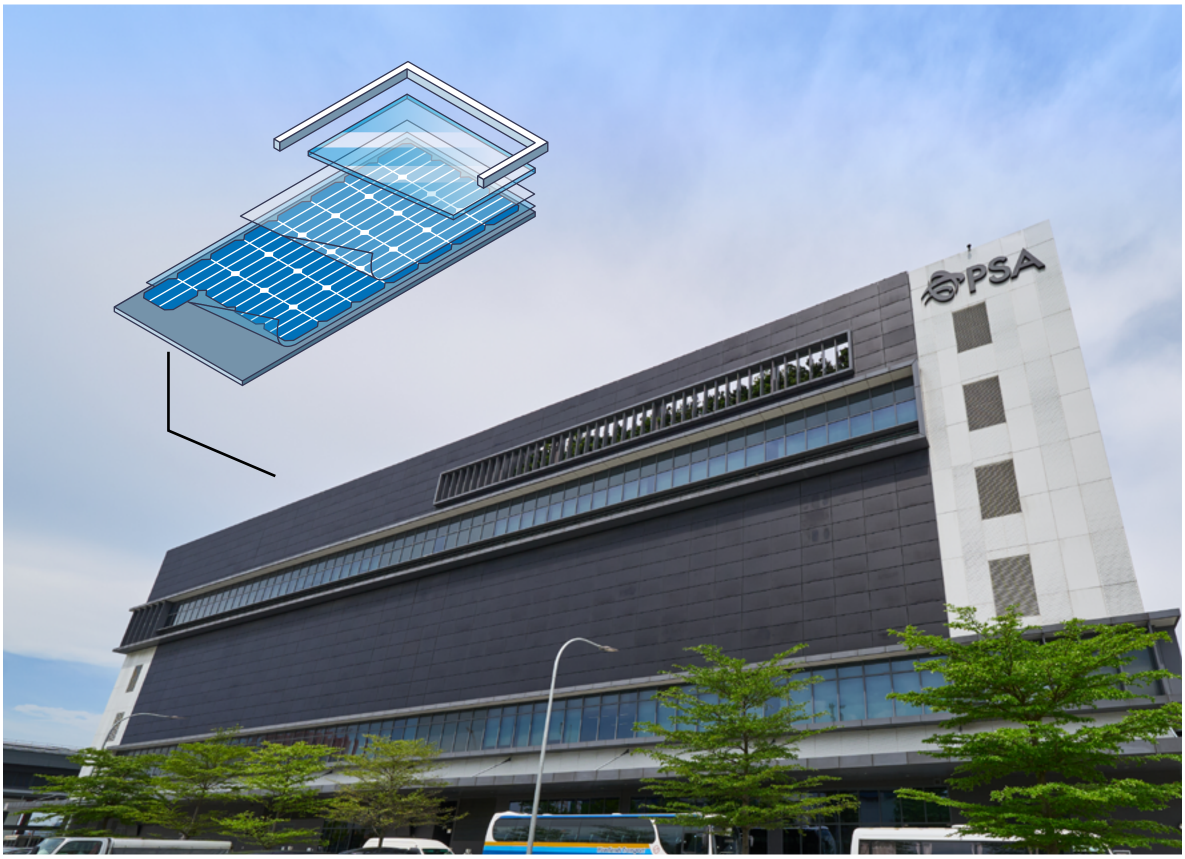
## Integration of next-gen renewable and green energy source

While solar energy remains the most viable renewable energy source for buildings in Singapore, limited roof space constrains the potential for on-site photovoltaic (PV) deployments. This limitation presents a critical challenge in offsetting building energy consumption and achieving net-zero status. Consequently, there is an urgent need to explore and develop alternative renewable and clean energy solutions that can be seamlessly integrated into building designs. Advanced building-integrated photovoltaics and other on-site energy generation types such as green hydrogen applications or micro-wind turbines can diversify Singapore's clean energy portfolio for buildings.

### Case Study on PSA Tuas Maintenance Base

#### Building Attached Photovoltaic System (BAPV)

Although the building has limited roof space, its façade offers a valuable opportunity to generate renewable energy through photovoltaic systems. The absence of shading from the surrounding area makes this an ideal location for installation. This product is not merely an add-on like rooftop solar panels. The BAPV also serves a dual function as an external cladding that can be maintained in the same ways as regular façade cladding while seamlessly generating renewable energy.




Source: BCA's Best-in-Class Super Low Energy Building Series on PSA Tuas Maintenance Base

Key Area #6:

## From Individual to Multi-Building Solutions

While optimising buildings individually will continue to be a baseline strategy to decarbonise the building sector, further optimisation can be unlocked through multi-building or district-level solutions.

Advanced technology can become more viable at scale economically, offering better returns on investment and more efficient operation than individual building installations. Examples include:

- Centralised cooling systems (CCS) such as district cooling can provide comparable efficiency to in-situ cooling systems while reducing the need for each building to own and operate a plant room. Such scale of operation creates opportunities for renewable energy integration, offering further carbon savings.
- Excess heat from one building (such as data centres or commercial kitchens) can be captured and utilised by neighbouring buildings with heating needs.
- Better load management becomes possible when diverse building types with different usage patterns are connected and optimised through district management solutions.

Traditionally, district solutions have only been considered for greenfield projects where provisions can be easily made in the design to allow the integration of building services. Recent developments have shown the technological and economic case for CCS solutions even at brownfield sites (see Tampines Study). Identifying building clusters with complementary loads and having a suitable demand aggregator will be key to replicating such solutions across the island.

### Case Study on Punggol Digital District (PDD)

#### District Cooling System (DCS)

Boasting a cooling capacity nearing 30,000 refrigeration tonnes, ENGIE Southeast Asia's (ENGIE) DCS at Punggol Digital District (PDD) represents an advancement in cooling infrastructure. The DCS will streamline operations and enhance energy efficiency within the district. Located at an underground central plant, the DCS distributes chilled water via an intricate network of pipes, transfer stations, and secondary networks within the district's buildings. The performance of this closed-loop circulation of chilled water is enhanced through energy storage systems, further balancing the production and consumption of energy. The entire cooling process is monitored from a centralised control room, ensuring optimal operational efficiency and performance.

Under the Design, Build, Own and Operate (DBOO) model with JTC, ENGIE manages the entire project life cycle and optimises the system from the outset for energy efficiency, reliability, and ease of maintenance. One engineering innovation was ENGIE's decision to install the chilled water pipes at a 45-degree angle—an unconventional approach compared to standard 90-degree layouts. This smart routing significantly reduced frictional loss, allowing the system to maintain pressure without the need for additional booster pumps.

*> Continue on next page..*

The DCS eliminates the need for individual buildings to maintain their cooling facilities. In doing so, the system can reduce carbon emissions by an estimated 3,700 tonnes per year and achieve up to 30% reduction in energy consumption compared to standard commercial buildings. Furthermore, individual building owners and businesses enjoy shared cost savings, whether in the form of plant room or electricity grid expenses. By going underground, the DCS also frees up roof-top space conventionally occupied by cooling systems, thus facilitating the creation of green pockets and allowing for more renewable energy initiatives, such as the installation of roof-top solar panels within the 50-hectare district.


Source: ENGIE Southeast Asia

## Case Study on Tampines (SP Group)

### Distributed District Cooling Network

SP Group (SP) has commenced operations for a distributed district cooling (DDC) network at Tampines, making it Singapore's first town centre retrofitted with this sustainable cooling solution. The DDC network is specially engineered for brownfield developments to provide the same cooling comfort while enhancing energy efficiency and lowering carbon emissions. Seven existing buildings across the town centre are connected to the network – Century Square, CPF Tampines Building, Income At Tampines Junction, OCBC Tampines Centre 2, Our Tampines Hub, Tampines Mall and Tampines 1.

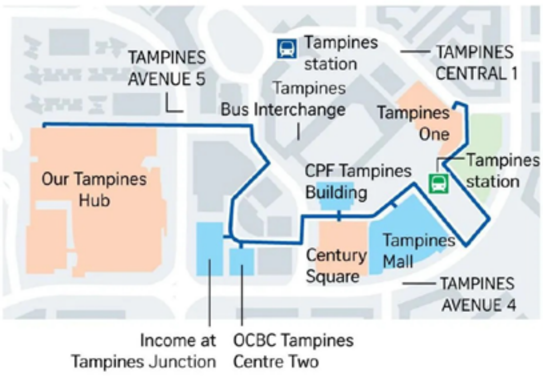
The network will strengthen Tampines Eco Town's ambitions by helping the town centre reduce its carbon emissions by 1,000 tonnes annually – equivalent to removing 910 cars off our roads. It will also achieve energy savings of more than 2,300,000 kilowatt-hours (kWh) annually, which can power more than 710 three-room HDB households for a year.

**Seven Tampines buildings to be part of distributed district cooling network**

Instead of constructing a new centralised cooling plant, a distributed cooling system will utilise existing chiller plants in multiple buildings within the network to supply chilled water for cooling needs.

This approach enhances efficiency through economies of scale while reducing carbon emissions and saving energy.

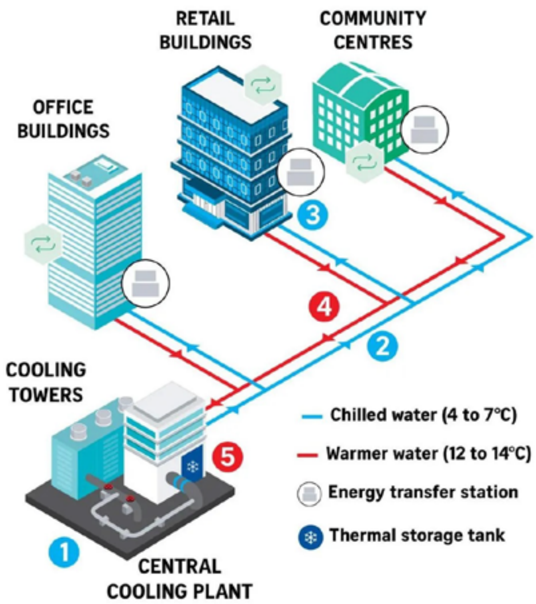
**Buildings with excess cooling capacity to supply chilled water** | **Buildings receiving chilled water** | **Underground pipes trasporting chilled water**




Source: SP Group

**District Cooling System**

Imagine a giant air-conditioner that can cool an entire district of buildings, rather than just individual buildings – but greener and more energy-efficient. How does it work?




