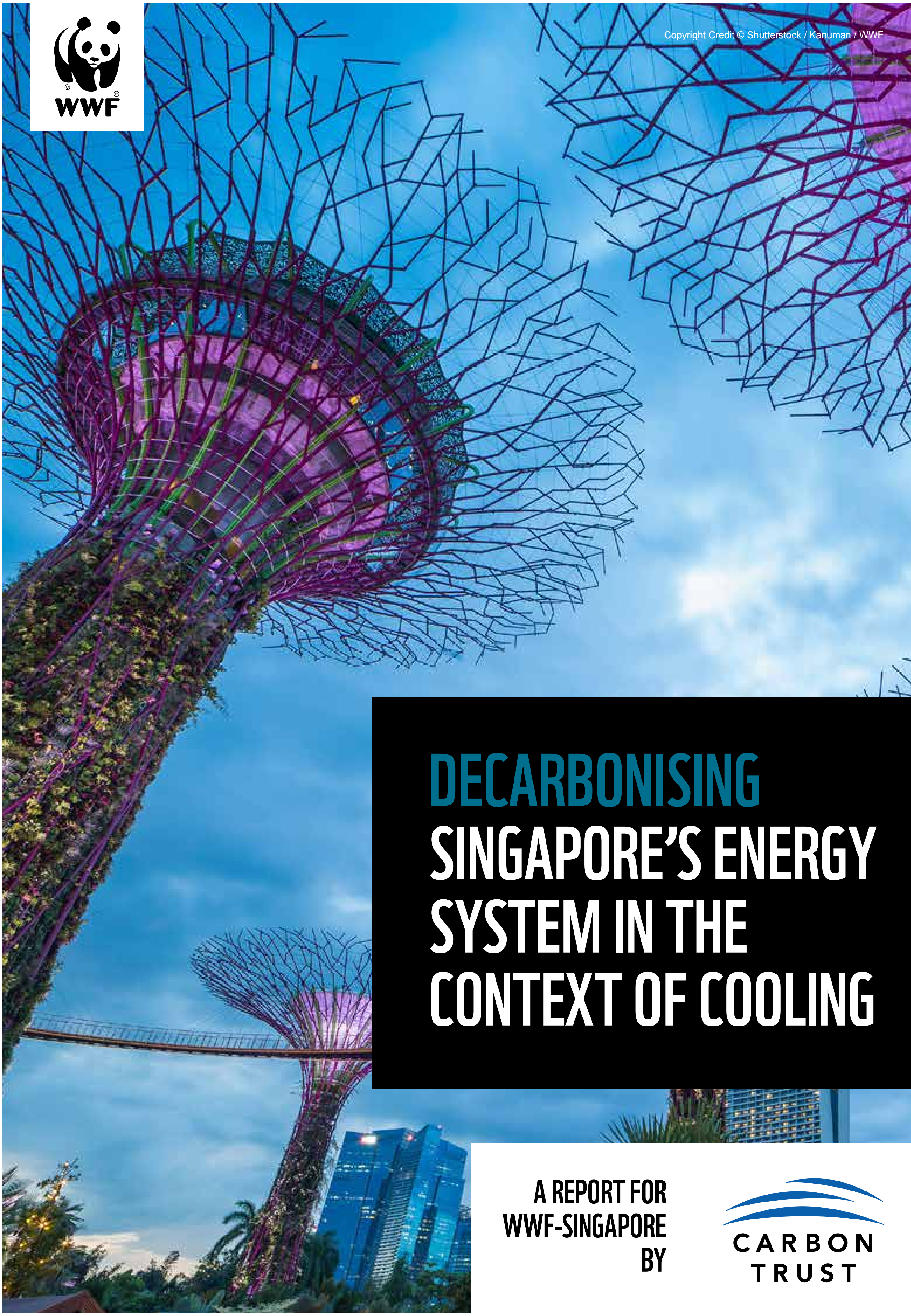

WWF

DECARBONISING SINGAPORE'S ENERGY SYSTEM IN THE CONTEXT OF COOLING

A REPORT FOR WWF-SINGAPORE BY

CARBON TRUST

ACKNOWLEDGMENTS

WWF-Singapore (World Wide Fund for Nature Singapore) commissioned the Carbon Trust to write this report on the role of clean cooling as an energy vector to efficiently and cost-effectively support Singapore's energy transition to a decarbonised future. The Carbon Trust wrote this report based on an impartial analysis of primary and secondary sources, including expert interviews. For the avoidance of doubt, this report expresses the independent views of the authors.

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CARBON TRUST

The Carbon Trust's mission is to accelerate the move to a decarbonised future.

We are a trusted, expert guide to Net Zero, bringing purpose led, vital expertise from the climate change frontline. We have been pioneering decarbonisation for more than 20 years for businesses, governments and organisations around the world.

We draw on the experience of over 300 experts internationally, accelerating progress and providing solutions to this existential crisis. We have supported over 3,000 organisations in 50 countries with their climate action planning, collaborating with 150+ partners in setting science-based targets, and supporting cities across 5 continents on the journey to Net Zero.

WWF

ABOUT WWF-SINGAPORE

World Wide Fund for Nature (WWF) is one of the world's largest and most respected independent conservation organisations. WWF's mission is to stop the degradation of the earth's natural environment and to build a future in which humans live in harmony with nature.

As one of WWF's international hubs, WWF-Singapore supports a global network spanning over 100 countries. WWF-Singapore works closely with local stakeholders towards a greener and more sustainable Singapore and the region around us. We work to address key conservation areas, such as climate change, sustainable finance, deforestation, illegal wildlife trade, marine conservation, and sustainable production and consumption, through collaboration, education and outreach efforts involving the community, businesses, and governments. For more information, please visit wwf.sg.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT.)

TABLES

FIGURES

ABBREVIATIONS

AC	Air-Conditioning
AI	Artificial Intelligence
BCA	Building and Construction Authority, Singapore
BMS	Building Management Systems
BTU	British thermal unit
CCUS	Carbon capture, utilisation, and storage
CO2	Carbon dioxide
DHCS	District Heating and Cooling Systems
DSM	Demand-side management
EMA	Energy Market Authority, Singapore
GHG	Greenhouse gas
GW	Gigawatt
GWh	Gigawatthour
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
HVAC	Heating, ventilation, and air conditioning
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IMDA	Infocomm Media Development Authority, Singapore
IRENA	International Renewable Energy Agency
IT	Information technology
LAES	Liquid air energy storage
LEDS	Singapore's Long-Term Low-Emissions Development Strategy
LNG	Liquefied natural gas
MSE	Ministry of Sustainability and the Environment, Singapore
MTI	Ministry of Trade and Industry, Singapore
MW	Megawatt
NCCS	National Climate Change Secretariat, Singapore
NDC	Nationally Determined Contribution
NEA	National Environment Agency, Singapore
NTU	Nanyang Technological University, Singapore
PCM	Phase change materials
PV	Photovoltaic
RAC	Refrigeration and Air-Conditioning
RE	Renewable Energy
SGD	Singapore dollar
TW	Terawatt
TWh	Terawatt hour
UHI	Urban Heat Island
UNEP	United Nations Environment Programme
UK	United Kingdom
URA	Urban Redevelopment Authority, Singapore
WWF	World Wide Fund for Nature

EXECUTIVE SUMMARY

WHY COOLING MATTERS TO SINGAPORE

Cooling is critical for health, prosperity, and the environment. It keeps our vaccines safe and food fresh, ensures we have comfortable buildings to live and work in and is central to our industrial and transport infrastructure. However, many standard cooling methods are energy intensive and highly polluting due to the emissions generated when powering cooling equipment using high carbon sources. The refrigerants and insulation gas used can also contribute to pollution, especially if not properly recovered and recycled.

Cooling emissions represented approximately 11.5% of Singapore's national greenhouse gas (GHG) emissions in 2016, and are expected to rise by nearly 40% by 2030 if cooling services are deployed in a business-as-usual fashion.[1] In 2019 cooling demand in Singapore was 15.3 Terawatt hours (TWh) representing approximately 30% of Singapore's total electricity demand and contributing to a quarter of peak power demand. In response to rising temperatures as a result of climate change[2] and further compounded by urbanisation and the Urban Heat Island effect,[3] where buildings trap heat during the day, cooling demand is expected to grow. By 2030, in the absence of any clean cooling inverventions, cooling demand in Singapore is projected to increase by 66% to 25.4 TWh and represent close to 30% of peak power demand.[4]

Growing cooling demand will put a strain on the power grid and could potentially increase grid infrastructure needs as total cooling demand rises. As more cooling demand comes on the grid, the total demand profile's variability could also increase. This is particularly significant, as the largest cooling consumers, the commercial and residential buildings, both have cooling demand profiles that are characterised by rapid ramp ups in cooling loads which directly contribute to sharp increases in power demand. Such variations lead to voltage disturbances as the utility operator has to adjust the power plant operations and this can adversely affect the functioning and life of equipment such as air-conditioners, motors, and lights. Given the current power system is supplied by highly flexible thermal gas generation, this variability has little impact on the current grid.

This could change in the future as the decarbonisation of our power system leads to an increase in renewable energy that is more variable and less flexible. Increasing low-carbon generation capacity will mean that addressing grid flexibility will become integral to Singapore's energy transition goals. Flexibility could be provided by demand-side management, supporting a more cost-effective transition. In this context, clean cooling has the potential to be a provider of demand side flexibility in the future.

1 *Cooling emissions were 5.53 Mt CO2eq in 2016, and are projected to reach 7.66 Mt CO2eq by 2030 under a BAU scenario. Green Cooling Initiative. Singapore. Retrieved January 24, 2022, from https://www.green-cooling-initiative.org/country-data#!country-data-sheet/702/all-sectors The calculation in the source accounts for direct (refrigerants) and indirect (energy consumption) emissions.*

2 *National Climate Change Secretariat (2022). Impact of climate change and adaptation measures. Retrieved 18th May, 2022, from: https://www.nccs.gov.sg/faqs/impact-of-climate-change-and-adaptation-measures/*

3 *Ministry of Sustainability and the Environment. Factsheet on Singapore's Efforts to Mitigate the Urban Heat Island Effect. Retrieved 20th June, 2022, from: https://www.mse.gov.sg/cos/resources/cos-annex-j.pdf*

4 *Please refer to Appendix 1 and 2 for the detailed calculation.*

POTENTIAL OF CLEAN COOLING SOLUTIONS

Our study defines clean cooling as solutions that reduce GHG emissions from cooling during the operational life of products[5] below. We therefore define clean cooling to include (i) passive cooling, where design and planning measures are used to reduce the need for mechanical cooling; (ii) cooling services, which includes the use of super-efficient equipment and ultra-low Global Warming Potential (GWP) refrigerants; and (iii) cold energy, which includes thermal energy solutions using cryogenic or other phase change materials that enable short to long term storage of renewable and excess electric energy at low or sub-zero temperatures.

Clean cooling is core to supporting Singapore's climate targets by contributing towards the decarbonisation of the power system. Firstly, clean cooling can be managed as an energy vector.[6] By reducing total demand and providing flexibility to allow the power system to manage new challenges related to renewables integration, clean cooling can play a key role in supporting Singapore's ambition to achieve net zero emissions by or around 2050. Secondly, clean cooling provides a solution for sustainably managing the growing cooling demand Singapore faces due to rising temperatures and the Urban Heat Island (UHI) effect, while ensuring that human health and productivity are not impacted.

Singapore has already made significant strides in the adoption of clean cooling. Initiatives focused on improving energy efficiency of cooling services, integrating passive cooling measures in the built environment to mitigate the UHI effect, test-bedding innovative solutions that optimise cooling and cold energy services, and consistently raising minimum energy performance standards of commonly used cooling equipment to encourage the adoption of best available technologies, have all served to decrease total demand from cooling.

As the country plans to increase the penetration of renewable energy via domestic solar photovoltaic (PV) and regional imports, a new set of challenges and opportunities will affect the power system that will increasingly require the power system to address flexibility on top of reducing total demand. With cooling demand being a large contributor to future power demand, managing cooling as an energy vector and an active contributor to flexibility gives significant opportunity to tackle the challenges of the future power grid.

However, the potential of clean cooling as an energy vector is yet to be leveraged in Singapore. The interaction of cooling demand with the energy system presents the opportunity for clean cooling to significantly contribute to the optimisation of the energy system by:

- **Reducing the total demand (and thus peak demand),** which in turn reduces carbon emissions associated with power production as well as the need for further power system infrastructure build out to provide added capacity to meet peak demand.
- **Increasing grid flexibility,** where cooling demand can be shifted to support peak shaving,[7] avoid renewable energy curtailment by consuming potential excess generation or smoothing dynamic variations through demand side response.

ROLE OF CLEAN COOLING AS A SUPPLIER OF FLEXIBILITY

Clean cooling solutions at the intersection of cold energy and cooling services are well placed to ease the constraint that cooling demand can represent for the power system operation, and contribute to the power system as a flexibility provider. The report looks to prioritise clean cooling strategies via two lenses: (i) by **identifying sectors where clean cooling solutions offer the biggest opportunity to provide grid flexibility services,** and (ii) by **identifying clean cooling solutions that address cooling demand, bring flexibility to the grid and have the potential to scale while limiting the growth of GHG emissions in Singapore.**

Through the first lens, it is concluded that **the commercial building sector[8] currently offers the biggest opportunity to provide grid flexibility today given the sector's magnitude of current and future cooling demand, the flexibility of this cooling demand, and the potential for clean cooling solutions to be adopted effectively.**

5 Excluding resource extraction and manufacturing.
6 An energy vector enables the transfer of energy at a specific time or place according to the needs of the end-user.
7 Peak shaving is a demand management strategy used to eliminate short-term spikes in demand by lowering the power consumption peak via scaling down demand, using alternative power generation systems or relying on energy storage solutions.
8 The commercial building sector comprises of offices, retail, hotels and mixed-use developments.

Through the second lens, **four clean cooling solutions are identified for further development in Singapore:**

1. **District cooling for grid flexibility:** District cooling minimises the use of energy by having central cooling plants supply chilled water to buildings through an underground network of insulated pipes, eliminating the need for buildings to install their own chillers. District cooling systems offer a high flexibility potential through their ability to store cold energy in thermal energy storage systems.

   A further scale-up of district cooling in Singapore will support peak demand and facilitate large-scale demand-side response from cooling systems. Benefits of district cooling related to energy savings, reduction in refrigerant use and emissions are widely known. However, to support the wider adoption of district cooling coupled with thermal energy storage, documenting the energy system and economic benefits of such projects in existing cooling networks in Singapore will build a business case for similar, grid-flexibility focused projects in district cooling to be developed.

2. **Control systems for demand side response:** In the context of cooling, control systems relate to the use of smart thermostats integrated with building management systems that can respond quickly and flexibly to temperature changes and other signals programmed into the system. Control systems used at large-scale have a strong grid flexibility potential, and provide support to balancing reserves by shifting the cooling load to different times of day through increasing or decreasing the temperature of buildings. The flexibility benefits of grid-interactive control systems are significant, but not widely known. As such, demonstration projects in commercial buildings or industrial facilities can offer an effective way to showcase the benefits of the technology to the grid and instil best practice in terms of effective installation for different use cases.

3. **Phase change materials (PCMs) providing short-medium duration storage capacity:** PCMs absorb large amounts of heat when it changes phase from solid to liquid, and the stored heat is released when the PCM solidifies again. The use of PCMs in heating, ventilation, and air conditioning (HVAC) systems can store low-carbon energy and release it during peak demand hours, thereby providing flexibility through demand-response. The extent of flexibility potential will depend on the type of technology used to deploy PCMs (e.g. thermal storage for district cooling, 'cool paints' for building envelopes).

   As PCMs are a nascent technology, industry-wide knowledge about their technical capability and extent of use cases is limited. Pilot projects and further research exploring the integration of PCMs across a wide range of technologies and use cases will support the development of an evidence base and bring PCMs one step closer to larger scale adoption.

4. **Cryogenic energy storage systems for longer duration energy storage:** Cryogenic energy storage systems are a form of phase change material technology that releases energy when specific chemicals are manipulated to change from liquid to gaseous phase, allowing the storage or re-use of wasted cold energy for other needs. The systems can store excess supply of renewable electricity at times of peak generation and release it back to the grid at times of high demand or low renewable electricity generation.

   Liquid air energy storage is one type of thermal energy storage that can achieve long duration storage by charging up energy storage during low demand or high generation hours and distribute it at times of lower supply or peak power demand. Given the technology is only just becoming commercial and solution providers are limited, developers in Singapore could benefit from international research collaboration.

RECOMMENDATIONS

While significant developments are noticeable in the direction of policy to support decarbonisation via renewable energy targets and sector-specific greening plans, the application of a whole-systems approach is relatively novel. However, the whole-systems approach has shown to have the potential to provide significant energy and carbon reduction in countries such as the United Kingdom (UK), Colombia, Denmark, Australia and China.[9] [10] [11] This approach considers all possible energy vectors based on their potential to provide flexibility to the grid and can deliver new pathways to support wider decarbonisation goals. **At the core, a focus beyond energy efficiency should be promoted where clean cooling solutions are used to enable grid flexibility. This should be:**

- **Informed by a data-driven approach to quantify the benefits versus costs of clean cooling,** via the following research topics: (i) mapping current cooling demand for sectors with limited data such as industry and transport; (ii) analysing new cooling demand areas such as indoor farming or electric vehicles[12] to identify the opportunities for

9 The Carbon Trust (2021). Zoning in on Net Zero: Developing flexible energy systems. Retrieved June 20, 2022, from https://www.carbontrust.com/news-and-events/insights/zoning-in-on-net-zero-developing-flexible-energy-systems

10 International Renewable Energy Agency (2018). Power System Flexibility for the Energy Transition. Retrieved June 20, 2022, from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Nov/IRENA_Power_system_flexibility_1_2018.pdf

11 International Energy Agency (2019). China Power System Transformation. Retrieved June 20, 2022, from https://iea.blob.core.windows.net/assets/fd886bb9-27d8-4d5d-a03f-38cb34b77ed7/China_Power_System_Transformation.pdf

12 In an electric vehicle (EV), the power electronics (the system that takes electricity from the battery to power the motor to turn the wheels) need to be maintained within a certain temperature window (on average 50°C), and the electric battery in an EV needs to be kept within a temperature range of 20–30°C. [The Economist, Cooling: Transporting us to net zero. Retrieved January 24, 2022, from https://impact.economist.com/perspectives/sites/default/files/cooling_transporting_us_to_net_zero.pdf] clean cooling; (iii) analysing the potential for non-technological clean cooling interventions to shift cooling demand and smoothen peaks; (iv) developing insights on the expected variability of future power demand and how this can be addressed through cold energy storage and batteries; (v) sizing the potential to replace traditional cooling with clean cooling solutions given challenges related to brownfield sites, capital costs, land-use constraints; (vi) mapping waste cold and waste heat energy flows from different industries to support the development of a circular economy through land use planning.

- **Enabled by detailed roadmaps and research and development (R&D) plans:** sector specific roadmaps can detail the activities required to transition towards clean cooling and how current initiatives can be enhanced to bring forward the energy system benefits. With existing and new clean cooling R&D projects, it is important to integrate an additional energy system and grid flexibility lens in their design and implementation. This will ensure that a data-driven approach is embedded into the R&D project so that the broader benefits of clean cooling solutions to the power system are captured and can be scaled up accordingly.
- **Executed on the whole-of-government level to ensure effective implementation:** which involves conducting a whole-system assessment of flexibility requirements, the use of policies that develop an ancillary market to remunerate flexibility providers, and refining tariff mechanisms. In addition, there is scope to expand financial incentive schemes to support the economic viability of novel clean cooling solutions and improve the business case for deep retrofits. Examples of this include expansions to the scope of current schemes such as the Green Mark Incentive Scheme for Existing Buildings including mandating the implementation of technologies that not only bring about efficiency gains but also offer flexibility benefits (e.g. control systems and PCMs).

1 INTRODUCTION

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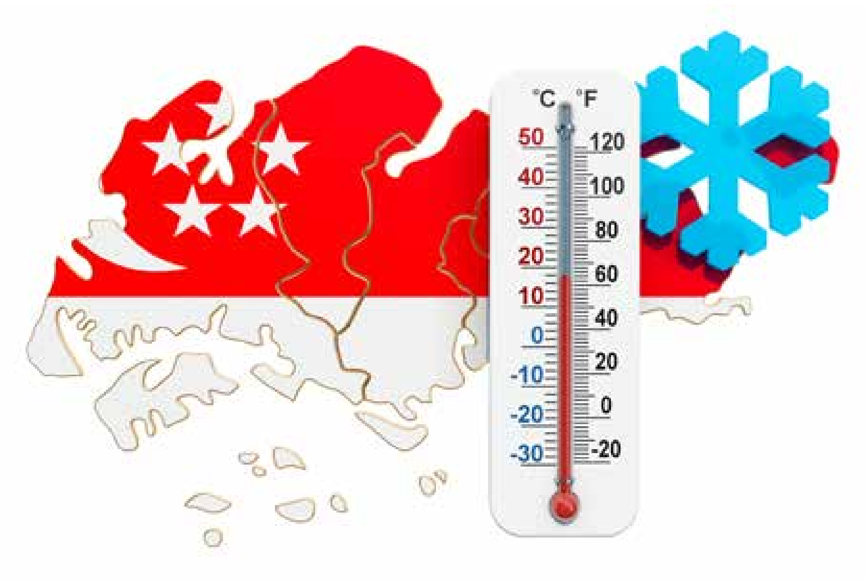


1. INTRODUCTION

1.1. PROJECT BACKGROUND

In February 2022, Singapore raised its climate ambition and made a commitment to achieve net zero emissions by or around 2050. In addition, the Energy 2050 Committee report commissioned by the Energy Market Authority (EMA) noted that it is realistic for Singapore's power sector "to aspire to [net zero] by 2050". In this context, cooling will play a critical role to meet the targets given the size of the sector in terms of electricity consumption and GHG emissions. Cooling demand represented 30% of Singapore's electricity demand in 2019, or 15.3 TWh. Cooling demand is poised to increase by 66% to 25.4 TWh by 2030. Cooling emissions were 5.53 Mt CO2eq[13] in 2016, approximately 11.5% of national GHG emissions and are projected to reach 7.66 Mt CO2eq by 2030 if cooling services are deployed in a business-as-usual fashion.

WWF-Singapore has commissioned the Carbon Trust to investigate the role of clean cooling as an energy vector to efficiently and cost-effectively support Singapore's energy transition to a decarbonised future. This study aims to build on Singapore's leadership in implementing energy efficient cooling measures and highlight the opportunity Singapore has in deploying comprehensive and innovative cooling solutions that can benefit the country's power sector while minimising emissions.

Study objectives

- Develop a holistic, qualitative review from the whole systems perspective that examines cooling decarbonisation opportunities, including leveraging clean cooling for supporting wider energy transition and decarbonisation goals.
- Understand how to unlock clean cooling technology opportunities in Singapore and conduct a deep dive on specific needle-movers that can enable rapid decarbonisation of the cooling sector.
- Use the findings of this study to develop informed recommendations that raise the ambition of public and private sector commitments to net zero.

This report first contextualises cooling in Singapore and its relationship to the power grid, and then focuses on clean cooling solutions that can alleviate the power system and further provide flexibility services as part of decarbonising the power system. The report also recommends a series of policies and research activities needed to mainstream the value of integrating cooling within the energy system across energy, urban and industry planning processes.

13 *Green Cooling Initiative. Singapore. Retrieved January 24, 2022, from https://www.green-cooling-initiative.org/country-data#!country-data-sheet/702/all-sectors The calculation in the source accounts for direct (refrigerants) and indirect (energy consumption) emissions.*

1.2. DEFINITIONS

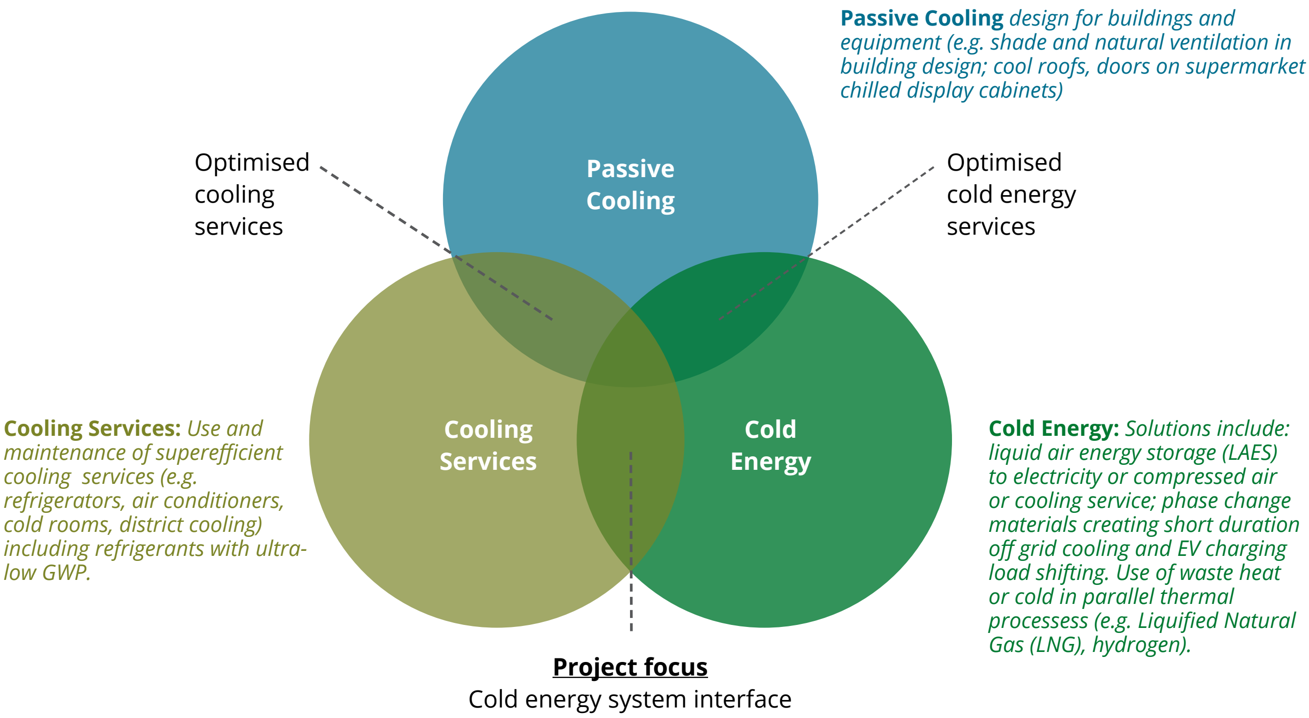
DEFINING CLEAN COOLING

Cooling refers to any human activity, design or technology that dissipates or reduces temperatures and contributes to achieving (i) reasonable thermal comfort for people, or (ii) preservation of products and produce (medicines, food etc.), and (iii) effective and efficient processes (e.g., data centres, industrial or agricultural production and mining).