1. Chilled water is generated in a central cooling plant.
2. A closed-loop network of underground insulated pipes distributes the chilled water to each building.
3. Energy transfer stations within each building circulate the cold energy from the network into the building's air-conditioning system, which dehumidifies and cools the air.
4. The warmer water is then circulated to the cooling plant, via the return pipes, to be chilled again. The whole process repeats.
5. Thermal storage tanks, are designed to store cold energy in the form of ice or chilled water. Thermal storage tanks help to regulate cooling demand and provide resilience. Not all district cooling system plants deploy thermal storage tanks.

Source: The Straits Times

# EMBODIED CARBON REDUCTION

**What is embodied carbon?**
Embodied carbon refers to the carbon emissions released throughout the manufacturing, transport, construction, maintenance, and disposal of building materials.

**Unlocking Embodied Carbon Reduction Across the Project Life Cycle**
Unlike operational carbon, which is generated from day-to-day operations of a building, embodied carbon is locked in once construction completes. Therefore, early intervention is critical to minimise a building's total carbon footprint as the most significant opportunity for minimising a building's overall carbon footprint arises during the initial project phases.

To effectively reduce embodied carbon, strategies must be integrated throughout the entire building life cycle. These strategies include:

1. Adopting carbon avoidance design by building less, light and efficient
2. Optimising material usage through low-carbon design
3. Implementing efficient construction technologies that minimise waste, planning for reuse and improving productivity
4. Offsetting within the project, organisational boundary or through verified offset schemes, where appropriate

These strategies are supported by digital tools that enable building life cycle accounting.

## Embodied Carbon Reduction Strategies

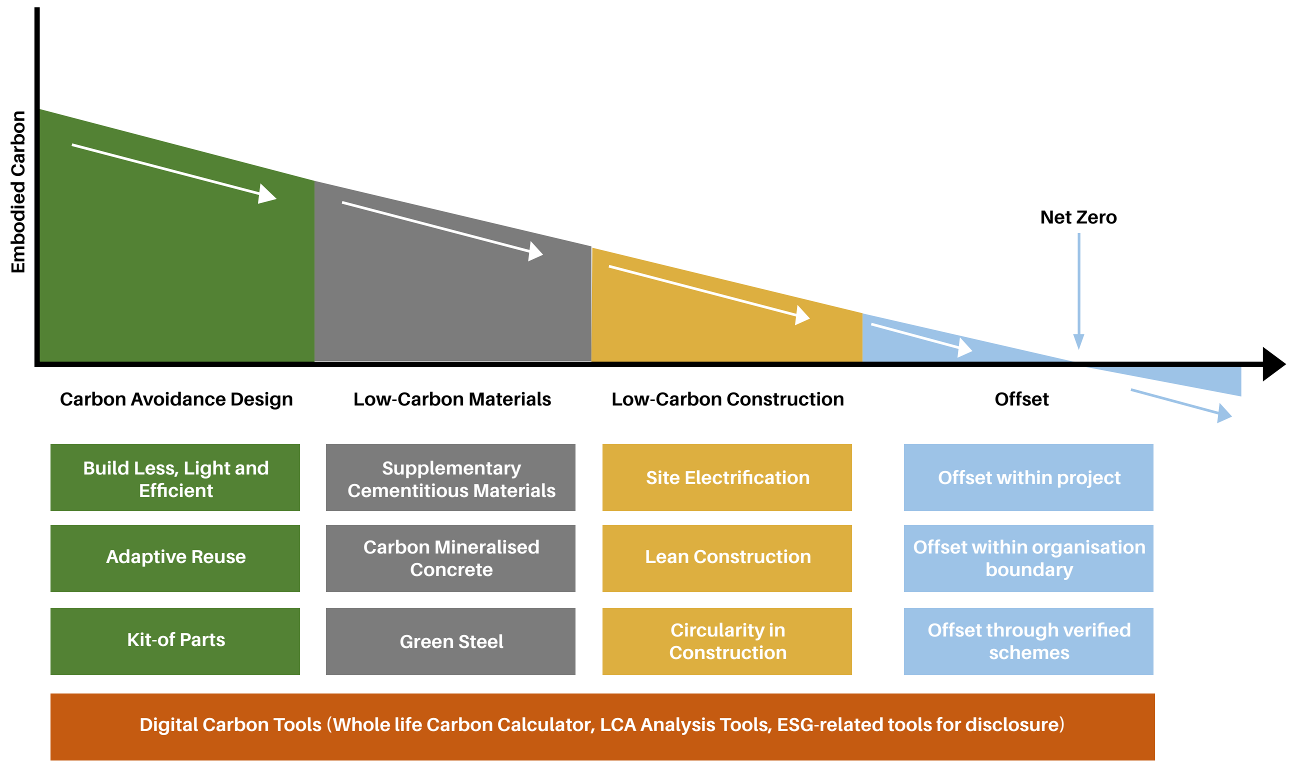



Figure 5: Embodied Carbon Reduction Strategies

Together, these approaches provide a robust and scalable framework for reducing embodied carbon emissions across the BE.

Key Area #1:

## Carbon Avoidance Approach through Building Less, Light and Efficient

Carbon avoidance represents a fundamental shift in how we approach building development, emphasising three key strategies: Build Less through Adaptive Reuse, Build Light and Efficient, and adopting Kit-of-parts methodology.

The Build Less strategy challenges conventional development assumptions by prioritising the evaluation of existing structures. At project inception, this requires rigorous assessment through retrofit feasibility studies and carbon optioneering. When weighing options between adaptive reuse and redevelopment, carbon considerations inform decision makers about structural retention, material selection, and systems integration. This comprehensive approach aligns carbon reduction with broader project goals, including financial performance, operational efficiency, and how does building less, building light etc contribute to occupant well-being.

### Case Study on Adaptive Reuse for SLA State Properties

The Singapore Land Authority (SLA) is embracing adaptive reuse to revitalise vacant state-owned sites while tapping their potential for community, social and economic use.

A parcellated site from the former Loyang Primary School site now houses Vidacity—a vibrant hub for sustainability and agri-tech innovation. Founded on the belief that real change stems from collective action, Vidacity brings together startups, businesses, and the community to co-create solutions for a greener future.

New Bahru represents another successful adaptive reuse project that has transformed the former Nan Chiau High School compound in River Valley into a dynamic lifestyle destination. The development is now a trendsetting hub, hosting over 40 local businesses, and demonstrating effective repurposing of state properties while preserving the site's architectural heritage.

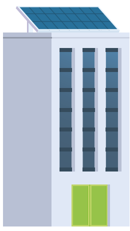
Source: Singapore Land Authority

## Case Study on Extensive Asset Enhancement Initiative (AEI) for Singapore Land Tower

Singapore Land Tower, originally completed in 1982, is a commercial office building located in Raffles Place, the heart of Singapore's central business district. The project demonstrates how retrofitting and asset enhancement can deliver significant carbon savings while revitalising the building's ageing infrastructure. Rather than opting to demolish-and-rebuild, Singapore Land Group (SingLand) undertook an extensive AEI that preserved the existing structure and avoided over 50% of embodied carbon emissions compared to redevelopment.

This project is a compelling example of how property owners can extend the lifespan of existing buildings and significantly reduce embodied carbon emissions, while achieving high environmental and commercial value.

In recognition of its carbon performance and green features, Singapore Land Tower was awarded Winner in the Carbon Performance category of the SGBC-BCA Leadership in Sustainability Awards 2024.



Preserved the existing structure and avoided over

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of embodied carbon emissions compared to redevelopment.

Source: Singapore Land Group (SingLand)

Where new construction proves necessary, the Build Light and Efficient approach emphasises structural optimisation to reduce material usage while maintaining performance standards. A significant opportunity lies in the reuse of existing structural elements, particularly foundation systems such as bored piles.

## Case Study on Reuse of Existing Bored Piles of former CPF building (CapitaSky)

Capitasky is the first redevelopment commercial project in Singapore's CBD to achieve 100% reuse of existing bored piles. This engineering feat saved 8,400 tonnes of concrete contributing to a 37% reduction in carbon emissions, marking a milestone in sustainable construction.

With only 42 new bored piles added, this achievement demonstrates advanced engineering and sustainable design. The former CPF building, which sat on 186 bored piles and a substantial cellular raft foundation supporting two deep basements, presented challenges due to its location near other skyscrapers and underground railway tunnels along Robinson Road. Additionally, being partially within the LTA Railway First Reserve required special clearance for engineering tasks.

The professional engineers and project team ensured the safety and reliability of reusing the piles through meticulous site investigations. These investigations included confirming the depth of the piles compared with original plans, checking the size and strength of existing piles, and monitoring the performance of the piles that support the new development. DfMA and Integrated Digital Delivery (IDD) are utilised to simplify the design and construction processes, ensuring efficiency and precision.

Source: P&T Consultants Pte Ltd

The Kit-of-Parts methodology is a design approach comprising a collection of pre-defined and engineered building components that are manufactured off-site and allow assembly in a multitude of ways on-site to achieve a variety of building products.

This approach also allows stakeholders to establish their sustainability targets at the onset derived from the embedded data (e.g. embodied carbon, resource efficiency) in the digital model to facilitate continuous improvement across projects over time.

By shifting the bulk of construction on-site to a factory setting, the following could be achieved:

### I. Reduction in material wastage

Kit-of-parts approach would require the accurate computation of the number of building components needed to assemble a building, hence establishing a certainty in quantity and sizes of components for factory production with a high level of precision. This would then translate to a more efficient automated manufacturing process with reduced material wastage from trimming the building components to the required size and dimension. Additionally, with visibility on the inventory stock vis-à-vis project schedule, better planning of the delivery of components to site will reduce carbon emissions from transportation.

### II. Disassembly for circularity

While the Kit-of-Parts approach emphasises the development of a library of building components to achieve efficient design and assembly of building, it also considers the recyclability of building components. This enables future disassembly of building parts to facilitate relocation or adaptation for other uses, thus supporting the transition towards a circular economy to maximise reuse while minimising environmental impact.

Building structure can be designed for disassembly by following key principles below:

i. Prioritise reversible dry mechanical connections (such as screws and bolts) over wet connections wherever structurally feasible, enabling future separation without material damage
ii. Design for efficient and economical disassembly processes through standardised components and accessible connection points
iii. Maintain comprehensive building information that tracks material quantities, specifications, locations, and connection details throughout the building's life cycle

By incorporating these deconstruction considerations into building design and planning for end-of-life scenarios, a higher proportion of materials can be reclaimed and reused. This ensures building structures, materials, products, and components remain within the circular economy rather than becoming waste, while potentially reducing future demolition costs and environmental impact.