Our study defines clean cooling as solutions that reduce GHG emissions from cooling during the operational life of products (excluding resource extraction and manufacturing) with the aspiration to be in line with the Paris Agreement and the Kigali Amendment to the Montreal Protocol.[14]

The broad definition of clean cooling and its wide range of applications (Industrial, Commercial, Households and Transport) result in clean cooling solutions that are diverse in terms of technology types and dependent on the sector of application. Solutions can either be technology focused, integrated in urban planning and building design processes or tackle consumption patterns through behavioural change or optimised services.

Figure 1: *Categories of clean cooling interventions*



The clean cooling categories defined in the figure above are:

- Passive cooling: measures that avoid or reduce the need for mechanical cooling including reduction in cooling loads, smart and human centric design, and urban planning.
- Cooling services: where any cooling equipment used is super-efficient (highest performing technology in the market) and uses refrigerants with ultra-low GWP.
- Cold energy: thermal energy solutions using cryogenic or other PCMs that enable short to long term storage of renewable and excess electric energy at low or sub-zero temperatures.

[14] *Parties who ratified the 2015 Paris Agreement have committed to substantially reduce global greenhouse gas emissions to limit the global temperature increase in this century to 2 degrees Celsius while pursuing efforts to limit the increase even further to 1.5 degrees. The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer is the multilateral environmental agreement that regulates the production and consumption of man-made chemicals (typically used in cooling systems) referred to as ozone depleting substances (ODS). In this process ODS have been replaced by hydrofluorocarbons (HFCs) which have high global warming potential, stronger than carbon dioxide (CO2) emissions. As a result, in 2016 the Kigali Amendment to the Montreal Protocol was created as an international agreement to gradually reduce the consumption and production of hydrofluorocarbons (typically used in cooling systems) to avoid over 80 billion metric tons of carbon dioxide equivalent cumulatively through 2050.*

Singapore has ratified the Kigali Amendment in June 2022 and will be phasing down the consumption of HFCs by 80% over the next two decades to meet the obligations. More information on Singapore's initiatives to tackle high GWP refrigerants are noted in Appendix 9.

COOLING AS AN ENERGY VECTOR

Whilst all three categories are important to improve cooling efficiency, the study seeks to provide a new perspective by focusing on the intersection of cooling services and cold energy and the potential interaction with the power system. This means recognising cooling as an energy vector that can play an active and key role within the energy system.

Cold energy could play a useful role in supporting existing cooling services by providing additional reductions or shifting electricity demand. When thought of as a cold store, cold energy can provide provisioning storage services for waste cold energy that can then be supplied as additional cold to cooling services at a different time to reduce electricity demands. If used during times of low access to renewable energy, stored cold energy can reduce use of fossil fuels. Additionally, excess renewable electricity generation could be converted and stored as cold energy and then released back to the grid during high-demand periods. This provides flexibility services (i.e., demand shifting, long term storage) while also mitigating the intermittency issue often associated with renewable energy.

Compared with a conventional electric battery, cold energy storage has several distinct benefits: (i) it can store renewable energy for longer, (ii) renewable energy can be supplied for productive work as cold energy with reduced energy transformation losses, (iii) renewable electricity can be generated with comparable or fewer system losses, and (iv) cold batteries last much longer than chemical batteries and do not suffer from life cycle limitations. Together, these functionalities could support a reduction in overall cooling demand as well as provide grid flexibility services, potentially reducing the cost to meet growing cooling demand.

1.3. METHODOLOGY

The study uses a mix of primary data (mainly qualitative) gathered from interviews with public and private sector institutions, academics and non-profit stakeholders on pilot and commercial clean cooling initiatives being progressed in Singapore, and secondary research on the characteristics of Singapore's current and future cooling demand and power system. Both sets of data and insights are used to develop the following analysis:

- **Characterising the current interaction between cooling demand and the power system:** A cooling demand curve is developed based on three sector-based metrics – (i) current volume of cooling demand; (ii) expected increase in the cooling demand; (iii) the profile of the cooling demand on a typical day.
- **Assessing the potential evolution of the cooling-power systems interaction in the absence of clean cooling:** The potential future cooling load is estimated from the expected growth in cooling demand by 2030 assuming a business-as-usual scenario (without the role of efficiency gains). The future power demand profile is also estimated and analysed together with the expected development in solar generation[15] and renewable energy imports from neighbouring countries, and their contribution to power generation supply in Singapore.
- **Potential role of clean cooling to provide flexibility services to the power system:** The types of challenges that arise from the future cooling power systems interaction - a high cooling load and rapid ramp up of peak demand - are used as the basis to determine the nature of services that cooling can provide to alleviate the strain on the grid.
- **Identifying clean cooling solutions in terms of their flexibility potential:** Based on the range of flexibility services needed by the grid , the study identifies clean cooling solutions that could provide these services.
- **Prioritising clean cooling solutions for further development:** The study identifies and prioritises solutions that are well placed to be adopted by sectors given each sector's current and future cooling demand and describes how this is expected to potentially provide flexibility services to the grid.

[15] *Energy Market Authority (2021). Solar Generation Profile. Retrieved 14th February, 2022, from https://www.ema.gov.sg/Solar_Generation_Profile.aspx*

1.4. LIMITATIONS OF THE STUDY

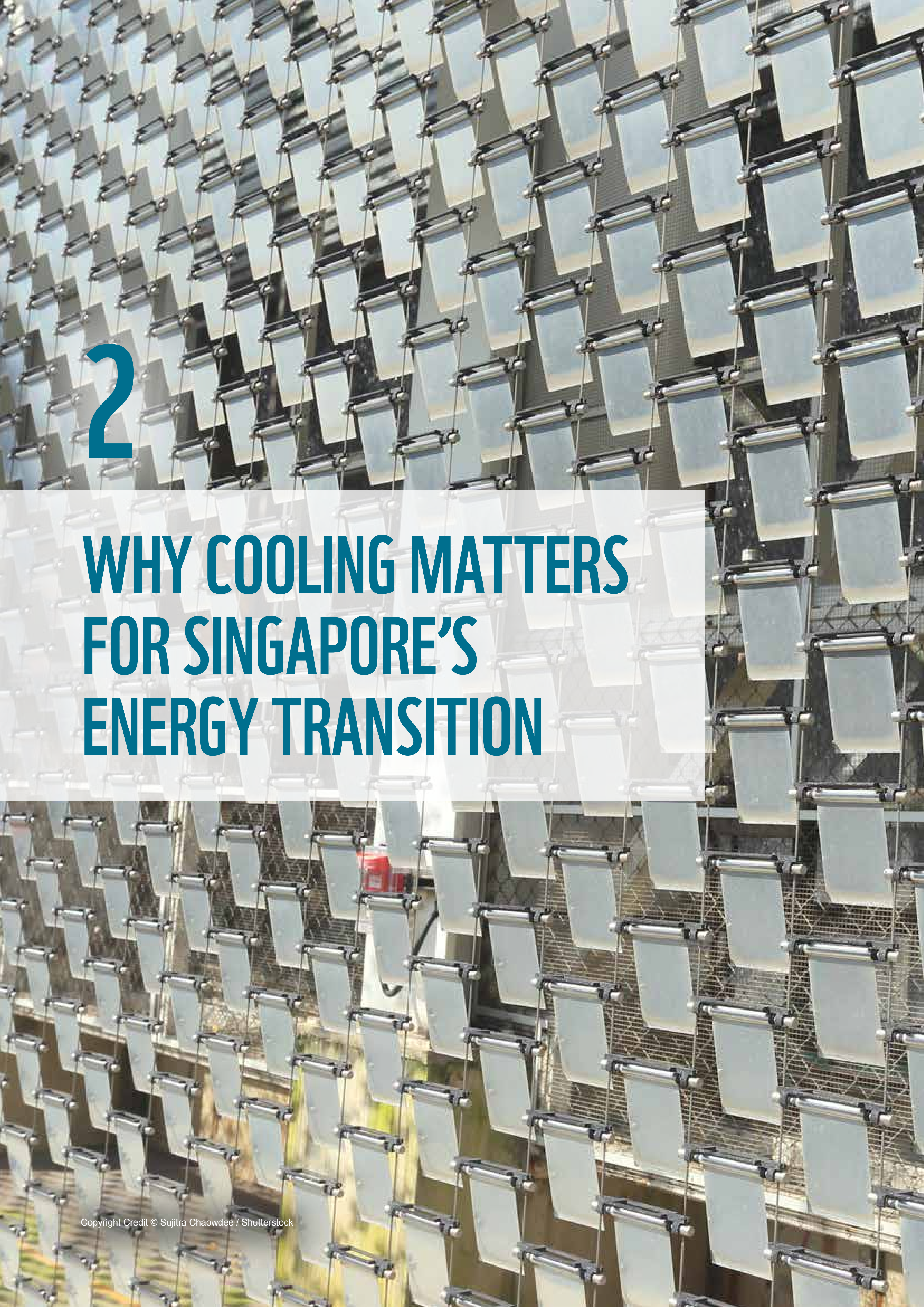
The main limitations encountered for this study relate to the lack of granular information at every sectoral level regarding cooling demand, how it is currently supplied, its interaction with the power system, and long-term projections. Research conducted and engagement with stakeholders in Singapore revealed that some of this information is not readily collected or isolated at the cooling level, while other figures may not be publicly available due to their sensitive nature.

Regarding long-term projections of the electricity sector, substantial uncertainties remain on Singapore's future mix. The recent Energy 2050 Committee report outlines three "critical uncertainties"[16] that could impact Singapore's power sector. Pathways in which the supply mix substantially differs have been developed to cover these uncertainties, with variations in the role of imports, hydrogen, renewables or nuclear for example.

To address data gaps, several assumptions have been undertaken to develop the study:

- In the absence of public information, current profiles of cooling and power demand are used to assess the potential cooling power system interactions in the future.
- While this study uses indicative profiles of power demand and cooling demand to illustrate trends, the profiles are not representative of the whole variability within the sectors and through the years.
- In the absence of granular public information for certain sectors, proxy data or assumptions have been used to inform the qualitative analysis. Examples of this include (i) the use of proxy data from a study based in Hong Kong to estimate the industrial sector's cooling demand profile in Singapore; (ii) a steady profile is assumed for data centre demand for cooling based on feedback from stakeholder interviews; (iii) the energy source used to power cooling systems is assumed to be electricity; (iv) future cooling demand growth is estimated based on proxy data on cooling equipment sales until 2030; (v) an even distribution was estimated between the continuous and occupancy-based cooling load profiles in Singapore's residential and commercial sectors.

[16] *The three "critical uncertainties" identified in the EMA's Energy 2050 Committee report commissioned by EMA are: Technology advancement of low-carbon energy technologies; pace of digital technology advancement in the power sector; impetus for collective action on power and carbon trading.*



2

WHY COOLING MATTERS FOR SINGAPORE'S ENERGY TRANSITION

2. WHY COOLING MATTERS FOR SINGAPORE'S ENERGY TRANSITION

Singapore plans to reach economy-wide net zero emissions by or around 2050 and the evolution of its power generation mix is integral to this goal.[17] According to the Energy 2050 Committee report commissioned by EMA in March 2022,[18] it is "technically viable for the Singapore power sector to achieve net zero emissions, while maintaining energy security and affordability", and it is "realistic for the sector to aspire to do so by 2050". While transitioning to low-carbon fuels is vital, other energy vectors that can tackle growing energy consumption and its corresponding constraints on the grid must also be considered.

Cooling is one such vector that affects Singapore's energy transition. Cooling contributed towards 30% of Singapore's electricity consumption in 2019, and the demand is projected to grow by 66% between 2019-2030. It is a significant source of peak demand, comprising of nearly a quarter of peak demand in 2019 and 15% of total installed capacity. Besides having a direct impact on the size of peak power demand, cooling demand from key sectors such as commercial buildings and households can also affect the grid due to rapid ramp ups in cooling load triggering sharp variations on the power demand curve. With sufficiently flexible capacity in the power system today provided by gas generation, the variability characteristics of cooling do not affect the grid. However, any increase in variable supply due to targeted renewable energy imports also imply the need to look at the value of flexible resources for the grid.

The impact of the growth in cooling on future power demand could not only result in less efficient power generation assets being used to meet peak demand and further grid infrastructure needs, but the total power demand profile could also change with cooling peaks becoming a more prominent part of the demand profile. Therefore, understanding and managing cooling as an energy vector and how it could contribute as a flexible resource for the grid can further contribute to overall emissions.

To date, Singapore has actively adopted energy efficiency measures for cooling across multiple sectors which has been critical to the country's energy transition (further details on these initiatives are noted in section 2.2.2). As such, this report seeks to add value by highlighting the importance of looking beyond reducing cooling demand to view cooling as an energy vector and provider of flexibility. With that lens, cooling can be seen as a pathway to solving critical issues related to growing energy demand and supporting the integration of variable low-carbon generation assets. The study is therefore complimentary to the renewable energy scenarios currently under assessment by the government and could be an asset in unlocking grid flexibility opportunities.

2.1. THE CHALLENGES OF COOLING ON SINGAPORE'S ENERGY TRANSITION GOALS

Singapore's energy transition targets and plans indicate that the country could reach economy-wide net zero emissions by or around 2050. Key strategies include the evolution of the power generation mix, importing renewable energy from neighbouring countries and relying on carbon capture and storage technologies as well as developments in alternative fuels such as hydrogen. Further, carbon tax will be raised progressively from 2024 to support and push businesses and individuals to lower their carbon footprint through investments in low-carbon technologies and solutions.[19]

Mapping the potential impact of cooling (in Appendix 6) on Singapore's energy transition targets shows that cooling has a direct or indirect limitation on achieving these targets:

- The growth in cooling demand could be attributed to the impacts of climate change (temperature rise) increasing cooling needs and leading to increased uptake of cooling technologies as more consumers are opting for such solutions;
- The growth in cooling demand contributes towards greater GHG emissions if we continue to rely on fossil fuel generated electricity;
- The required installed capacity, network dimensioning, or share of renewable penetration will directly depend on the total power demand, significantly determined by cooling;
- A high or inflexible cooling demand can lead to higher peak power demand, increasing the operational and infrastructure costs to support an increase in the installed capacity of the power system

[17] *Singapore Economic Development Board (2022). Budget 2022: New net zero emissions target a bold move that will create jobs. Retrieved 18 May, 2022, from https://www.edb.gov.sg/en/business-insights/insights/budget-2022-new-net zero-emissions-target-a-bold-move-that-will-create-jobs.html*

[18] *Energy Market Authority (2022). Charting the Energy Transition to 2050. Retrieved 22 March, 2022, from https://www.ema.gov.sg/cmsmedia/Publications_and_Statistics/Publications/Energy-2050-Committee-Report.pdf*

[19] *National Climate Change Secretariat (NCCS) (2022). Singapore Will Raise Climate Ambition to Achieve Net Zero Emissions By or Around Mid Century, and Revises Carbon Tax Levels from 2024. Retrieved 18 May 2022 from Singapore Will Raise Climate Ambition to Achieve Net Zero Emissions By or Around Mid Century, and Revises Carbon Tax Levels from 2024 (nccs.gov.sg)*

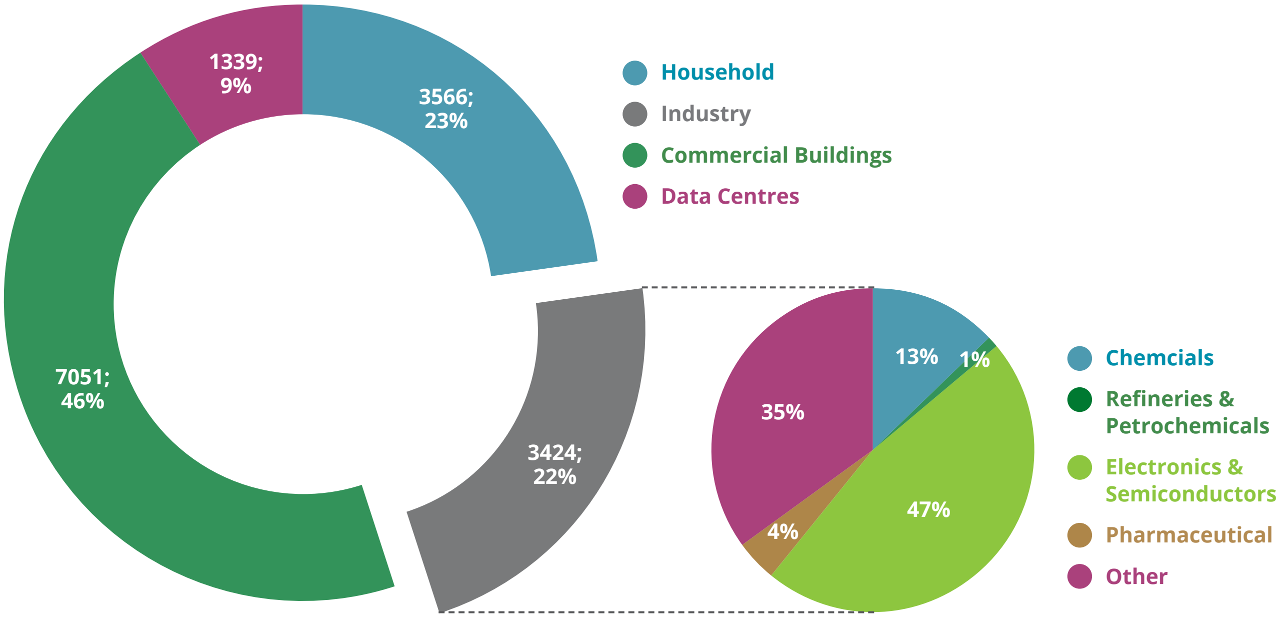
2.2. THE IMPACT OF COOLING ON CURRENT AND FUTURE ENERGY CONSUMPTION

2.2.1. COOLING DEMAND IS A LARGE CONTRIBUTOR TO TOTAL CURRENT AND FUTURE POWER DEMAND

Current cooling demand

Cooling services accounted for 15 TWh of Singapore's electricity demand in 2019, approximately 30% of the country's total power consumption. Figure 2 shows the estimated breakdown of cooling service users. The calculation methodology is documented in Appendix 1.

Figure 2: *Breakdown of Cooling Demand (GWh) 2019*



Commercial building sector: Highest demand for cooling consuming 7.05 TWh in 2019 and representing 13.6% of the total electricity consumption. This is the result of the continuous operations of commercial buildings which necessitates demand being met by large-scale systems such as water- and air-cooled chilled water plants, and district cooling.

Household sector: Second largest cooling demand in Singapore due to the use of air conditioners, refrigerators, and freezers, representing 6.9% of the total electricity consumption.[20] While regulations such as the Minimum Energy Performance Standards have been effective in improving the efficiency of equipment available in the market, it is not possible to expect all households to install the most energy efficient technologies, thereby limiting the potential to minimise energy use required for cooling.

Industry:[21] While energy consumption by cooling systems across industry is not specified, the National Environment Agency (NEA) notes that chilled water systems consumed approximately 3.42 TWh[22] of electricity in 2019, which is equivalent to 16% of the total electricity consumed by the sector.[23] The primary contributor to cooling demand in industry is the electronics and semiconductor sector which consumed 3.11% of Singapore's total electricity consumption in 2019. However, chiller systems in electronics and semiconductor facilities are one of the most efficient in the industry.

[20] *With the household sector's total energy consumption at 747.2 ktoe in 2019, and Singapore's total energy consumption at 16,135 ktoe, energy consumption from cooling in the household sector represents 1.89% of the country's total energy consumption. Assuming that all the energy consumed for cooling is powered by electricity, it is estimated that cooling contributed to 3.57 TWh of electricity consumed by the household sector in 2019.*

[21] *The breakdown of cooling demand by industrial sub-sector is calculated based on cooling system data provided by NEA, as well as the percentage energy use by industrial sub-sector as a proportion of total industrial primary energy use noted in the 2010 study by NCCS for Chemicals (42% of total industry energy use), Refineries and Petrochemicals (34% of total industry energy use), Electronics and Semiconductors (6% of total industry energy use), Pharmaceutical (1% of total industry energy use). It is assumed that the percentage energy use by each sub-sector in 2010 remains constant for 2019, and that there is no significant difference in drawing insights from both primary energy use and final energy use data from 2010 and 2019 respectively. Source: National Climate Change Secretariat (2010). Industry Energy Efficiency Technology Roadmap. Retrieved 14th January 2022, from https://www.nccs.gov.sg/docs/default-source/default-document-library/industry-energy-efficiency-technology-roadmap.pdf*

[22] *This was estimated using data from 2017 and 2019. 2017 data from NEA cited in footnote 22 noted that approximately 16% of the industry's total electricity consumption was from chiller systems, and data from EMA's Singapore Energy Statistics cited that total industry electricity consumption was 21.4 TWh in 2019. Final energy consumption in the industrial sector in 2019 was 10,961 ktoe.*

[23] *National Environment Agency (2019). Singapore To Extend Energy Efficiency Requirements To Cooling Systems In Industrial Facilities. Retrieved 14th January, 2022, from https://www.nea.gov.sg/media/news/news/index/singapore-to-extend-energy-efficiency-requirements-to-cooling-systems-in-industrial-facilities*

NEA's Minimum Energy Efficiency Standards for cooling systems in industrial facilities is expected to improve the adoption of more efficient water-cooled chilled water systems by 2029, enabling sub-sectors with more inefficient chiller systems such as refineries and petrochemicals, and the food and beverage sector to benefit from greater efficiency gains.

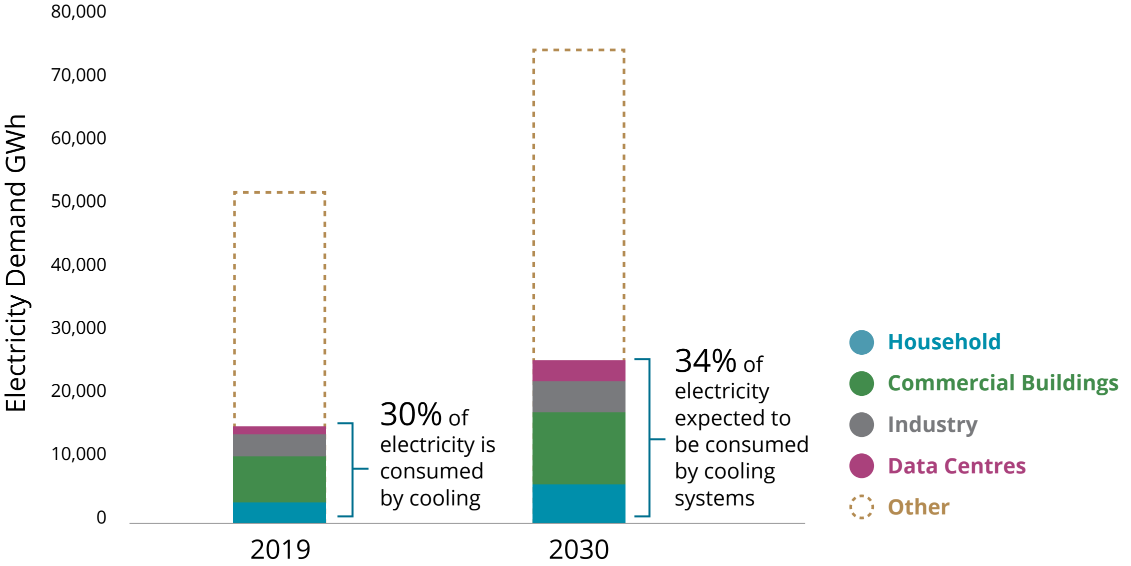
Data centres: Cooling systems consumed 1.34 TWh of electricity in 2019, representing 2.6% of Singapore's total electricity consumption. This is due to the energy required to cool information technology (IT) equipment which accounts for approximately 37% of the total energy consumed by the sector.

Transport: As data on energy demand from cooling systems in cold chain transportation and mobile air conditioning systems is not available for Singapore, estimates by the International Council on Clean Transportation note that mobile air conditioning systems installed in vehicles typically consume up to 20% of total fuel use in very hot, humid regions with traffic congestion.[24] Assuming this statistic applies to Singapore, it is estimated that cooling systems contribute towards 3.2% of Singapore's total energy consumption.[25]

Future cooling demand

For Singapore, power consumption for cooling services is projected to grow by 66% by 2030, rising from 15,381 GWh in 2019 to 25,380 GWh. This is based upon analysis of projections by United Nations Environment Programme (UNEP) for the household sector, Green Cooling Initiative for the industrial and household sectors, and from the Ministry of Trade and Industry (MTI) for data centres (see Appendix 2 for assumptions).