Looking ahead, design for disassembly could be augmented through emerging technologies:

i. AI-powered generative design tools could propose structural designs and modular configurations that optimise both disassembly potential and cost efficiency. These tools could simulate various end-of-life scenarios and recommend the most sustainable and economical design solutions.
ii. Advanced technologies like computer vision, drones, and embedded sensors could revolutionise material assessment by identifying and classifying materials (e.g., volume and grade of concrete, metals) in existing structures. This technological integration could enable precise estimation of remaining material lifespan and residual value, facilitating efficient material sourcing from deconstructed buildings for new construction projects.

**Key Area #2:**

## Design and Procurement of Low-Carbon Materials (e.g. Concrete, Green Steel and MET)

Concrete is the most used building material worldwide and contributes to approximately 7-8% of the world's total $CO_2$ emissions. Its carbon footprint stems from its energy-intensive production process and raw ingredients used for cement-making.

Since concrete is the main building material, there are two primary approaches to reduce the carbon footprint in a building – (1) Replacing conventional concrete with low-carbon concrete or (2) Using alternative materials such as green steel and MET.

### Low Carbon Concrete

There are three general avenues to produce low carbon concrete:

i. Using additives (such as chemical admixtures or materials like steel fibre or geopolymer materials) that allows a reduction in the amount of cement needed to achieve concrete with comparable strength
ii. Direct replacement of conventional materials for concrete production with alternative materials
iii. Utilising carbon dioxide in the process of concrete production.

Although cement makes up about 20% of concrete by weight, the production of cement contributes 70% to 90% of the embodied carbon of concrete. Hence, reducing cement usage offers the greatest potential for lowering concrete's carbon footprint. There are already commercially available solutions in the market that can reduce the carbon footprint of concrete.

### Avenues of Reducing the Carbon Footprint of Reinforced Concrete

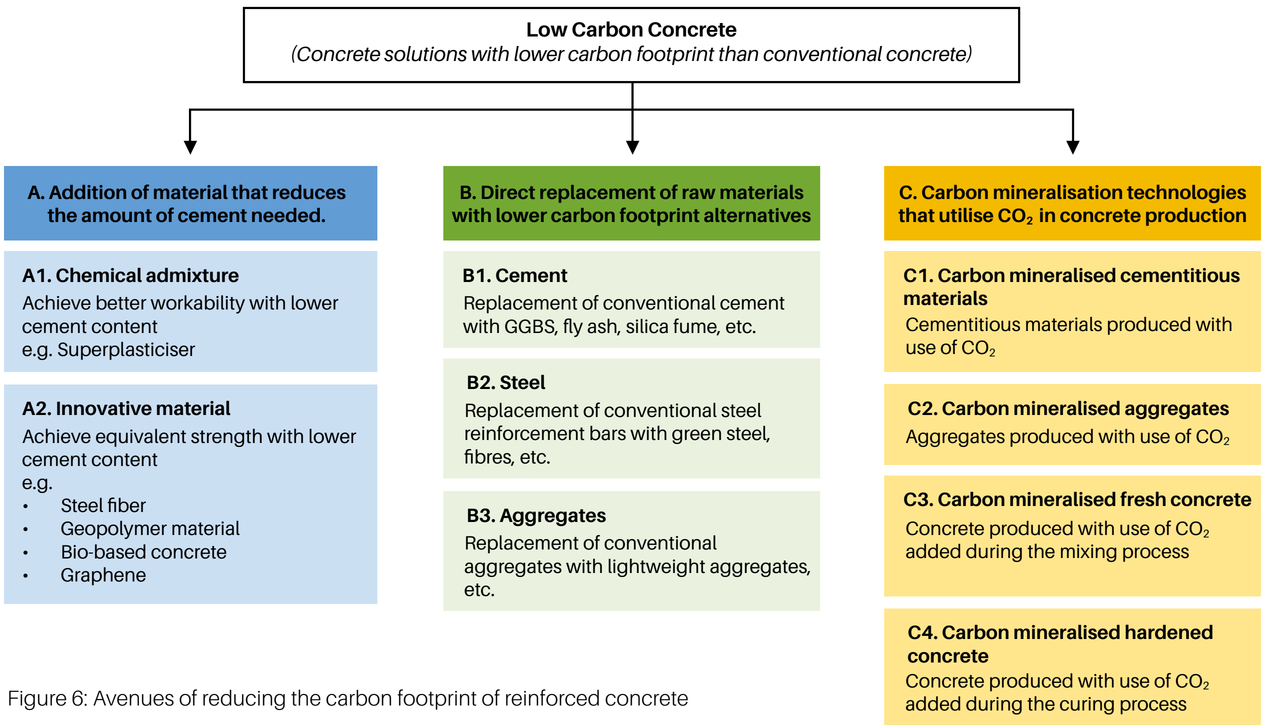



Figure 6: Avenues of reducing the carbon footprint of reinforced concrete

Source: BCA

Beyond reducing the carbon footprint of concrete, utilising carbon dioxide in the production process of concrete presents a pathway to carbon negativity. This is achieved through mineralising carbon dioxide and using mineralised products to replace conventional ingredients in concrete, effectively sequestrating and enhancing absorption of carbon dioxide during the concrete life cycle.

Mineralisation can be carried out at different stages of the concrete production process: during the cement production, aggregates production, concrete mixing, and the curing process. Carbon mineralised concrete, which incorporates captured carbon dioxide, is one approach being developed to achieve carbon negativity.

### Case Study on Carbon Mineralised Concrete (CMC)

The Geneo, a life sciences and innovation cluster in Singapore Science Park demonstrated large-scale implementation of CMC. CMC was extensively used in the building's superstructure, comprising 44% of total concrete volume. The technology was applied to critical structural elements including vertical components (columns and core walls) and horizontal elements (post-tensioned beams and slabs). This significant adoption of CMC resulted in an estimated reduction of 3,400 tons $CO_2e$ in embodied carbon emissions, representing a 28% decrease compared to conventional concrete construction.

Source: BCA Award 2024

Reduction of

**3,400** tons $CO_2e$

in embodied carbon emissions, representing a 28% decrease compared to conventional concrete construction.

Beyond commercially available solutions, there are plans for potential R&I efforts to develop $CO_2$ sequestration technologies such as developing Geopolymer Concrete that has $CO_2$ sequestration potential and Carbon Mineralised Aggregates using local waste materials, for construction and building applications.

#### Geopolymer Concrete with $CO_2$ sequestration

Geopolymer concrete, produced using geopolymer cement, is emerging as an eco-friendly construction solution.

Geopolymer cement utilises materials such as like fly ash, slag, or other industrial by-products, and hence has lower carbon footprint than Ordinary Portland Cement (OPC). Research has shown that geopolymer concrete has the potential to be able to sequester $CO_2$, with further technological advancement.

If such potential is realised, the innovative concrete offers multiple-fold climate benefits: (i) utilisation of industrial waste, (ii) reduction in the demand of OPC, and (iii) the capability to sequester $CO_2$ and contribute to the $CO_2$ emission targets.

## Carbon Mineralised Aggregates

There are multiple streams of waste materials, with some that can potentially be upcycled into carbon sinks.

Technological advancements have developed capabilities with the potential to bind captured carbon dioxide with waste materials, to derive greater value.

Generally termed carbon mineralised aggregates, the waste materials are binded with $CO_2$ through mineralisation and utilised in concrete production to produce low carbon concrete.

If such potential is realised, the innovative concrete offers multiple-fold climate benefits: (i) utilisation of industrial waste, and (ii) the capability to sequester $CO_2$ and contribute to the $CO_2$ emission targets.

### Case Study on Carbon Mineralised Aggregates

The notable feature of V-ZUG's six-storey Zephyr Ost factory is its use of carbon mineralised concrete, developed in partnership with a climate technology firm. This process captures biogenic $CO_2$ and injects it into recycled concrete from demolition, storing the carbon within the building material.

The construction used 4,200 cubic metres of carbon mineralised aggregates, resulting in measurable environmental benefits. The project reduced $CO_2$ emissions by 71 tonnes compared to conventional construction methods, with 21 tonnes saved through the carbonation process—equivalent to the annual $CO_2$ absorption of 3,500 trees.

The Zephyr Ost facility demonstrates a practical application of sustainable construction technologies, showing how carbon mineralised concrete can be implemented in commercial projects.

Source: https://www.vzug.com/sg/en/sustainability/a-workplace-with-a-vision
https://www.vzug.com/sg/en/stories/the-factory-goes-vertical

Locally, there are ongoing R&I efforts in two key $CO_2$ sequestration technologies for Singapore's built environment: Geopolymer Concrete with $CO_2$ sequestration and Carbon Mineralised Aggregates, which could be used for construction and building applications.

## Future Integration with 3D Concrete Printing

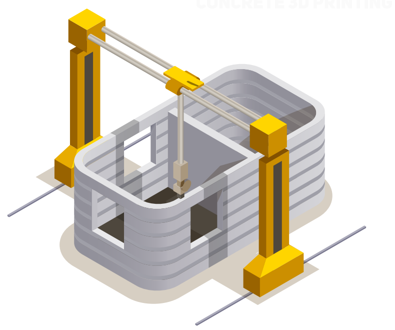
The advances in 3D concrete printing (3DCP) enable the production of geometrically complex, custom-designed structures while significantly reducing material waste and accelerating construction timelines. Moreover, the integration of low-carbon concrete technologies into 3DCP adds further benefits, with the potential to reduce both carbon emissions and material costs.

However, incorporating low-carbon materials presents rheological challenges for 3D printing. Supplementary cementitious materials can modify material rheology, potentially affecting the precise flow properties required for successful printing. Similarly, the type and amount of recycled aggregates utilised to reduce carbon emissions must also be balanced against the design requirements for the properties of the printed component to ensure successful printing performance and structural integrity.

To address these challenges, chemical admixtures and nanomaterials such as nanoclay can be used to tune the extrudability and buildability properties. Selection of the appropriate admixture types and dosing is determined through an iterative process of rheological characterisation, trial prints, and hardened-state testing, thus optimising sustainability and performance.

### Case Study on 3D printing

NTU Researchers developed an innovative 3D concrete printing system that simultaneously captures carbon dioxide while improving structural performance. The system connects $CO_2$ pumps and steam jets to a 3D printer, injecting both $CO_2$ and steam into the concrete mix during printing. The $CO_2$ reacts with concrete components and becomes permanently trapped within the material, whilst steam enhances $CO_2$ absorption and improves the structure's properties.



The enhanced concrete showed 50% better printability, making it easier to shape and print efficiently. Structural strength also increased substantially, with compression strength improving by up to 36.8% and bending strength by up to 45.3% compared to conventional 3D printed concrete. Most notably from an environmental perspective, this method absorbed and sequestered 38% more carbon dioxide than traditional 3D printing approaches.

Source: https://www.ntu.edu.sg/news/detail/ntu-singapore-scientists-develop-3d-concrete-printing-method-that-captures-carbon-dioxide

## Green Steel

Steel represents one of the largest contributors to a building's embodied carbon. The iron and steel industry contributes approximately 7-9% of global greenhouse gas emissions. This represents a growing opportunity to optimise upfront carbon emissions after concrete. This is especially critical given the common usage of reinforced concrete in our building structural systems and increasing use of structural steel elements.

Implementing low-carbon steel in construction requires careful consideration of several critical factors throughout the project life cycle. Early supplier engagement is crucial to verify Environmental Product Declarations (EPDs) and validate claims about production methods, particularly regarding recycled content and Electric Arc Furnace (EAF) manufacturing processes.

While EAF technology efficiently processes recycled steel, its capacity to meet global demand is limited by scrap availability. This constraint highlights the need for developing low-carbon methods for virgin iron production. Additionally, project teams must weigh the carbon implications of sourcing decisions, as transportation emissions can significantly impact the total embodied carbon footprint.

Emerging technologies, such as hydrogen-reduced steel and carbon capture methods, offer promising solutions for future steel production. However, their current market availability remains limited, requiring project teams to balance innovation with practical implementation.

### Case Study on Green Steel

Steel production traditionally ranks among the most carbon-intensive industrial processes. Thyssenkrupp, as a major steel manufacturer, faced mounting pressure to decarbonise its operations while maintaining competitive production capabilities in an increasingly climate-conscious market.

Thyssenkrupp transformed their steel production infrastructure by replacing conventional blast furnaces with an advanced hydrogen-based Direct Reduction (DR) plant complemented by electric melting units. This technological shift fundamentally reimagines the steelmaking process by eliminating coal dependency. The new plant is designed for 100% green hydrogen use.

Source: https://www.thyssenkrupp.com/en/newsroom/press-releases/pressdetailpage/thyssenkrupp-is-accelerating-the-green-transformation--decision-taken-on-the-construction-of-germanys-largest-direct-reduction-plant-for-low-co2-steel-146809

Additionally, structural steel presents significant opportunities for salvage and reuse in new applications, owing to its durability and inherent recyclability. BCA is advancing these circular economy principles through initiatives focused on structural steel reuse. The design guide BC1 – 'Design Guide for the Use of Alternative Structural Steel to Eurocode 3', published by BCA in 2008 and updated in 2012 and 2023, currently provides guidance in Section 6 on reused structural steel for Earth Retaining or Stabilising Structures (ERSS).

Moving forward, BCA is exploring opportunities to expand the guidance for structural steel reuse beyond ERSS to include permanent works, supporting the industry's shift towards more sustainability and future readiness (Refer to local case example of Reusing Existing Steel Bridge for Proposed Steel Bridge at Sungei Lanchar and Overseas Case Example on Circular Construction- Holbein Gardens below)

### Case Study on Reusing Existing Steel Bridge for Proposed Steel Bridge at Sungei Lanchar

The potential for reusing existing steel bridges is demonstrated in Land Transport Authority's (LTA) proposed steel bridge at Sungei Lanchar. The reclamation process of the existing steel bridge involved careful dismantling, with particular attention to preserving the structural integrity of each component. After thorough verification of the existing steel on its condition and suitability for reuse, the project team modified the existing steel bridge through trimming to suit the project requirement to achieve a 35-metre span. The modified structure weighs 71 tonnes with pin-roller end connections.

Source: Land Transport Authority

### Holbein Gardens: A Case Study in Circular Construction

In London, the 25,000 sqft Holbein Gardens workplace development demonstrates significant achievements in steel reuse, with 25 tonnes of reclaimed steel incorporated into the construction. This steel was sourced through two channels: from an existing project scheduled for demolition and from reclaimed steel specialist Cleveland Steel and Tubes (CST). The salvaged steel was successfully refabricated for the building's rooftop extension. The environmental impact is substantial - the reuse of steel reduced the embodied carbon by a factor of eight compared to new steel, saving approximately 60 tonnes of embodied carbon. This contributed to achieving an overall building embodied carbon of 267.9kg$CO_2$e/$m^2$, with structural elements accounting for 67.5kg$CO_2$e/$m^2$.

Source: Grosvenor Article on 19 July 2022

## Mass Engineered Timber

MET is an engineered wood product that could replace concrete and steel as an alternative building structural material. MET products include Cross Laminated Timber (CLT) and Glued Laminated Timber (Glulam).

MET must be sourced from sustainably managed forests. The material acts as a carbon sink, with carbon sequestered during tree growth remaining stored throughout the building product's life. Hence, compared to traditional building construction using concrete or steel, MET buildings generally have lower embodied carbon footprint. Other benefits of using MET for building construction include improved construction productivity, quality control and reduced waste and disamenities to surrounding areas.

MET can also be integrated with traditional materials like steel or concrete in hybrid construction. This strategic approach enables architects and engineers to leverage timber's benefits while employing alternative materials where their properties are more advantageous to maximise each material's strengths.

Adoption of MET is determined by the needs of the developer. If MET is used, developers are encouraged to engage experienced professionals in the design of MET buildings to include features that best address and prevent possible downstream issues. Being a biological material, timber would require proper maintenance especially if exposed to weather. Excessive moisture or constant wetting can cause timber, regardless of source or species, to decay over time.

Construction materials including MET used for building works in Singapore are required to meet the performance and objectives prescribed in the Building Control Regulations and other local agencies' requirements (such as fire safety) regardless of the source of supply. MET that comply with the European standards in the Approved Document are deemed to have satisfied the prescribed performance. Additionally, other MET can be used if they meet the prescribed performance and objective requirements. Thus far, majority of MET used for buildings in Singapore have been sourced from European suppliers.

Moving forward, there could potentially be opportunities for timber that are sourced from the region to be used for MET production. Utilising regional MET products could reduce carbon footprint compared to the European sources due to emissions savings from transportation.

### Case Study on Hybrid Mass Engineered Timber: Eunoia Junior College

Eunoia Junior College showcases hybrid MET construction within its 48,000$m^2$ development. The project demonstrates effective integration of traditional and engineered timber materials through two key features: a façade system incorporating Cross Laminated Timber (CLT) with aluminium cladding, and the CREE hybrid slab system - an advanced prefabricated floor structure combining precast concrete slabs with Glued Laminated Timber (Glulam) beams.

The use of the hybrid slab system combines the benefits of reinforced concrete slab and Glulam beams, as vibration is reduced and the structure remains lightweight. Hence, the CREE hybrid slab can be produced in larger panel sizes and their use brings about savings in man-hours during installation. In addition, no skim coat is required for the underside of the CREE panels which further enhances construction productivity.

To meet fire safety requirements, non-combustible vapour barrier boards were used. The board covered the external face of the CLT wall, with aluminium panels cladded over the board as a protective layer against fire and weather. To ensure each floor is compartmentalised, the façade system is separated with cavity/air gap and fire-stop at every level. With the use of CLT for the façade, there was a productivity improvement of more than 30% as compared to using precast concrete walls since the lighter CLT eases installation on site.

In addition, a row of fast response sprinkler heads called deluge fire sprinkler system was also installed. The sprinkler system protects the internal wall in case of any fire incident. The internal face of the CLT is exposed without any cladding or fire protection board.

Source: Eunoia Junior College

Developers play a key role in procurement process to specify low carbon materials. This can be achieved through either prescriptive specification, which mandate the use of specific products, or performance-based specifications, which set carbon performance targets and require collaboration across the design and construction teams to meet them. Developers can refer to the Singapore Green Building Product (SGBP) Certification Scheme on high-impact materials, particularly steel and ready-mixed concrete.

Key Area #3:

## Towards Low-Carbon Construction Sites

While construction phase emissions are relatively small compared to product manufacturing, they remain significant as they directly impact local communities. Construction phase strategies primarily focus on reducing emissions from construction activities and transport while minimising waste.

Most construction equipment currently relies on gas or diesel power, contributing to emissions and poor air quality through on-site combustion. The transition to electrified equipment, such as electric or hydraulic excavators, electric crawler cranes, and battery storage systems, is essential for reducing on-site emissions. Alongside these clean energy initiatives, lean design and construction methodologies are implemented to optimise resource allocation and minimise waste. This includes just-in-time delivery practices to prevent over-ordering of concrete and materials, and DfMA approaches that reduce material waste through standardised components and efficient construction processes.

Looking further ahead, the construction industry's transition to low-carbon operations requires strategic changes in power sources, equipment, and work processes. The transformation will require collaboration between public and private sector partners- Firstly, builders and contractors should reduce their dependence on diesel by increasing access to cleaner energy on-site; and secondly, there needs to be redesigning of work practices around maximising use of this cleaner energy. Additionally, the construction industry should explore maximising on-site renewables generation, adopting cleaner fuels such as hydrogen and biodiesel; and deploying robust energy storage systems for various construction tasks.

These focus areas should be supported by digital solutions that manage the different energy sources available on-site such as smart micro-grids and help contractors and sub-contractors plan their work around battery life and charging through leveraging on IDD for electric construction (see case study on Site Electrification).

Alongside these initiatives, integrated supply chain strategies reduce transport-related emissions through facility consolidation and optimising logistics through streamlined material flows. Companies operating within an integrated construction park would benefit from the improved efficiency in co-locating related activities (see Jurong Port Integrated Supply Chain below).

## Case Study on Site Electrification

Expand Construction, Volvo Construction Equipment and the Energy Research Institute at Nanyang Technological University (ERI@N) carried out a site study comparing use of an electric excavator with that of an equivalent diesel model. This study intended to quantify the benefits of electric construction equipment and was conducted at the NS Square construction site from 1 November to 31 December 2024. Both excavators were used to clean mud from the sheet pile wall.

The electric excavator demonstrated a 64% reduction in $CO_2$ emissions as compared to the diesel counterpart. Noise levels were also significantly lower (77 dB vs. 89 dB), which made for a more pleasant environment for both the operator and nearby pedestrians (worksite is next to a high-footfall area).