Figure 3: *Projected growth in electricity demand for cooling and other services* (GWh)*



Sector	Growth between 2019 – 2030 (%)	Growth between 2019 – 2030 (GWh)
Commercial Buildings	65%	4,576
Household	63%	2,247
Data Centres	149%	1,963
Industry	39%	1,300

While data centres will see the fastest demand growth, commercial building cooling demand will still represent close to half of 2030 cooling demand from the sectors analysed. New power demand for cooling can also emerge when sectors see greater electrification, including as a replacement of the direct use of fossil fuels. Electrified transport and indoor farming are examples of new growth sectors, which have yet to be fully analysed given the lack of data for approximations.

The adoption of electric vehicles is expected to see the current cooling demand in the transport sector of 6,013 GWh shift from direct fossil fuels to electricity. Singapore's tropical climate is an added challenge to ensuring that electric vehicles have sufficient battery capacity based on The Economist's report on cooling.[26] The power requirement to cool the cabin and the battery in 30°C temperatures can reduce battery range by 25%. As such, energy consumption from cooling is not only an important issue to address in terms of managing emissions in the transport sector but also in terms of enabling a widespread adoption of electric vehicles.

These shifts, and other potential sectoral changes, could result in a further strain on the power system level, but also at specific nodes depending on how future charging or land-use planning incorporates these changes.

[24] *International Council on Clean Transportation, Mobile Air Conditioning. Retrieved January 24, 2022, from https://theicct.org/sites/default/files/publications/ICCT_mobile-air-cond_CBE_201903.pdf*

[25] *The total energy consumption in the transport sector was 2,583 ktoe in 2019. Assuming 20% of the annual fuel consumption of vehicles is for cooling, this is approximately 516 ktoe.*

[26] *The Economist, Cooling: Transporting us to net zero. Retrieved January 24, 2022, from https://impact.economist.com/perspectives/sites/default/files/cooling_transporting_us_to_net_zero.pdf*

2.3. THE IMPACT OF COOLING ON GRID FLEXIBILITY

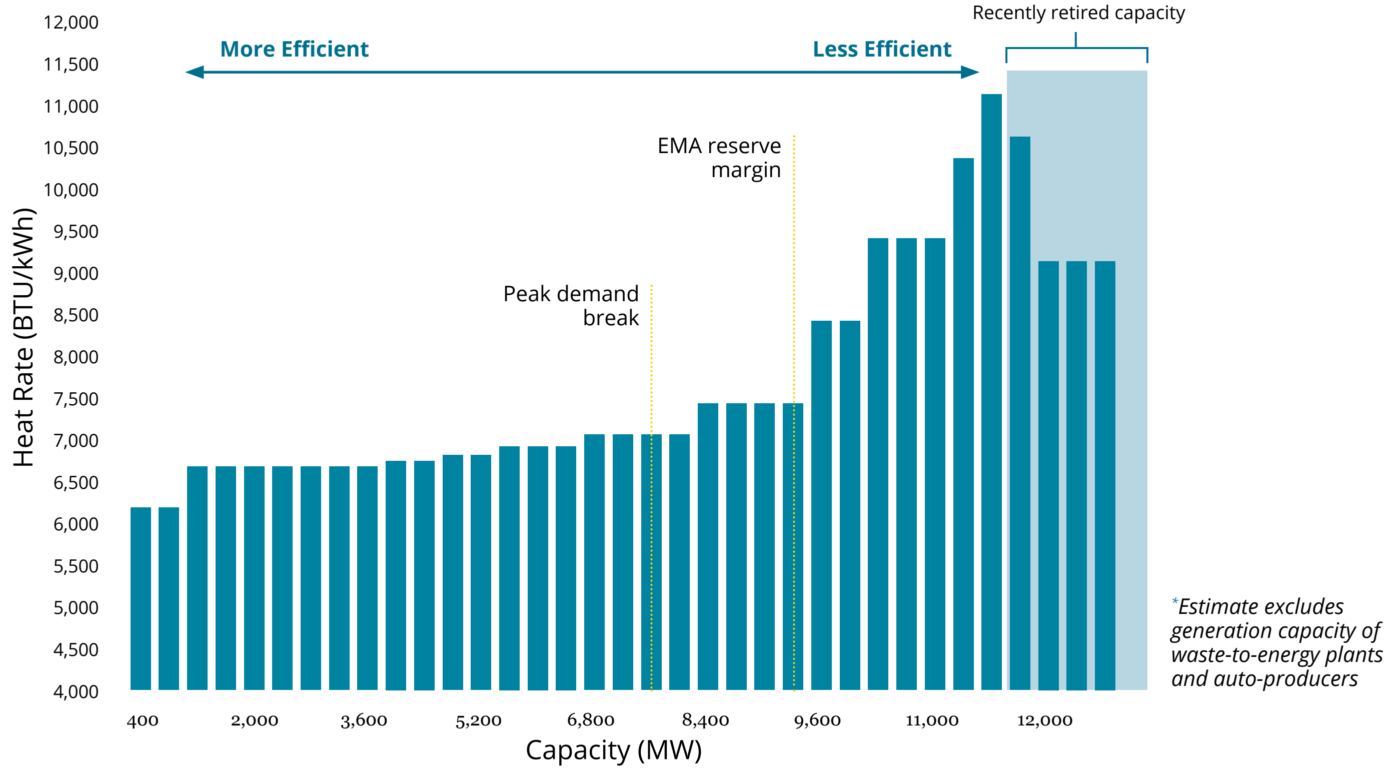
2.3.1. THE STATE OF CARBON INTENSITY AND FLEXIBILITY OF THE GRID TODAY

Singapore's power system today is heavily reliant on natural gas, which represents 95% of the current power generation mix. Currently, the power system is stable and displays a high reserve margin, with peak demand significantly lower than installed capacity. The carbon efficiency of the installed capacity (CO2eq/MWh) is relatively constant even at the capacity needed to satisfy Singapore's peak demand. With low strains on the grid to date, flexibility is not a critical issue to manage at present and the emissions intensity impact of power demand increases within this peak is low. It is also worth noting that the government is recognising flexibility as a lever to achieve a net-zero energy system owing to the larger benefits it could provide to this sector.

Peak demand: Peak power demand in Singapore has been consistently lower than installed capacity. In the past five years the excess capacity (the difference between peak demand and installed capacity) ranged from 47% in 2017 to 36% in 2021 (as of October 2021).[27]

Role of merit order on meeting peak demand: During peak demand hours, more capacity is needed to meet demand. According to the merit order, the most efficient assets will be called first, but less efficient assets may be called to fulfill demand: the lower efficiency implies higher fuel consumption and carbon emissions per unit of power generation.

Figure 4: *Merit Order of Singapore's Generation Capacity* (adapted from Deloitte 2021)* [28]



However, the assessment of the merit order curve (Figure 4) shows that the efficiency of gas assets remains constant for 8,000MW of installed capacity, which is higher than the peak load since 2017. Therefore, in the current state of the power system, emissions intensity associated with each unit of power consumption are not expected to substantially vary in time.

Current strains on the power system: According to the power system performance data collected by EMA,[29] the average number of power interruptions per customer has continued to decrease between 2018 to 2020 from 3.65 minutes to 0.17 minutes of interruption per customer. The power disruption in 2018[30] was largely a result of a partial loss of electricity supply from two power generation companies due to an equipment fault. Overloading of the grid has not been cited recently as an issue affecting the grid.

[27] *Please refer to Appendix 4 for more details.*
[28] *Please refer to Appendix 4 for more details on merit order.*
[29] *Energy Markets Authority. Singapore Energy Statistics. Retrieved January 11th 2022, from https://www.ema.gov.sg/cmsmedia/Publications_and_Statistics/Publications/EMA-Annual-Report-FY2020-2021.pdf*
[30] *Ministry of Trade and Industry. Parliament Q&A 1st October 2018. Retrieved January 11th 2022, from https://www.mti.gov.sg/Newsroom/Parliamentary-Replies/2018/10/Oral-reply-to-PQ-on-electricity-disruption*

2.3.2. THE ROLE OF THE CURRENT COOLING LOAD ON THE GRID

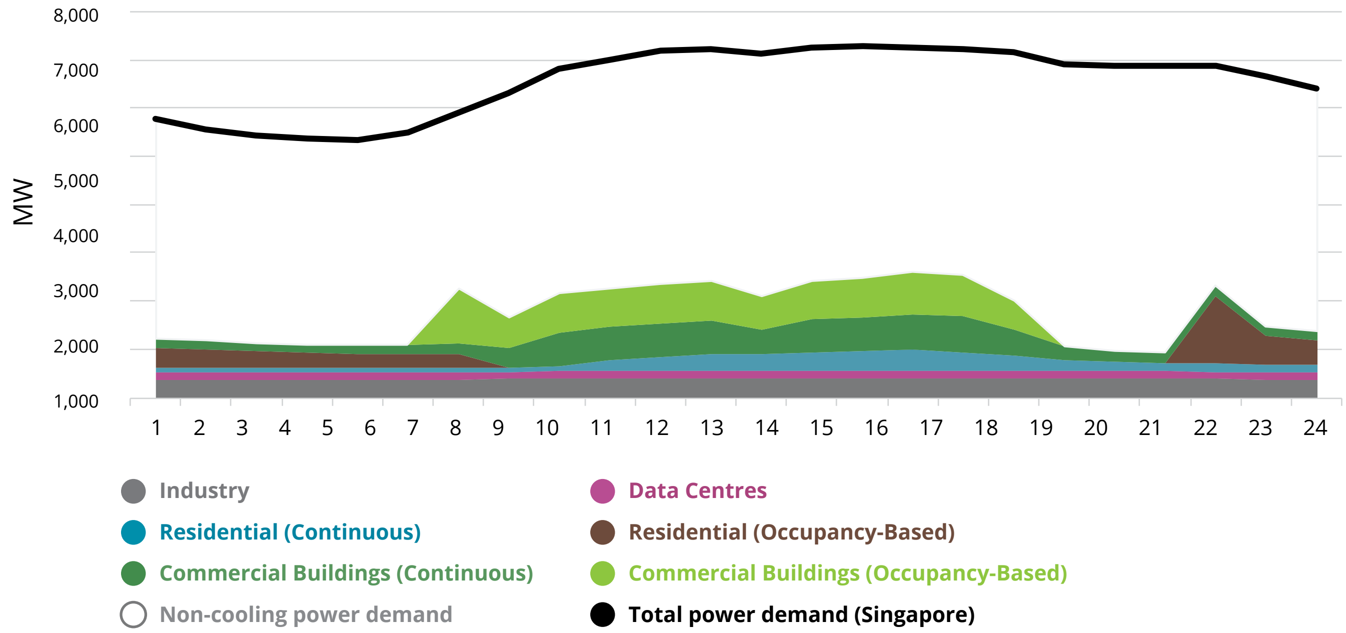
Although the current contribution of cooling load to peak demand is significant, it does not impact the grid's carbon efficiency because the installed capacity of the most efficient gas assets is greater than the current peak demand (see Figure 4).

Contribution of cooling to peak demand: Singapore's cooling electricity demand is equivalent to 1.75 GW of power capacity required for cooling every hour under the assumption that the demand is evenly distributed throughout the day. This represents nearly a quarter of peak demand in 2019 and 15% of total installed capacity.

Based on the estimation of sectoral cooling demand (Figure 2), we can further estimate the hourly electricity required to meet the cooling demand across sectors. The commercial buildings sector has the highest cooling demand, and an average 0.8 GW of power generation capacity is needed every hour to meet the 7 TWh cooling demand in 2019.

Hourly profile of cooling demand: Power consumption for cooling will not be constant across all hours of the day. It varies across the day depending on the activities of each sector and is correlated with ambient temperature. Figure 5 below illustrates the profiles and shares of hourly cooling demand across different sectors (as stacked areas) compared to the total power demand in Singapore (as the black line). (Appendix 3 illustrates the sector-specific cooling demand profiles, and Appendix 4 illustrates the total power demand in Singapore).

Figure 5: *Hourly profile of cooling demand by sectors* [31]



This figure provides the following insights:

- Cooling demand significantly contributes to the power demand curve, and the concentration of commercial building demand for cooling during the 7am-7pm window is synchronised with peak power demand;
- The high-power demand at 10pm is simultaneous to the occupancy-based residential cooling demand increase in the evening before a decrease from 11pm;
- A high share of occupancy-based cooling demand can trigger sharp variations in the cooling load on the power sector, both in the commercial building and residential sectors. This translates to an increase in cooling demand at 7am and 10pm.

COVID-19's impact on cooling's contribution to peak demand: It is expected that the depiction of cooling demand over a typical day in 2019 may change when considering the shift towards flexible working, which involves a mix of working from home and the office following the impact of COVID-19. This is expected to raise the demand for continuous cooling in the daytime in the residential sector. For the commercial sector, cooling demand may be maintained at the present trend or an occupancy-based cooling schedule may be encouraged. Remote working would contribute towards the peak in power demand within the 7am-7pm window, while smoothening the increase in power demand noted at 10pm that occurs in occupancy-based residential cooling behaviour.

[31] *A continuous cooling demand is where cooling is operated from 00:00 to 24:00, and an occupancy-based use of cooling is where the cooling system is operated from 7:00 to 18:00 in commercial buildings and 22:00 to 7:00 in residential buildings. 50% of cooling demand in these sectors is assumed to follow an occupancy-based schedule.*

Implications of the cooling demand profile on the grid: Presently, the timing of cooling demand, that is cooling demand's contribution to peak demand, is not expected to significantly impact the carbon emissions intensity to provide for cooling. This is because the installed capacity of the most efficient power generation assets exceeds peak demand, implying that cooling's contribution to peak demand will not result in more energy-intensive assets being called online to meet this demand. Reducing the amount of electricity consumption however, through efficiency gains for example, will directly reduce emissions because of avoided power generation.

2.3.3. INCREASING NEED FOR GRID FLEXIBILITY IN THE FUTURE

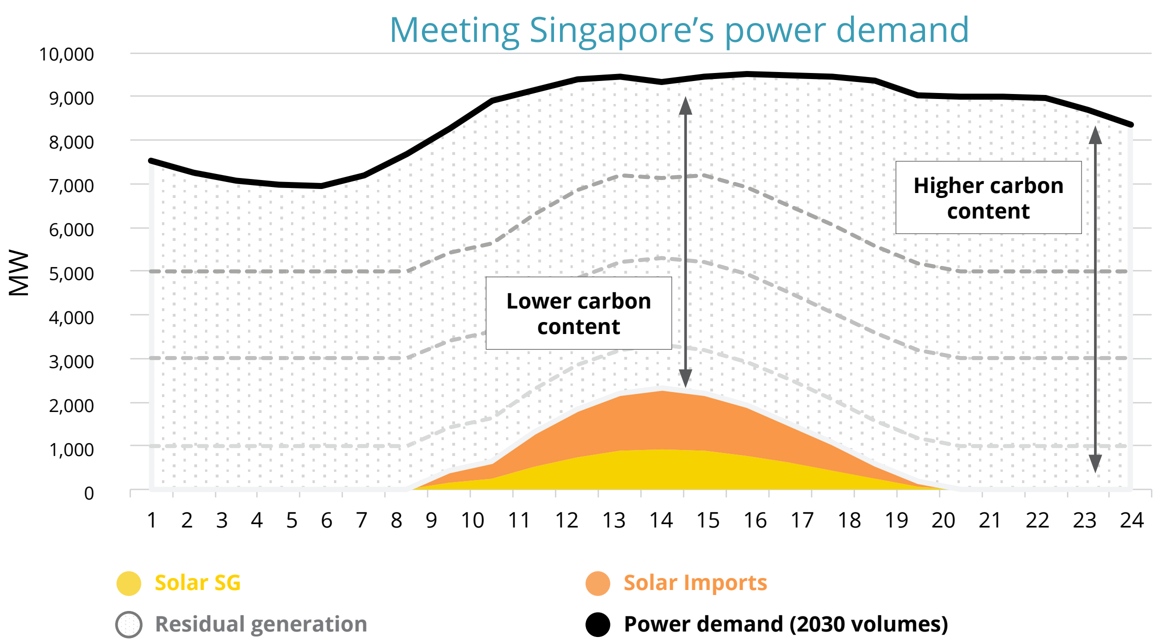
Future peak power demand might require less fuel-efficient gas generation assets to come online. Unless significantly more efficient power generation assets are installed to meet growing future energy demands, this could result in greater emissions intensity. Even though more renewable energy sources are expected to contribute to the power mix, they are less flexible. If renewable generation does not align closely with peak demand, it is likely that inefficient, carbon-intensive assets will be called to provide peak power. As such, investing in grid flexibility can become critical to support Singapore's low-carbon energy transition.

Singapore's peak demand is projected to reach between 9.8 – 10.6 GW by 2030 according to EMA.[32] Based on the current generation asset mix illustrated in the merit order chart shown in Figure 4 above, this would mean calling on generation assets that could be at least 20% less efficient than at today's peak demand.

Singapore has set targets to decarbonise and increase the share of renewable energy in its power mix.[33] Through the journey to net zero, the fleet of assets will show heterogeneity in terms of generation profiles and associated carbon emissions. Optimising the grid further for efficiency will lead to calling on low-carbon technologies first, in the hours they are available. Installations relying on fossil fuels and associated to carbon emissions are expected to be called last to fill the residual generation needs, as fuel and emissions lift their short-run marginal costs. Given the uncertainties of the evolution of Singapore's mix and power demand, Figure 6 is an illustration of a potential future day, in which several layers of technologies (based on carbon intensity) are stacked to meet power demand.

Increased generation and imports of renewable energy, from solar PV, will lead to the generation of decarbonised energy in the daytime when solar energy is available. The dashed lines illustrate potential different technologies that will be used to meet the power demand based on the merit order. During hours with high demand and/or low renewable generation, the residual generation necessary to meet demand will increase. At this time, less efficient assets will be used to meet the demand, and the overall carbon content of power generation will increase. Maximising the use of future renewable generation coming onto the grid will require further investment into flexible resources for the grid, which can also come from flexible demand, like cooling.

Figure 6: *Meeting Singapore's future power demand: solar PV, imports and residual generation*



Note: The grey dashed lines are illustrative of the size of the residual generation. Should Singapore's fleet of power generation assets evolve towards the addition of low-carbon technologies, the different layers illustrate different assets with different carbon content that could be called to answer the power demand, with the lowest carbon content assets called first. The solar generation profile is based on EMA estimated solar generation output[34] and can present substantial variations depending on the day and weather patterns.

[32] *Energy Market Authority. Singapore Electricity Market Outlook 2021. Retrieved January 13, 2022, from: https://www.ema.gov.sg/cmsmedia/PPD/Singapore-Electricity-Market-Outlook-2021.pdf*

[33] *Singapore's energy transition targets are developed in section 2.3.4*

[34] *Energy Market Authority (2021). Solar Generation Profile. Retrieved 14th February, 2022, from https://www.ema.gov.sg/Solar_Generation_Profile.aspx*

CASE STUDY: Energy storage system saved about $40 million across 2018

A Tesla battery storage installation of 100MW/129MWh in Australia is providing grid services to the power system and is estimated to provide substantial benefits to the whole system. The impact evaluation estimates that "the battery allows annual savings in the wholesale market approaching $40 million by increased competition and removal of 35MW local FCAS [Frequency Control Ancillary Service] constraint".[35]

While this case study relies on battery storage, it illustrates the value of flexibility that energy storage can bring to the broader power system.

2.3.4. POTENTIAL IMPACT OF FUTURE COOLING DEMAND ON THE PEAK DEMAND AND GRID FLEXIBILITY

The importance of cooling in Singapore's power demand means that cooling will continue to substantially determine the power system design and operation:

- The installed capacity and network infrastructure needs to be sufficient to meet peak demand.
- By impacting the power demand profile, cooling demand will influence when different power generation capacity is used and therefore associated carbon emissions.
- Depending on the variability and flexibility of cooling demand, alternative flexibility technology solutions will be needed in Singapore to mitigate generation and demand fluctuations.

Increase in cooling demand can impact the total power demand curve. Estimations from Section 1.2.1 showed that the increase of cooling demand could account for 10 TWh, while total power demand is expected to grow by 20 to 25 TWh by 2030.[36]

If it is assumed that cooling demand is evenly distributed across all hours, then on average this would represent a total of 2.9 GW of hourly demand dedicated to cooling. With peak demand projected to reach between 9.8 – 10.6 GW by 2030 according to EMA,[37] the average hourly cooling demand in 2030 would represent between 27% - 30% of the peak demand. This significant growth in cooling demand could result in the less efficient assets coming online to provide power at peak hours, unless cooling demand growth is better managed to minimise variations in demand.

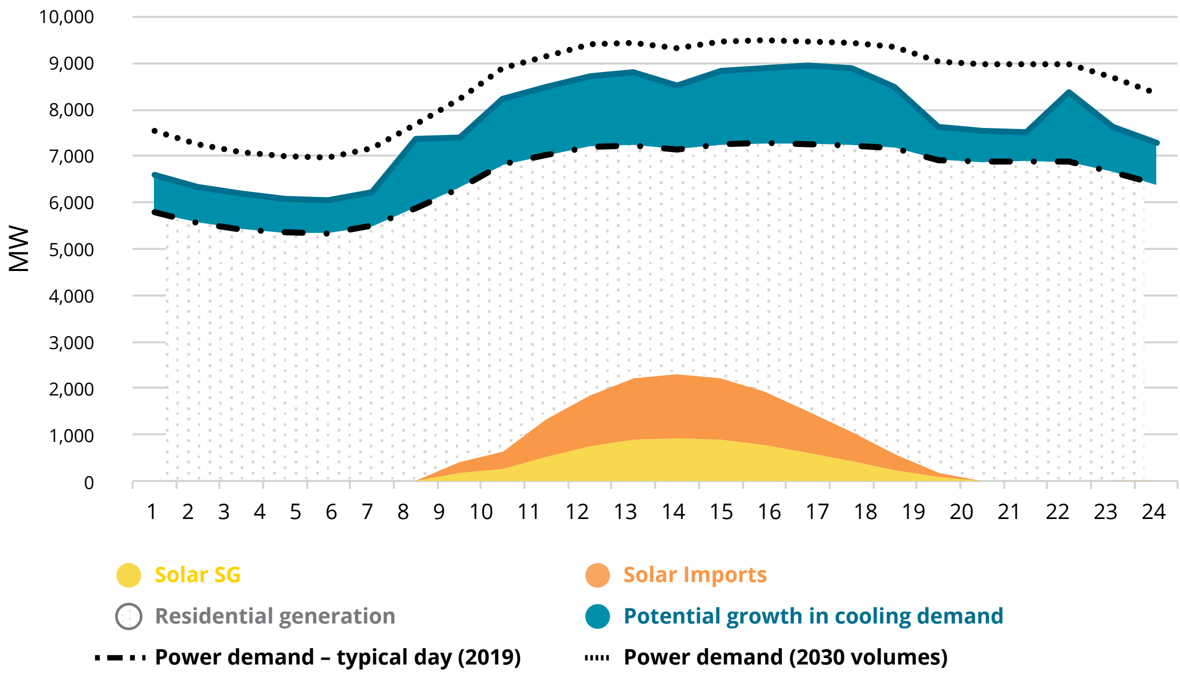
Cooling can also significantly impact the future power demand profile in Singapore in terms of the variance between peaks and valleys, and its relationship with renewable energy when available. Figure 7 demonstrates how the increase in cooling demand (light blue area) can impact the power demand curve, should the profiles of cooling demand across sectors remain consistent with current demand profiles and assumptions (50% continuous and 50% occupancy-based schedules in the residential and commercial sectors).

[35] *Electrek (2018). Tesla's giant battery saved $40 million during its first year, report says. Retrieved 14 February, 2022, from https://electrek.co/2018/12/06/tesla-battery-report/*

[36] *According to EMA, annual system demand could rise from 51.7TWh in 2019 to 71.3 to 76.4TWh in 2030 (Singapore Electricity Market Outlook 2021 - 2021-10-24 VF (ema.gov.sg))*

[37] *Energy Market Authority. Singapore Electricity Market Outlook 2021. Retrieved January 13, 2022, from: https://www.ema.gov.sg/cmsmedia/PPD/Singapore-Electricity-Market-Outlook-2021.pdf*

Figure 7: *Potential impact of cooling growth on power demand (2020-30)*



Note: the 2030 power demand curve uses the 2019 typical day to illustrate the order of magnitude of future power demand in Singapore, but the profile is expected to evolve according to uses for power in Singapore, including for cooling.

This depiction, along with Figure 5, shows that the combination of cooling demand growth across the sectors can impact the shape of the power demand (unless changes in other uses for electricity mitigates the profile of cooling demand), notably:

- An increase in residential cooling could trigger a sharp peak in power demand in the evening as a share of residential cooling will operate on an occupancy-based schedule.
- An increase in continuous cooling in the residential sector, which could emerge due to increased work from home, would reduce cooling demand in the late evening and transfer demand to the daytime.
- The increase of cooling demand in the day, especially for commercial uses, is synchronised with solar generation and imports. Enabling cold energy storage to be paired with cooling demand during the day can thus facilitate the absorption of significant volumes of variable renewable power for use at other times on the grid.