Operating costs were also lower over the duration of the study, with SGD 61.95 for electricity charges versus SGD 136.50 spent on diesel, reflecting a 120% cost advantage. The findings suggest strong environmental and economic benefits for electric excavators.

Volvo ECR25 electric compact excavator deployed at NS Square

Volvo ECR25 being used to clean sheet piles at NS Square

Source: Energy Research Institute @ NTU (ERI@N)

### Case Study on Site Electrification

Grand Dunman, a residential development employs the Prefabricated Prefinished Volumetric Construction (PPVC) method - Modules that often contain entire rooms with internal finishes are manufactured off-site in a controlled environment before being delivered and connected on-site. The aim is to improve construction productivity and minimise on-site construction waste.

The project also showcases an innovative shift in construction site power management. Initially dependent on diesel generators consuming 1,140 litres daily at SGD 65,000 monthly and producing 1.2 million kg of annual carbon emissions, the site transformed its operations through battery energy storage systems (BESS). Implemented by China Construction Realty in partnership with Infinity Cube, the BESS solution has reduced diesel generator usage from 21 to 2 units. The technology, which produces 90% less carbon emissions than conventional generators, demonstrates the viable integration of sustainable power solutions in Singapore's construction sector.

This transition achieves significant cost savings while aligning with the industry's carbon reduction goals through cleaner, more efficient power management.


Source: SingHaiyi Group Pte Ltd

### Case Study on Jurong Port- Integrated Supply Chain

Jurong Port's multi-purpose port RMC Ecosystem, which began operations in October 2023, capitalises on the port's existing cement import infrastructure to handle cement, construction aggregates (sand and granite), and steel. By consolidating various construction supply chain facilities including terminals, storage yards, and ready-mixed concrete batching plants into one location, Jurong Port enhances collaboration among BE sector stakeholders while optimising land use and integrating complementary activities. The implementation of conveyor belt systems replaces the need for over one million truck and 216 barge trips annually, thereby saving approximately 23,500 tonnes of $CO_2$ emissions per year.

Future developments, including the proposed expansion of the RMC Ecosystem, Integrated Construction and Prefabrication Hub (ICPH), Steel Ecosystem, and additional Cement Berth will further streamline construction supply chain activities through strategic co-location. These enhancements are projected to potentially deliver an additional 11,400 tonnes of $CO_2$ emissions savings.

| Facility within JP's multi-purpose port | Logistics Savings | Estimated Carbon Reduction Savings ($tCO_2e$) in a year |
|---|---|---|
| RMC Ecosystem | 1 million trips eliminated (Wharf to Aggregate Plots to RMC plants fully via conveyers) | 23,500 |
| ICPH | 0.152 million trips eliminated (Aggregate and cement truck trips removed) | 3,650 |
| Steel Ecosystem | 0.05 million trips eliminated | 1,176 |
| Cement Terminal | 0.275 million trips eliminated (Wharf to Silos via Conveyers) | 6,600 |

Data from Jurong Port

Key Area #4:

## Circularity in Construction

Singapore currently utilises the DIN 91484 guidance for selective demolition to enable the recovery of high-value materials from C&D waste. While Singapore recycles an estimated 90% of C&D waste, the majority of the recycled materials are of low-value and predominantly used as backfill material.

The current recycling process in Singapore utilises a crushing and dry screening method that crushes the C&D debris into different sized aggregates. Without processing and washing, these recycled aggregates, which have adhered cement paste, will result in concrete products with low structural performance, limiting their use to non-structural purposes or lightly-loaded structures. Currently, the use of recycled aggregates for non-structural purposes is more commonplace.

Using recycled materials as opposed to new/virgin materials reduces resource extraction as well as embodied emissions. For example, it has been estimated that the $CO_2$ emissions of recycled aggregates are around 15% lower compared to virgin aggregates[5].

Moving forward, to minimise waste going to our landfill, maximise resource efficiency, and reduce environmental impact from our BE, demolished materials should be upcycled into higher value products. For example, with proper waste recovery and processing, demolished concrete can be upcycled into clean recycled aggregates, clean sand and recycled concrete paste, to be utilised in new batches of structural concrete.

With the adoption of alternative recycling technologies, high-value building materials can be recovered from C&D waste for more widespread use in structural concrete applications, tapping into the full circularity of building materials (refer to case study on Concrete Circularity). Some alternative recycling methods include:

1. Wet processing, which involves high-pressure washing and abrasion systems to remove adhered cement paste and fine contaminants from crushed concrete debris. This allows the separation of concrete debris into its original constituents, leaving behind clean recycled aggregates.
2. Electrodynamic fragmentation, which utilises short, high-energy electrical pulses while the debris are submerged in water, generating shockwaves that cause the material to fracture selectively along the boundaries of different constituents, such as between the cement paste and aggregates. This results in the production of clean aggregates that are of higher quality.

Besides supporting improvements in our waste processing infrastructure to enable these alternative waste recycling capabilities, efforts such as the development and adoption of material passports can also contribute to carbon accounting and future life cycle assessments (refer to case study on Material Passports). Material passports document the type, quantity, composition, and condition of materials in a building, helping to increase transparency of a material's origin and its properties across the value chain, which will enable future owners or contractors to identify components and materials that can be reused or recycled.

[5] The Concrete Centre, "Specifying Sustainable Concrete – Understanding the role of constituent materials."

### Case Study on Concrete Circularity

Heidelberg Materials had commissioned a new recycling plant in Katowice, Poland, in 2024, to fully recycle demolished concrete. The first-of-its-kind facility enables sophisticated separation and sorting capabilities to fully recycle demolished concrete and substitute virgin materials in concrete production. With a capacity of up to 100 tonnes of concrete per hour, Heidelberg Materials is the first company in the industry to introduce high-quality, selective concrete separation at this scale.

As part of the company's patented ReConcrete process, demolished concrete is broken down into its original constituents through a newly designed, proprietary crushing mechanism. The fractions obtained include sand and gravel of the highest quality, equivalent to virgin raw materials. Recycled concrete paste (RCP) is the finest fraction of the separation process, which can be either used as an alternative raw material for clinker production replacing limestone and reducing $CO_2$ emissions or as a secondary cementitious material.

Source: https://www.heidelbergmaterials.com/en/pr-2024-07-25

### Case Study on Material Passports

The Amsterdam Metropolitan Area (AMA) has started a material passports pilot project to support the regional circular economy. The municipalities and provinces within the AMA will each be offered a material passport for each of their buildings.

The documentation that material passports provide make materials easier to recover and reuse. Buildings, thus, become documented 'storage units' of materials. In addition, circular and financial information flows are linked, thus revealing the historical, current and future value of materials, products, elements, and hence, the building itself. This provides users insights into the material and financial value of their related real estate.

By implementing and applying material passports, government authorities in Amsterdam are taking an essential step towards supporting circular construction and demolition practices.

Source: https://madaster.com/inspiration/amsterdam-metropolitan-area-uses-material-passports-to-boost-the-circular-economy-in-the-region/

## Key Area #5:
## Deploying Digital Tools for Design Optimisation Across Building Life Cycle

Digital tools play a fundamental role in enabling stakeholders to quantify and understand their building's carbon intensity throughout its building life cycle. Through carbon calculators, stakeholders can identify high carbon emissions from cradle to grave-encompassing material sourcing and construction through to operation, demolition, and disposal.

This data-driven approach informs critical design decisions, allowing stakeholders to target areas with significant potential for carbon reduction during the design phase. These insights enable stakeholders to optimise architectural and structural designs, while guiding the selection of more efficient mechanical and electrical equipment for reduced carbon impact.

**Tool: Singapore Building Carbon Calculator (SBCC)**

To encourage the adoption of low-carbon design and construction materials, BCA, in collaboration with JTC, SGBC, and NUS-ESI, developed the Singapore Building Carbon Calculator (SBCC). This integrated platform enables industry stakeholders to calculate and manage embodied carbon emissions across both building structures and mechanical and electrical components.

While many international carbon calculators exist, they often rely on regional averaged data, reducing their relevance for Singapore-based projects. To address this, the SBCC integrates the Building Embodied Carbon Calculator (BECC) and the Mechanical & Electrical Carbon Calculator (MECC)—both built with localised datasets. This ensures more accurate carbon assessments and empowers project teams to make informed material choices that support decarbonisation goals and reduce the carbon footprint of construction projects.

Source: https://www.sgbc.sg/carbon-resources/


Looking ahead, R&I efforts are shifting towards understanding carbon impacts at broader district and industry levels. District level carbon accounting provides a comprehensive approach to measuring and managing carbon emissions across multiple buildings and shared infrastructure within a defined area. This method enables the evaluation of collective carbon impacts and synergistic opportunities that may be overlooked when assessing buildings in isolation.

The district-wide perspective enables stakeholders to optimise shared resources and infrastructure, including district cooling systems and renewable energy installations. It creates opportunities for circular economy practices through waste heat recovery and material reuse between facilities. It establishes a systematic and clearer decarbonisation pathway for various urban sectors, enhancing the ability to coordinate and implement effective district-wide carbon reduction strategies. Beyond initial design optimisation, AI-driven agentic solutions are enabling real-time operational carbon management through intelligent ACMV optimisation across airside and waterside systems, continuous emissions monitoring, and automated carbon reporting.

# NEXT STEPS

The decarbonisation of Singapore's BE sector requires sustained commitment and collaborative effort across the entire value chain— comprising developers, building owners, architects, engineers, contractors, suppliers, and facility managers. Implementation focuses on three strategies:

1. Accelerating the adoption of established local solutions,
2. Facilitating the implementation of proven international technologies,
3. Driving R&I to address capability gaps

Supporting these efforts are enabling platforms such as funding support through various programmes, technical infrastructure for validation and compliance and knowledge-sharing mechanisms. This ecosystem facilitates innovation to accelerate the adoption of decarbonisation solutions across the industry.