3

CLEAN COOLING CAN SUPPORT A COST-EFFECTIVE ENERGY TRANSITION IN SINGAPORE

3. CLEAN COOLING CAN SUPPORT A COST-EFFECTIVE ENERGY TRANSITION IN SINGAPORE

To address the impact of cooling on the energy system and its contribution to emissions, clean cooling solutions that reduce energy demand and increase grid flexibility will need to be pursued. Specifically:

1. Reduced cooling demand can be achieved through (i) efficiency improvements, (ii) passive design, and (iii) behavioural changes, directly reducing energy consumption and in effect, emissions.
2. Increased grid flexibility can be achieved by (i) shifting the cooling load to different times of the day as part of peak shaving efforts, and (ii) using cold energy storage as a short to long-term solution which can store renewable electricity at times of over-production and then release this electricity back to the grid at times of increased or peak loads, whether for additional cooling or electricity demand.

Singapore is a leader in progressing initiatives to reduce cooling demand, having focused on passive cooling designs, mitigating the UHI effect, and consistently raising minimum energy performance standards of commonly used cooling equipment to encourage the adoption of best available technologies. Increasing grid flexibility allows for cooling's role as an energy vector to be most effectively leveraged. As such, pursuing initiatives to increase the flexibility of cooling can provide an impactful decarbonisation pathway that can be further explored in Singapore.

3.1. ROLE OF CLEAN COOLING

Clean cooling can play two main roles in supporting Singapore to meet its energy transition objectives: (i) reducing total demand and; (ii) increasing grid flexibility.

3.1.1. CLEAN COOLING AS A PATHWAY TO REDUCING TOTAL DEMAND

The continued development of highly efficient cooling appliances and centralised services, passive cooling and increased harnessing of cold energy, will reduce the amount of energy needed to provide cooling to consumers, thus lowering the overall power demand.

Using clean cooling solutions to reduce total demand can bring about significant gains for Singapore and the achievement of the energy targets by:

- **Reducing the carbon emissions associated with power production:** As long as fossil-related generation is still an anchor to the generation mix in Singapore, the reduction of total and peak demand will reduce the need for the least-efficient assets to be called to match supply and demand.
- **Reducing the need for infrastructure:** According to EMA, every megawatt reduction of peak demand in Singapore could translate to system-wide savings of about $1.6 million.[38] A lower cooling demand contributing towards total electricity and peak hours will mean less energy (MWh) must be generated, and less capacity (MW) is necessary to support the peak. As the power system must supply enough electricity to meet demand and ensure the security of supply, a lower cooling demand will minimise the need for greater capacity, thereby lowering the costs of infrastructure development.

3.1.2. CLEAN COOLING AS A PATHWAY TO INCREASE GRID FLEXIBILITY:

Using cold energy to support existing cooling services, as well as installing cold energy storage of varying durations can add flexibility to the energy system. The flexibility introduced into the system can support peak shaving, improve the alignment of cooling demand to renewable energy generation to promote its integration, and mitigate further demand-side variability:

- The potential peak shaving of cooling demand will further impact the required sizing of the system capacity and network needs, providing additional economic gains;
- Increasing cooling demand's reactivity to renewable generation fluctuations can help integrate these variable technologies by absorbing the potential excess generation (increasing cooling demand) or smoothing the dynamic variations of renewable generation (activating cooling demand response). Figure 6 shows that significant amounts of cooling demand occur during hours of high solar generation. In fact, the estimated average peak power demand for cooling in 2019 (1.75 GW) and 2030 (2.9 GW) is comparable to solar capacity (2GWp) and low-carbon electricity import capacity (4 GW)

[38] *Energy Market Authority (2016). EMA Launches Pilot Programme to Help Consumers Optimise Energy Consumption. Retrieved 14 February 2022, from https://www.ema.gov.sg/media_release.aspx?news_sid=20161021Qsd1gxVBtn8q*

targets for 2030. Introducing flexibility through absorbing excess renewable energy could reduce potential occurrences of renewable curtailment, or the need for alternative flexible technologies.

- Low synchronisation of cooling demand with renewable generation would mean the need to ensure other dispatchable low-carbon assets can satisfy demand. While this could be through the use of other flexible sources like hydrogen, this would translate into energy losses due to conversions between energy vectors.
- The flexibility from cooling can be used to match/complement other sources of variability from the demand side. Mitigation of electric vehicles consumption patterns or participation to ancillary services are potential use examples.

3.2. SINGAPORE'S CLEAN COOLING INTERVENTIONS

Singapore has extensive experience in implementing passive cooling measures to better adapt the city to its existing climate and reduce the UHI effect as well as introducing optimised cooling services. Singapore continues to test and/or deploy innovative interventions of optimised cooling and cold energy services to attain high levels of cooling efficiency and optimise thermal comfort. Table 1 below provides an overview of existing clean cooling technologies being researched, piloted or implemented in Singapore. Given both the academic research background and strong industry interest, there is significant potential in further exploring how cold energy can support optimisation of cooling services, how it can provide flexibility to the grid, and how it can provide direct delivery industrial services (e.g., compressed air, cold logistics, blast freezing).

Table 1: *Examples of Singapore's clean cooling interventions*

<table>
<tr><th></th><th>Households</th><th>Commercial Buildings</th><th>Industry</th><th>Data Centres</th><th>Transport</th></tr>
<tr><td>Passive cooling</td><td colspan="4">• Optimising building design and orientation to capture natural wind flows, exterior shading and vegetation
• Incentivising behaviours to reduce cooling consumption – i.e. increasing temperature settings on air-conditioners, reduce frequency of air-conditioner use.</td><td>• Install shading in carparks
• Shift commuting patterns</td></tr>
<tr><td>Cooling Services</td><td>• District Cooling
• Promotion of more efficient appliances</td><td>• District Cooling
• Promotion of more efficient appliances
• Radiant Cooling Panels/Active Chilled Beam
• Non-compressor air-conditioning system
• Efficient Dehumidification Solution for Air-Conditioning System
• Hybrid thermal air-conditioner
• Water cooled chilled-water systems</td><td>• District Cooling
• Promotion of more efficient appliances</td><td>• Promotion of more efficient appliances
• Innovative heat exchange mechanisms: Desiccant-Coated Heat Exchanger; KoolLogix (Uses an innovative heat exchange and phase change approach to reduce energy consumption); Liquid-air exchanger
• Novel technologies:[39] Air-cooled tropical data centre; enhanced Indirect Evaporative Cooling for Tropical Operations; Direct Chip Hybrid Cooling; Digitalised cooling solutions to enable real-time monitoring and artificial intelligence (AI)-based optimisation; Direct liquid cooling; Immersion cooling; Close-coupled refrigerant cooling</td><td>• Promotion of more efficient appliances
• Use of water to cool air on bus stop seats to deliver cool air zones for commuters in transit</td></tr>
<tr><td rowspan="3">Cold Energy</td><td colspan="4">• Cryo-Polygen can harvest, store and use cold energy from the regasification of LNG</td><td></td></tr>
<tr><td colspan="3">• Smart Demand-Side Management (Smart-DSM) integration with Energy-efficient Thermal Storage System to harness LNG's cold energy for district cooling</td><td rowspan="2">• Integration of Cold Energy for Sustainable and Energy Efficient Data-Centres (ICE-SEED) by NUS Engineering and Singapore LNG Corporation
• Semiclathrate Thermal Energy Carrier System</td><td rowspan="2">• Not currently applicable</td></tr>
<tr><td></td><td colspan="2">• Absorption of waste heat from diesel generators in buildings by cold energy and used to support energy demand for other functions</td></tr>
</table>

[39] *More details on these technologies are listed in Appendix 8*

3.2.1. SINGAPORE'S PASSIVE COOLING SOLUTIONS

Passive cooling is a common clean cooling intervention that is actively deployed across sectors in Singapore. Building design and layout are optimised to achieve effective natural ventilation, and exterior shading and vegetation are leveraged to reduce heat gains into the buildings. These initiatives are complementary to Singapore's broader efforts to mitigate the UHI effect, led by the Ministry of Sustainability and Environment (MSE) and the Urban Redevelopment Authority (URA). Efforts to mitigate UHI effects include the use of sensors to collect temperature, humidity and wind speed data for modelling purposes to identify wind corridors and green spaces to safeguard, inform building alignment, and assess the implications of shade analysis. In addition, pilot studies on the use of "cool materials" on buildings to reduce heat absorbed and lower wall surface temperatures are being piloted by the JTC Corporation, Building and Construction Authority (BCA) and Housing and Development Board (HDB). These initiatives have several co-benefits, such as improving thermal comfort, and reducing electricity demand.

3.2.2. SINGAPORE'S COOLING SERVICES SOLUTIONS

Cooling services is another area of focus for Singapore as it is part of the country's drive towards greater energy efficiency. This is primarily observed in the household and industry sectors where NEA has been implementing more ambitious regulations related to the adoption of high-efficiency equipment. Within cooling equipment, this relates to the introduction of minimum energy efficiency standards in 2020 for water-cooled chilled water systems in industrial facilities, and the revision of the Minimum Energy Performance Standards for air conditioners and refrigerators in households in January 2022.

In addition, there has been a restriction imposed on the import and supply of Refrigeration and Air-Conditioning (RAC) equipment that use high GWP refrigerants from October 2022.[40] The BCA administers the Grant for Low-GWP Refrigerant Chillers (LoGR) for existing buildings-encouraging owners and operators of existing buildings to adopt water-cooled chillers using refrigerants with low GWP before this ban comes into place. The BCA's Building Retrofit Energy Efficiency Financing Scheme is another incentive to encourage building owners to undertake energy efficient retrofits via an energy performance contract. The scheme offers financing to pay for the upfront costs of energy retrofits of existing buildings, through an energy performance contract arrangement and covers the cost of equipment, installation and professional fees. As such, further potential for efficiency gains for existing technologies is seen to be limited since action to switch towards best available technology is already embedded within regulation.

The scope for efficiency gains through the adoption of novel technologies is deemed to be significant, especially in data centres where investments into research and development and pilot projects continue to grow. However, commercialisation of these technologies will take time and delay large scale adoption. While innovations in cooling are most evident in data centres, there remains challenges for these to be adopted within the existing stock of data centres even where there is a clear business case for future profits. Based on stakeholder insights, deep retrofits to optimise cooling will impact data centres' ability to serve existing customers and meet service-level agreements.

In terms of residential and commercial districts, there is ongoing adoption of district cooling systems and this is likely to continue as more greenfield sites emerge. However, there are certain limitations with district cooling specific to brownfield sites due to the high upfront cost of capital to replace the current cooling load, the logistical challenges related to securing permits, and the land-use constraints that limit wider adoption. As 80% of Singapore's built environment is brownfield, it is important to tackle these challenges. An example of this is SP Group and Temasek's recent investment in the development of district cooling in Tampines town centre. Under the project, seven existing buildings in Tampines will be retrofitted so that they can become part of a new distributed district cooling network that will be operationalised in 2025. This district cooling network will rely on existing chiller plants in selected buildings rather than constructing a new centralised cooling plant, and connect the rest of the buildings in the network to the injection nodes to obtain chilled water to meet their cooling needs.[41]

[40] *National Environment Agency (2021). Environmental Protection and Management (Amendment) Bill to mitigate emissions of refrigerants with high GWP used in RAC equipment. Retrieved 17 May, 2022, from https://www.nea.gov.sg/docs/default-source/default-document-library/circular-on-epm(amendment)-bill-to-mitigate-emissions-of-refrigerants-with-high-gwp-used-in-rac-equipment.pdf*

[41] *Channel News Asia (2022). Tampines to be first town centre in Singapore with district cooling system, network operational in 2025. Retrieved 20 April, 2022, from https://www.channelnewsasia.com/singapore/tampines-be-first-town-centre-singapore-district-cooling-system-network-operational-2025-2631566*

3.2.3. SINGAPORE'S COLD ENERGY SOLUTIONS

Cold energy solutions are yet to see large-scale adoption across Singapore and are largely under a research and development or pilot phase. Some of the solutions being explored include:

- **Smart demand-side management (Smart-DSM) integration with energy-efficient thermal storage systems to harness LNG's cold energy for district cooling:**[42] This will be done through developing novel heat transfer materials that can achieve energy efficiency improvements and space savings for district cooling systems. The National University of Singapore and Keppel's District Heating and Cooling Systems (DHCS) have developed an innovative PCM which can improve energy carrying capacity of district cooling systems by up to three times. The solution has been deployed at Keppel's DHCS.
- **The use of cold energy storage for shifting demand from off-peak to peak hours** is also being explored by The Smart Grid and Power Electronics Consortium Singapore (SPECS). The consortium is also studying the potential of waste heat from diesel generators in buildings to be absorbed by cold energy and used to support energy demand for other functions in terms of the cost savings this would present.
- **Cryo-Polygen:** Surbana Jurong and Nanyang Technological University are developing an integrated urban power generation system that can harvest, store and use cold energy from the regasification of LNG, with the option of using liquefied hydrogen as an additional source of energy. This Cryo-Polygen solution combines the concurrent generation of electricity, gas, cold energy, steam and hot water into a single plant operation. The cold energy generated from the system can be used to power cold storage warehouses and to cool data centres, industrial parks and buildings.