# Annex A - Matrix for Categorisation of Solutions

| Technology Readiness Level (TRL) | Description |
|---|---|
| TRL 1-3 | Basic research and concept proofing phase. |
| TRL 4-6 | Validation and demonstration phase. |
| TRL 7-9 | Deployment phase (solutions in the market). |

| Impact | Operational Carbon | Embodied Carbon[6] |
|---|---|---|
| High | Up to 30% energy reduction over comparable existing best-in-class solutions. | Up to 30% reduction in embodied carbon emissions comparable to conventional system. |
| Significantly High | >30% energy reduction over comparable existing best-in-class solutions. | >30% reduction in embodied carbon emissions comparable to conventional system. |

| Market Adoption | Description |
|---|---|
| Limited Adoption (R&D/Pilots) | Solution not adopted in the market or still undergoing pilot testing/demonstration phase. |
| Niche Adoption | Solution has some market adoption locally but confined to specific typologies or use cases. |
| Potential Future Industry Norm | Solution is slowly gaining wider adoption or could become an industry norm. |

[6] Potential Impact at system level* (*the impact on the overall carbon footprint of the concrete when the material replaces conventional materials)

# Annex B - Technologies and Strategies for Operational Carbon Reduction

| S/N | Strategies | | Technologies | Description | Technology Readiness Level (TRL) | Potential Energy Savings Impact | Market Adoption |
|---|---|---|---|---|---|---|---|
| 1 | Optimisation across Multiple Buildings in District-Level | - | Switch to DCS with distributed pumping systems and/or renewable energy capabilities | DCS use a centrally managed plant to chill water and distribute it to multiple buildings. When operated by renewable energy sources, DCS deliver significant reductions in energy consumption and carbon emissions. | 7-9 | High | Niche Adoption (Dependent on Availability of DCS Supply) |
| 2 | | | Urban energy modelling software | Advanced tools to model, simulate, and optimise energy systems across districts for scenario planning. | 4-6 | Significantly High | Limited (R&D/ Pilots) |
| 3 | | | District-level control algorithms for energy efficiency (e.g. MPC) | Algorithm control to coordinate and optimise multiple building systems (e.g., ACMV, lighting) and distributed energy systems (e.g., solar PV, EV charging) simultaneously across building networks. | 4-6 | Significantly High | Limited (R&D/ Pilots) |
| 4 | Passive Strategies | Reduce Solar Heat Gain for Façades | Façade enhancement solutions for existing buildings | "Add-on" solutions that enhance building envelope performance of existing buildings through non-disruptive additions (e.g. fit outs onto existing windows and façades). | 4-6 | Significantly High | Niche Adoption (Fewer providers locally) |
| 5 | | | Photochromic window film | Smart window technology that automatically adjusts the level of tint in response to changes in light intensity (e.g., darken when exposed to sunlight and return to a clearer state when the light levels decrease). Process is driven by a photochromic material that changes its chemical structure in response to UV light or visible light exposure. | 7-9 | High | Niche Adoption (Depends on receptiveness of end-users to tinting solutions. Challenging in Multi Tenanted buildings) |
| 6 | | | Electrochromic window system (active) | Smart glass or window technology that changes its colour/tint or transparency in response to an applied electrical voltage. | 7-9 | High | |
| 7 | | | Ventilated façade systems | Ventilated façade systems are integrated into a building's envelope to leave an air chamber between the exterior and inner walls. As air circulates between the walls during warm weather, it is heated through a "chimney effect," whereby air is pushed upward and building temperature is reduced. | 7-9 | High | Niche Adoption (More R&D required on simplicity in design and maintenance complexities) |

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| S/N | Strategies | | Technologies | Description | Technology Readiness Level (TRL) | Potential Energy Savings Impact | Market Adoption |
|---|---|---|---|---|---|---|---|
| 8 | Passive Strategies | Improve Insulation | Phase change materials for passive cooling | Materials that act as "Thermal Batteries" by absorbing/ releasing heat when changing state. Can be used as passive energy storage or integrated into building façades as insulation. | 4-6 | High | Limited Adoption (Further R&D needed to address fire safety challenges) |
| 9 | | | Aerogel insulation | Aerogels are a type of synthetic porous material derived from a gel. Air bubbles are captured in the gel material, giving them low density and low thermal conductivity, and thereby good thermal insulation properties. | 7-9 | High | Niche Adoption (Fewer providers locally) |
| 10 | | | Vacuum insulation panel (VIP) | By evacuating air from a sealed panel containing microporous core materials like fumed silica or aerogel, VIPs achieve thermal resistance values 5-10 times higher than conventional insulation materials. Exceptional space efficiency makes them particularly valuable in applications where space is at a premium. | 7-9 | High | Niche Adoption |
| 11 | | | $CO_2$ absorbing coatings with sequestration or removal capabilities | Specialised coatings with additives to breakdown ambient $CO_2$ or capture $CO_2$ in concrete, reducing Urban Heat Island effect. | 4-6 | High | Niche Adoption (Fewer providers in market with scope for greater commercial validation) |
| 12 | | | Thermal break | Architectural and engineering solution designed to prevent heat transfer by using low thermal conductivity materials across building elements that would typically conduct heat easily (e.g. Metal window frames). | 7-9 | High | Niche Adoption (Scope for further R&D to simplify design for cost effectiveness) |
| 13 | Active Strategies | Alternative Cooling Technologies | Hybrid cooling | A cooling system where the design and operational indoor set-point temperature of the air-conditioning system is increased (≥ 25.5°C with a typical target of 27°C) and supplemented with elevated air speed to achieve acceptable occupants' thermal comfort. | 9 | Significantly High | Potential Future Industry Norm (Growing Momentum as strategy to reduce cooling load towards SLE building) |
| 14 | | | Passive displacement cooling | This system uses natural convection to distribute cool air, reducing the need for mechanical ventilation. It enhances thermal comfort and energy efficiency by leveraging the natural movement of air. | 7-9 | High | |
| 15 | | | Mixed-mode ventilation | Mixed-mode ventilation uses both natural ventilation (e.g., operable windows) and mechanical systems. This hybrid approach maximises energy efficiency by using natural ventilation when conditions are favourable and mechanical cooling when necessary. Advanced solutions can be supported by motorised systems and sensors to automate opening/ closing. | 7-9 | Significantly High | Niche Adoption (User Acceptance of Full Natural ventilation mode can be challenging) |

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| S/N | Strategies | | Technologies | Description | Technology Readiness Level (TRL) | Potential Energy Savings Impact | Market Adoption |
|---|---|---|---|---|---|---|---|
| 16 | Active Strategies | Alternative Cooling Technologies | Radiant cooling | Radiant cooling systems use chilled surfaces to absorb heat from the environment. Advanced designs prevent condensation by physically separating the cold panel from the humid room air (e.g. through membranes or vacuum cavities), allowing the panel to operate below the dew point. | 9 | High | Potential Future Industry Norm (Growing Momentum as strategy to reduce cooling load towards SLE building) |
| 17 | | | Passive chilled beams | Cooling system that uses natural convection, where chilled water passes through ceiling-mounted beams to cool the surrounding air, which then falls naturally into the space below. | 9 | High | |
| 18 | | | Active chilled beams | Cooling systems that combine ventilation with cooling by using pressurised air to induce room air via suction effect through a cooling coil, delivering both conditioned fresh air and enhanced cooling performance. | 9 | High | |
| 19 | | | Hybrid radiative/desiccant cooling | Advanced hybrid materials or coatings tailored to address humidity constraints, significantly improving passive cooling efficacy in humid tropical environments. | 4-6 | Significantly High | Niche Adoption (Scope for further R&D to efficiently regenerate desiccant) |
| 20 | | | Dual temperature chiller plant | Provide greater feasibility in meeting different cooling needs simultaneously. For example, chillers with high temperature setpoint to cater to sensible cooling and low temperature setpoint for dehumidification. Ideal to be used together with chilled beam/ radiant panel systems that require higher chilled water supply temperature. | 9 | High | Potential Future Industry Norm (Design Strategy that can be readily adopted) |
| 21 | | Non-Vapour Compressor Cooling Chiller Systems | Advanced solid-state/ thermoelectric cooling | Thermoelectric (TE) cooling offers a solid-state, refrigerant-free solution for energy-efficient cooling in buildings. Its applications focus on localised cooling, waste heat recovery, and energy harvesting, contributing to sustainability and smarter ACMV systems. | 4-6 | Significantly High | Limited (R&D/ Pilots) |
| 22 | | | $CO_2$ based air-conditioning system | $CO_2$-based air conditioning systems use carbon dioxide as a refrigerant, offering a refrigerant-free and energy-efficient alternative to traditional cooling methods. Waste heat produced at high temperatures can be used for hot water applications. | 4-6 | Significantly High | Limited (R&D/ Pilots) |

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| S/N | Strategies | | Technologies | Description | Technology Readiness Level (TRL) | Potential Energy Savings Impact | Market Adoption |
|---|---|---|---|---|---|---|---|
| 23 | Active Strategies | Non-Vapour Compressor Cooling Chiller Systems | Magnetocaloric cooling chillers | Magnetocaloric chillers rely on the magnetocaloric effect - where certain materials change temperature when exposed to changing magnetic fields. The higher efficiency comes from a simpler, more direct cooling process with fewer energy conversion steps compared to traditional vapor compression systems. Such chillers do not use refrigerants and typically have fewer moving parts. | 4-6 | Significantly High | Limited (R&D/ Pilots) |
| 24 | | | High efficiency absorption chiller (double and triple effect) | An absorption chiller is a cooling system that uses heat energy rather than mechanical energy to provide cooling, using a thermal-chemical process involving a refrigerant (usually water) and an absorbent (typically lithium bromide or ammonia). Heat energy from solar or waste heat drives the process instead of a mechanical compressor, leading to energy savings. Double and triple chillers have multiple absorption loops within the chiller, increasing the amount of heat utilised. | 7-9 | High | Niche Adoption (Requires a consistent supply of waste heat to keep operating costs low) |
| 25 | | Energy Recovery | Absorption heat pump | An absorption heat pump is a thermally driven cooling system that uses heat energy (from waste heat or PV) rather than mechanical energy to provide cooling or heating. Unlike conventional heat pumps that rely on electricity-powered compressors, absorption heat pumps use a chemical process involving an absorbent (typically lithium bromide) and a refrigerant (usually water) to achieve the desired temperature change. | 7-9 | High | Niche Adoption (Fewer providers locally) |
| 26 | | | Energy/heat recovery wheels for fresh air load reduction | Reuses exhaust cooled air at 25°C to pre-cool hot outdoor fresh air. This reduces the cooling load for the downstream air conditioning systems. | 9 | High | Potential Future Industry Norm (Sufficient providers in the market) |
| 27 | | | Energy recovery through water-to-water heat pump | System that transfers heat from a lower temperature water source to a higher temperature water destination via a heat pump to maximise energy efficiency. This works in both heating and cooling modes. Use cases include using wastewater heat from cooling towers to pre-heat water for hot water uses or offset building cooling. | 4-6 | High | Limited (Further R&D for local context required) |
| 28 | | Use of Direct Current (DC) Systems | Multiple DC plug fans | Multiple smaller sized DC fans are installed to replace a single large AHU fan. It ensures a better minimum flow rate at lower cooling load, addresses redundancy of fans, increases efficiency, along with lower vibration and fewer system components. | 9 | High | Potential Future Industry Norm (Growing number of providers in the market) |

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| S/N | Strategies | | Technologies | Description | Technology Readiness Level (TRL) | Potential Energy Savings Impact | Market Adoption |
|---|---|---|---|---|---|---|---|
| 29 | Active Strategies | Use of Direct Current (DC) Systems | DC network for LED lighting system | Minimise power conversion losses through a DC network that allows equipment designed to operate on DC to operate without additional electrical components for energy conversion. | 4-6 | High | Limited Adoption (Requires further R&D on safety and readiness of other building components that can tap on DC network for cost effectiveness) |
| 30 | | | Brushless DC motor driven pump | A brushless DC (BLDC) motor driven pump employs permanent magnets or electronic controls to control motor operation. This requires lesser power due to lower friction loss. | 9 | High | Potential Future Industry Norm (Growing number of providers in the market) |
| 31 | | Improve Air-Side Efficiency | IE5 AC motors on pumps | IE5 motors are ultra-premium efficiency motors that significantly reduce energy consumption. When used on pumps, these motors enhance the overall efficiency of the pumping system, leading to lower operational costs and reduced carbon emissions. | 9 | High | Potential Future Industry Norm (Growing number of providers in the market) |
| 32 | | | Enzyme tool for odour control | Enzyme-based odour eliminators use biological enzymes to break down organic compounds that cause odours. These tools are effective in maintaining indoor air quality without increasing energy use, making them a sustainable option for odour control in retail environments. | 9 | High | Niche Adoption (May require application-specific formulas) |
| 33 | | | Dynamic air balancing – determined by tenant mix and cooling loads | Adjusting the ACMV system to ensure even air distribution based on tenant mix and cooling loads. This process optimises airflow, enhances comfort, and reduces energy consumption by ensuring that each area receives the appropriate amount of air. | 9 | High | Potential Future Industry Norm (Growing number of providers in the market) |
| 34 | | Managing Fresh Air Intake | Dedicated Outdoor Air System | System to treat outdoor air to a building independently from the building's cooling system. Its pre-conditions (e.g., cools, dehumidifies) 100% outdoor air to meet ventilation requirements and handle the latent (moisture) loads of a building. | 9 | High | Potential Future Industry Norm (Growing number of providers in the market) |
| 35 | | | Decarboniser that absorbs $CO_2$ | Decarboniser reduces indoor $CO_2$ levels, reduces the air change frequency and decreases the air conditioning system energy consumption. | 4-6 | High | Limited Adoption (Requires further R&D for local context) |
| 36 | Smart Energy Management | - | Hybrid ventilation with AI control | Hybrid ventilation combines natural and mechanical ventilation. By using AI to control fans and adjust air conditioning set points, this system optimises energy use while maintaining comfort. AI can predict occupancy and environmental conditions to switch between natural and mechanical ventilation as needed. | 4-6 | Significantly High | Niche Adoption (Requires further R&D to optimise solution) |

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| S/N | Strategies | | Technologies | Description | Technology Readiness Level (TRL) | Potential Energy Savings Impact | Market Adoption |
|---|---|---|---|---|---|---|---|
| 37 | Smart Energy Management | - | Occupant-centric ACMV optimisation (with heat maps and MPC) | AI-driven occupant-centric optimisation for Air Conditioning and Mechanical Ventilation (ACMV) systems focuses on maintaining thermal comfort while minimising energy use by predicting occupancy patterns and adjusting settings in real-time. This can be done through model predictive control (MPC) or heat maps. | 7-9 | High | Potential Future Industry Norm (Growing number of providers in the market) |
| 38 | | | Hot water systems | Optimising hot water systems involves managing the temperature and flow of water to reduce energy consumption. This can include using smart thermostats, efficient heating elements, and algorithms that adjust settings based on usage patterns. | 9 | High | |
| 39 | | | Self-calibration reference sensors | Self-calibrating precision temperature sensors automatically adjust their output to maintain accuracy over time, eliminating the need for frequent manual calibrations and improving reliability in critical applications. | 7-9 | High | Niche Adoption (Fewer providers locally) |
| 40 | | | Smart operations with digital twins | A live, data-driven model of a building/estate that fuses data streams from various building systems into an operational digital twin for monitoring, optimisation and workflow execution. | 4-6 | Significantly High | Potential Future Industry Norm (Growing number of solutions in the market) |
| 41 | | Technology to Influence End-User Energy consumption patterns | Perception-based temperature set point control | Adjusting temperature set points based on occupant perception can enhance comfort and reduce energy consumption. This approach uses feedback from occupants to maintain optimal thermal conditions. | 9 | High | Niche Adoption (Requires user buy-in) |
| 42 | | | Game theory principles for tenant energy use management | Incentivising tenants to manage energy consumption from their plug loads more effectively through Game Theory principles. This approach often involves using smart plug loads and other monitoring devices to track, communicate and manage use. | - | High | |
| 43 | | | Social influence to persuade users to increase thermal comfort range | Leveraging social norms and community influence can encourage occupants to accept a wider range of temperatures and reducing energy use. Studies show that community fit and habituation to thermal comfort can significantly impact energy conservation behaviours. | - | High | |

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| S/N | Category | Strategies | Technologies | Description | Technology Readiness Level (TRL) | Potential Energy Impact | Market Adoption |
|---|---|---|---|---|---|---|---|
| 44 | Renewables | Façade Solar | Transparent PV panel | Semi-transparent solar cells such as organic PV, dye-sensitised solar cells, or perovskites that function both as glazing elements (i.e. windows) and energy-generating devices. Panels allow visible light to pass through while converting infrared and ultraviolet light into electricity. | 7-9 | High | Niche Adoption (Fewer Providers locally) |
| 45 | | | Flexible solar panels | Thin-film photovoltaic modules composed of solar cells that are lightweight and bendable, allowing deployment on curved, soft, or mobile surfaces. | 7-9 | High | Niche Adoption (Fewer Providers locally) |
| 46 | | Rooftop Solar | Single-axis tracker bi-facial PV | Engineered reflective albedo (e.g. reflective surfaces of paint, white rock, mirrored plastic of polished metal) allows PV panels to absorb light bi-directionally, improving efficiencies The single axis rotates the tilt of the PV panel to optimise the solar gain according to the time of day. | 7-9 | High | Niche Adoption (Increased Installation and upkeep complexity) |
| 47 | | Non-Solar | Vibration energy harvesting (piezoelectric materials) | Materials that convert mechanical energy and stress into electrical energy (e.g. generate energy from human activities such as walking). | 7-9 | High | Niche Adoption (Requires wide area of adoption to be significant) |
| 48 | | | Micro wind turbines | Small-scale wind energy systems designed for localised power generation, typically in urban or building-integrated settings. | 4-6 | High | Limited Adoption (R&D/pilots) |

# Annex C - Technologies and Strategies for Embodied Carbon Reduction

| S/N | Strategies | | Technologies | Description | Technology Readiness Level (TRL) | Potential Carbon Reduction Impact | Market Adoption |
|---|---|---|---|---|---|---|---|
| 1 | Low-Carbon Materials (Concrete-related materials) | Addition of material that reduces the amount of cement needed | Addition of chemical admixture | Chemical admixture such as superplasticiser could be added into the concrete production, in addition to the raw materials for concrete, to achieve better workability, strength or durability properties of the concrete. This allows a potential reduction of the OPC content to achieve comparable strength to conventional concrete. This leads to a lower carbon footprint of the concrete. | 7-9 | High | Potential Future Industry Norm (for Superplasticizer) |
| 2 | | | Addition of materials eg. Polypropylene fibres and steel fibres, etc. | Innovative materials such as polypropylene fibres and graphene could be added into the concrete production, in addition to the raw materials for concrete, to achieve better strength or durability properties of the concrete. This allows a potential reduction of the OPC content to achieve comparable strength to conventional concrete. This leads to a lower carbon footprint of the concrete. | 7-9 | High | Ranges from R&D/Pilots for Graphene, biochar to Niche adoption (for steel fibres/PP fibres) |
| | | | Addition of materials eg. graphene, biochar, etc | | 4-6 | | |
| 3 | | Direct replacement of raw materials with lower carbon footprint alternatives | Replacement of OPC with alternatives eg. GGBS, ternary blend, etc. | Materials such as GGBS, fly ash that has a lower carbon footprint than OPC could be used to partially replace OPC in concrete production. This leads to a lower carbon footprint of the concrete. | 7-9 | Significantly High | Potential Future Industry Norm (with widespread adoption of supplementary cementitious materials) |
| | | | Replacement of OPC with alternatives eg. geopolymer, limestone calcined clay cement, etc. | | 4-6 | | |
| 4 | | | Replacement of aggregate with alternatives eg. RCA, granite dust, etc. | Materials such as recycled concrete aggregate (RCA), engineered clay aggregates that has a lower carbon footprint than conventional aggregates could be used to partially replace conventional aggregates in concrete production. This leads to a lower carbon footprint of the concrete. | 7-9 | High | Ranges from Industry norm (for RCA) to Pilot (for engineered clay aggregates) |
| | | | Replacement of aggregate with alternatives eg. engineered clay aggregates, biochar, etc | | 4-6 | | |
| 5 | | Carbon mineralisation technologies that utilise $CO_2$ in the production | Carbon mineralised cementitious material | Carbon mineralised cementitious materials are produced with the use of $CO_2$ in its production process. These materials have a lower carbon footprint than OPC and could partially replace OPC in concrete production. This leads to a lower carbon footprint of the concrete. | 4-6 | Significantly High | Limited Adoption (as there are commercialised solutions overseas with no known supply/ adoption in Singapore) |

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| S/N | Strategies | | Technologies | Description | Technology Readiness Level (TRL) | Potential Carbon Reduction Impact | Market Adoption |
|---|---|---|---|---|---|---|---|
| 6 | Low-Carbon Materials (Concrete-related materials) | Carbon mineralisation technologies that utilise $CO_2$ in the production | Carbon mineralised aggregate | Carbon mineralised aggregate is produced with the use of carbon dioxide in its production process.<br>These materials have a lower carbon footprint than conventional aggregates and could partially replace conventional aggregates in concrete production. This leads to a lower carbon footprint of the concrete. | 4-6 | Significantly High | Limited Adoption (as there are commercialised solutions overseas, with no known supply/adoption in Singapore) |
| 7 | | | Carbon mineralised fresh concrete | Carbon mineralised fresh concrete is produced with the use of carbon dioxide introduced during the mixing process.<br>The introduction of carbon dioxide into the concrete leads to a lower carbon footprint of the concrete. | 7-9 | High | Potential Future Industry Norm (as there are commercialised solutions available) |
| 8 | | | Carbon mineralised hardened concrete | Carbon mineralised hardened concrete is produced with the use of carbon dioxide introduced during the curing process.<br>The introduction of carbon dioxide into the concrete leads to a lower carbon footprint of the concrete. | 4-6 | High | Limited Adoption (where applications are in demonstration/ small scale trials) |
| 9 | Low-Carbon Materials | 3D Printing | 3D printing using low-carbon materials | The integration of low-carbon concrete technologies into 3DCP offers additional benefits, potentially reducing both carbon emissions and material costs. | 4-6 | High | Limited Adoption (R&D Pilots) |
| 10 | Low-Carbon Materials (Non-concrete-related material) | Direct replacement with lower carbon footprint alternatives | Replacement of reinforcement bar | Materials such as green steel, steel fibre that has a lower carbon footprint than conventional steel reinforcement bars could be used to partially replace conventional reinforcement bars in reinforced concrete production.<br>This leads to a lower carbon footprint of the reinforced concrete structure. | 7-9 | High | Niche Adoption (for specific use case applications) |
| 11 | | | Direct replacement of concrete with MET | Materials such as MET that has a lower carbon footprint than concrete could be used to replace concrete as the construction material.<br>This leads to a lower carbon footprint of the building. | 7-9 | Significantly High | Niche Adoption (for mid-rise developments) |
| 12 | Low-Carbon Construction | Reduce dependence on diesel by increasing access to cleaner energy on-site | On-site battery energy storage systems | Batteries can be sized and designed for various construction purposes. These can range from large batteries for heavy lifting operations to smaller mobile batteries for MEP works. | 6 | Significantly High | Niche Adoption (due to high switching costs associated with moving from conventional diesel generators to battery systems) |

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| S/N | Strategies | | Technologies | Description | Technology Readiness Level (TRL) | Potential Carbon Reduction Impact | Market Adoption |
|---|---|---|---|---|---|---|---|
| 13 | Low-Carbon Construction | Reduce dependence on diesel by increasing access to cleaner energy on-site | Smart microgrids | A smart microgrid for a construction site dynamically manages grid, solar, battery, and diesel power, optimising supply based on demand.<br><br>It allocates energy to subcontractors efficiently, monitors usage in real time, and prioritises clean sources to reduce emissions and costs. | 5 | Significantly High | Limited Adoption (due to complex and dynamic nature of each construction site) |
| 14 | | | Diesel genset retrofits | Diesel gensets are converted using fuel system upgrades for biodiesel or dual-fuel kits and modified injectors for hydrogen, enabling cleaner combustion with minimal engine redesign. | 4 | Significantly High | Limited Adoption (due to performance concerns and supply chain availability) |
| 15 | | Redesigning work practices around maximising use of cleaner energy | IDD for electric construction | Digital planning solutions integrated with energy management systems that track equipment usage, predict power needs, and schedule charging.<br><br>This enables contractors to efficiently operate electric tools and vehicles with minimal downtime. | 5 | Significantly High | Limited Adoption (as more research is needed on the feasibility of on-site electrification, ahead digitalisation efforts) |
| 16 | | | Power electronics for on-site fast charging | Fast-charging power electronics using high-efficiency converters and smart controllers to rapidly charge electric equipment, in order to minimise downtime. | 5 | Significantly High | Limited Adoption (as builders would only need this if there are a greater number of electric vehicles on their site, which is not the case presently) |
| 17 | Recycled C&D Waste | High-value recycling of concrete | C&D waste material processing | Recycling technologies that enable the full circularity of concrete.<br><br>Such technologies utilise selective separation to disintegrate concrete into their original constituents, including recycled concrete paste with hydrated cement, which can be used in structural ready-mixed concrete, increasing the usage value of demolished concrete. | 7 | High | Limited Adoption (Have been adopted overseas) |
| 18 | | Resource Tracking of component/ materials to be reused | Material passports | Material passports document the type, quantity, composition, and condition of materials in a building, which will enable future owners or contractors to identify components and materials that can be reused or recycled.<br><br>This will help to increase transparency of a material's origin and its properties across the value chain, allowing for ease of carbon accounting and future life cycle assessments. | 8 | High | Niche Adoption (Utilised in other industries such as in EV recycling) |

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| S/N | Strategies | | Technologies | Description | Technology Readiness Level (TRL) | Potential Carbon Reduction Impact | Market Adoption |
|---|---|---|---|---|---|---|---|
| 19 | Digital Solutions | Carbon management | Whole-life carbon calculator | Tool to measure the total greenhouse gas emissions of a building project over its entire life cycle. This includes both embodied carbon (materials, construction, maintenance, demolition) and operational carbon (energy use in-use). | 7-9 | High | Niche Adoption (adopted by leading firms who embed WLC assessments in their standard practices) |
| 20 | | | Life cycle assessment (LCA) analysis tools | LCA provides a robust, data-driven methodology that enables decision-makers to weigh trade-offs and identify the most sustainable options from an all-encompassing environmental, social, and governance perspective. | 7-9 | High | Niche Adoption (adopted by leading firms who embed WLC assessments in their standard practices) |
| 21 | | | Whole-life carbon management in BE | Integrated Agentic AI system with multiple autonomous agents managing ACMV optimisation, system reliability monitoring, and carbon compliance reporting. | 4-6 | High | Niche Adoption (technical complexity of integrating AI with legacy building systems) |

# Annex D - Established Solutions for Operational Carbon & Embodied Carbon

| | Technologies | Description |
|---|---|---|
| Operational Carbon Reduction (Towards SLE building) | Organic and inorganic shading devices | Organic shading includes natural elements like trees and plants, which provide shade and improve air quality. Inorganic shading materials, such as metal screens or louvres, can be designed to block or redirect sunlight, reducing heat gain and glare inside the building. |
| | Thermal insulation | Reduction of the conductive heat transfer components of external loads, contributing to lower use of air-conditioning. |
| | Insulated glazing | Reduction of conductive heat transfer through glazing, contributing to lower use of air-conditioning. |
| | Cool coatings | Coatings that reflect solar infrared radiation (IR), reducing heat absorption reducing the cooling load. |
| | Solar films | Thin multi-layered materials applied to windows or glass surfaces to control solar heat and light. |
| | Light shelves | Passive architectural element (e.g. horizontal surfaces mounted above eye level on window) to increase the depth of penetration of useful daylight into the building and reduces the use of artificial lighting. |
| | Lighting tubes | Cylindrical tubes with highly reflective internal surfaces that capture and transmit daylight to unlit spaces like corridors and bathrooms. Complicated and expensive implementation in refurbishment but suitable for new low-rise projects. |
| | Façade greenery | Shades the surfaces and cools the air through evapotranspiration. |
| | High-efficiency electronically commutated (EC) fans | Fans that use advanced brushless DC motor technology with integrated electronic controls to provide superior energy efficiency and precise speed control compared to conventional AC motor fans. |
| | High volume low speed (HVLS) fan | Fans that can move huge columns of air efficiently at low speed. |
| | Energy efficient monitoring for ACMV system | Implementing advanced monitoring systems helps track and optimise energy use. These systems provide real-time data and insights, enabling better energy management. |
| | 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. |
| | DALI smart lighting control | DALI (Digital Addressable Lighting Interface) Smart Lighting Control Systems are standardised digital lighting control protocols that enable intelligent and flexible management of building lighting. |
| | Underfloor air distribution (UFAD) | UFAD uses open space below a raised floor platform to supply cooling air to the occupied space. Energy savings achieved through thermal stratification where occupied zones are cooled while non-occupied zones (e.g., close to ceiling) are at a higher temperature. |
| | Smart plugs | Plugs that automatically turn off unused appliances and reduce standby power. |
| | Photovoltaic thermal (PVT) panel | Hybrid solar devices that combine solar photovoltaic (PV) and solar thermal technologies in a single panel to generate both electricity and heat. |
| | Co-location of solar PV and greenery | Use of both greenery and solar PV on the same roof space. |
| | Non-chemical based electrolysis cooling tower water treatment system | Improves cycles of concentration (COC) of condenser water systems and heat exchange efficiencies from cooling towers and chillers due to reduced scaling and biofilm growth. |

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| | Technologies | Description |
|---|---|---|
| Embodied Carbon Reduction | Battery energy storage system | BESS provides clean, reliable power storage and supply for construction sites, offering an alternative to diesel generators. Ideally connected to the grid and charged using grid electricity during off-peak periods. Possibility for integration capability with renewable energy sources. |
| | Hybrid/ electric construction vehicles (e.g. excavator, wheel loader) | Construction vehicles utilising hybrid (diesel-electric) or fully electric powertrains reduce emissions and operational costs (e.g. fuel savings, maintenance requirements). They offer a sustainable alternative to traditional diesel-powered machinery, contributing to a greener construction process. Other benefits include regenerative braking energy recovery and enhanced torque response for improved equipment performance. |
| | Hydrogen fuel cell systems | Fuel Cell systems produce electricity using hydrogen as a fuel, offering a clean alternative to diesel generators with zero emissions. Good for off-grid sites but green hydrogen is limited in supply. |
| | Mass engineered timber | Materials such as MET that has a lower carbon footprint than concrete could be used to replace concrete as the construction material. This leads to a lower carbon footprint of the building. |
| | Singapore building carbon calculator (SBCC) | The SBCC is a web-based embodied carbon calculator designed for Singapore's BE. The SBCC accounts for the upfront carbon of materials used. Carbon emission factors in the SBCC are adapted to reflect the carbon footprint of projects in Singapore's context. |
| | Supplementary cementitious materials | Materials such as fly ash and Ground Granulated Blast-furnace Slag (GGBS) that have significantly lower carbon footprints than OPC could be used to partially replace OPC in concrete mixtures. These industrial by-products reduce the overall embodied carbon of concrete by decreasing the proportion of high-carbon OPC required, whilst often improving concrete durability and performance characteristics. This leads to a lower carbon footprint of the building whilst maintaining structural integrity and compliance with local building requirements. |

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