While the findings from the cold energy pilot projects are promising, these solutions have yet to reach commercial scale.

3.2.4. ALTERNATIVE NON-TECHNOLOGICAL COOLING SOLUTIONS

In addition to the deployment of clean cooling technologies, additional levers can further influence the reduction and flexibility of cooling demand in Singapore:

Behavioural changes: Examples include setting higher indoor temperatures, promoting light clothing, adjusting working and travel times to reduce cooling consumption when temperatures are highest.

Japan's Cool Biz Campaign

In 2005 Japan's Ministry of the Environment launched a first of its kind Cool Biz campaign to address over-cooling and reducing electricity consumption in offices. To quickly reduce carbon emissions, Cool Biz encourages offices to set air conditioner temperatures to no less than 28 °C **and introduce more casual summer dress codes in summer. In its first year alone the Ministry of the Environment estimated that the campaign resulted in a 1.14 million ton reduction in CO_2 emissions.**[43]

Implementing power price signals for consumers: For cooling technologies relying on electrical power, such as air conditioners, the electricity price can influence the operation of the cooling system. As such, power prices can translate into signals for consumers to operate cooling systems while considering potential strains on the power system. Such signals can be provided through dynamic power pricing, from pre-designed rates that vary as a function of the day or hour, to more agile pricing design in which prices vary on a half-hourly basis for example.

[42] *Energy Market Authority (2021). New Technology to Boost Energy Efficiency of District Cooling Systems. Retrieved 1 March, 2022, from* *https://www.ema.gov.sg/media_release.aspx?news_sid=20211014FMuNyMVgif2U*
[43] *Ministry of the Environment (2006). Report of this year's COOL BIZ achievement. Retrieved 11 April 2022, from:* *Report of this year's "COOL BIZ" achievement [MOE] (env.go.jp)*

Time-of-use tariffs

In the United-Kingdom, time-of-use tariffs are seen as a way to reduce electricity bills to consumers and generate benefits to the system. The UK energy regulator expects half-hourly time-of-use tariffs to lead to net benefits for consumers in Great-Britain of £1,500m-£4,500m over the period 2021-2045.[44]

An additional study[45] by the independent organisation Citizen Advice, based on a direct survey on nearly 3000 UK electricity customers, estimated that time-of-use tariffs can reduce consumers' peak demand by 5 to 10%. This decrease in peak demand is valuable to the electricity system, although current benefits to individual customers remain modest and are limited by the absence of automation.

3.3. HARNESSING CLEAN COOLING'S FLEXIBILITY BENEFITS

The mapping of clean cooling solutions implemented in Singapore as well as stakeholder insights show that numerous initiatives have been undertaken to reduce cooling demand through efficiency improvements, passive cooling, and the mitigation of the UHI effect. The focus on clean cooling to reduce total energy demand is significant in Singapore's current context given the power generation mix and the availability of efficient gas assets that more than satisfy peak demand. The consideration of cooling as an active part of the energy system however remains in an exploratory phase.

However, the evolution of the power system as part of Singapore's energy transition strategy will see greater supply side variability with the integration of renewable energy generation. This, combined with rising energy demand from current growth areas like cooling coupled with new growth sectors such as electric vehicles will mean that managing grid flexibility becomes critical to achieving Singapore's energy transition goals. This would mean maximising the use of renewable energy generation when it is available and reducing the growth in peak demand which will need to be met by less efficient, more carbon-intensive power generation assets resulting in greater carbon emissions. If cooling could be more flexible, it could support a reduction in peak demand, minimise the need for carbon-inefficient power generation assets. It is now possible to flexibly generate and store renewable cold energy which can then be consumed later at times of increased cooling demand (or a set if associated industrial services).

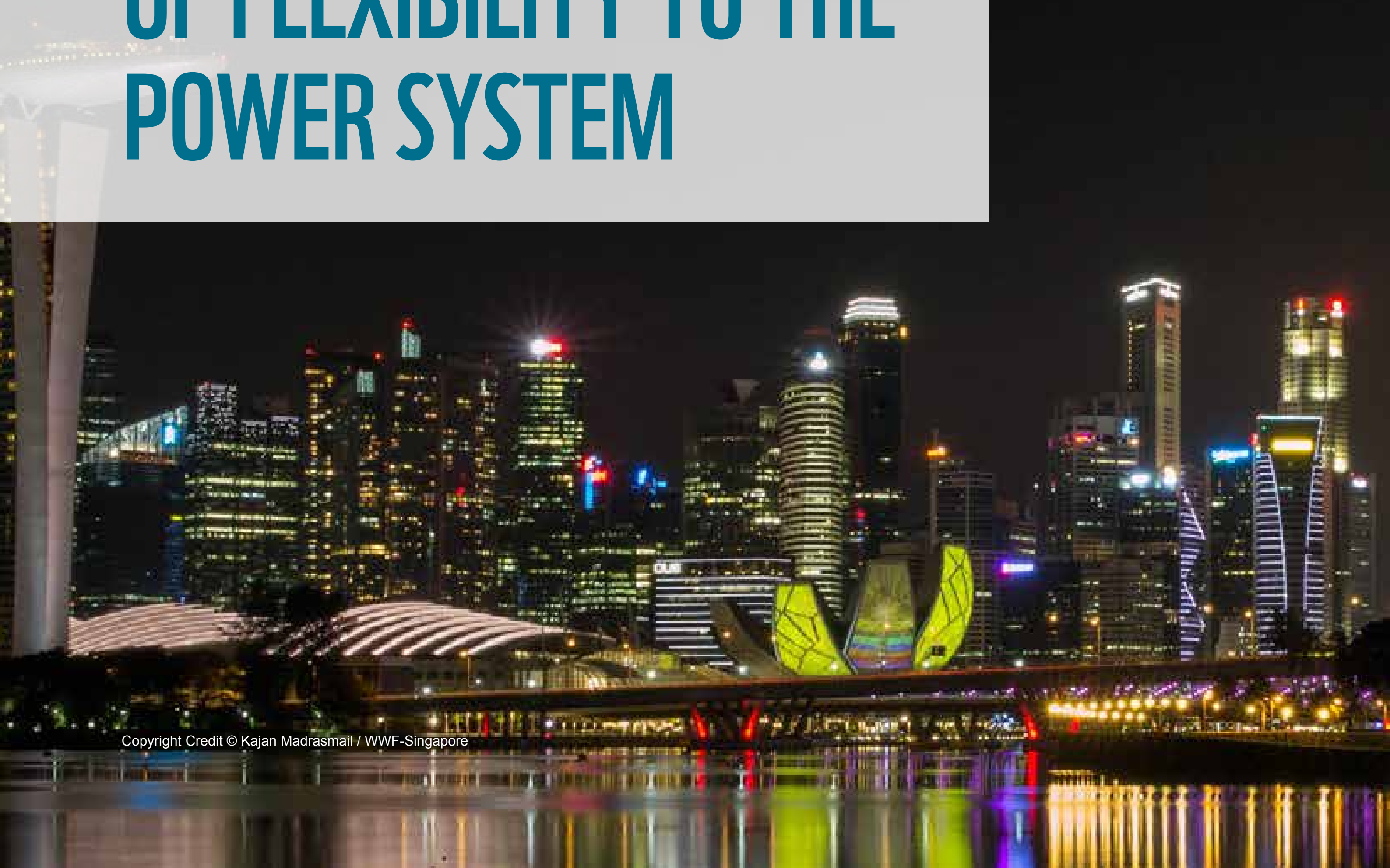
As such, to leverage upon clean cooling's benefits to the energy system, the following sections focus on the solutions that interface between cooling services (using super-efficient cooling equipment) and cold energy (which includes thermal energy solutions using cryogenic and other phase change materials), which have the highest potential to provide flexibility to the grid. Given the Energy 2050 Committee report's emphasis on energy storage, flexibility and end-user roles in Singapore's transition to a net-zero power sector, it is important to consider clean cooling solutions that will facilitate this.

[44] *Ofgem, 2021. Electricity Retail Market-wide Half-hourly Settlement: Decision and Full Business Case, from: https://www.ofgem.gov.uk/publications/electricity-retail-market-wide-half-hourly-settlement-decision-and-full-business-case*

[45] *Citizen Advice, 2017. The Value of Time of Use Tariffs in Great Britain, from: https://www.citizensadvice.org.uk/about-us/our-work/policy/policy-research-topics/energy-policy-research-and-consultation-responses/energy-policy-research/the-value-of-time-of-use-tariffs-in-great-britain/*

4

THE ROLE OF CLEAN COOLING AS A SUPPLIER OF FLEXIBILITY TO THE POWER SYSTEM



4. THE ROLE OF CLEAN COOLING AS A SUPPLIER OF FLEXIBILITY TO THE POWER SYSTEM

Singapore has invested strongly in clean cooling solutions that reduce cooling demand through optimising cooling services and investing in passive cooling strategies. Singapore has the opportunity to use these technologies to further support the energy transition in the country by using them to provide demand-side flexibility.

Clean cooling solutions at the intersection of cold energy and cooling services are well placed to bring a wide range of flexibility services to the grid. These services will be different depending on the type of flexibility needed. In some cases, one type of clean cooling solution can provide multiple grid services.

Each sector's current demand profile was used to establish its potential to provide each type of grid service. Together with an analysis of the applicability of clean cooling solutions to each sector, a high-level prioritisation of sectors was done, The commercial building sector emerges as the highest priority for further exploration of deployment of clean cooling solutions in Singapore's context.

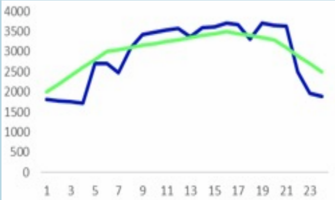
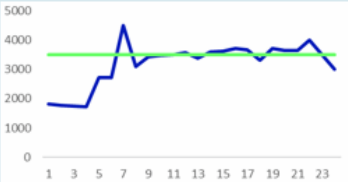
4.1. FLEXIBILITY SERVICES PROVIDED TO THE GRID BY COOLING

While dispatchable assets such as gas generation power plants can provide flexibility services, as the power system decarbonises with more penetration of renewables, the need for flexibility will grow and consequently the need to seek other options for flexibility. This flexibility can come from demand, including cooling demand.

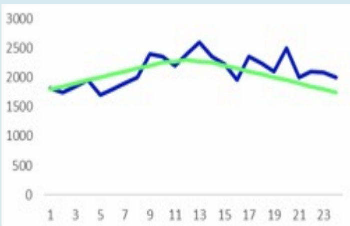
Table 2 shows an overview of seven services that cooling can provide to the grid, both to ease the constraint that cooling demand can represent for the power system operation (services 1 to 3), and to contribute to the power system as a flexibility provider (services 4 to 7).

The characteristics of clean cooling solutions have been used to determine which flexibility services each solution type could provide to the grid. This analysis demonstrates that cold energy can enhance the value of existing cooling services by providing flexibility benefits for the grid. In addition, one clean cooling solution could even provide multiple flexibility services if the use-case is optimised. On the other hand, long duration energy storage will be needed specifically to enable flexibility services 6 and 7.

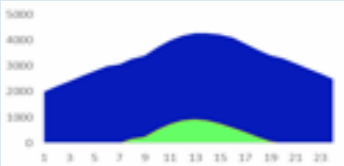
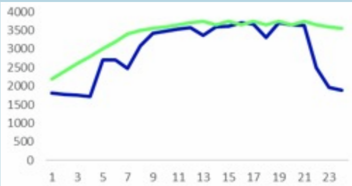
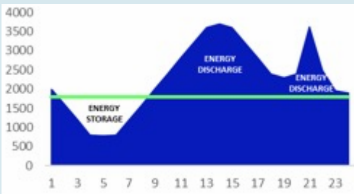
Table 2: *Overview of flexibility services that could be provided by clean cooling solutions*

Service*	Service Description	Duration of flexibility need	Clean Cooling Solution	Suitability of solution to sectors
1- Smooth ramps (variations in time) from cooling demand 	Cooling demand profiles in commercial buildings and households have high volatility and can therefore trigger sharp variations in demand on the power sector or lead to the emergence of new peak hours desynchronised to solar PV generation. This would require cooling systems to be flexible to shift power demand in time while ensuring delivery of the cooling service (indoor temperature) at the desired hour thanks to storage. For example, a shift in time of cooling demand by 1 to 2 hours, with the associated storage, can ensure delivery at the desired hour while avoiding a surge of cooling demand concentrated on one hour (e.g. at 10pm in the residential sector).	Minutes to few hours • Variations in cooling demand can be smoothed by distributing cooling demand across 2 or 3 hours.	Cooling services • District cooling with thermal energy storage capacity	Commercial buildings and households with occupancy-based profiles; Industry
2- Limit new peak emergence 		Minutes to few hours • Shift cooling demand in time by 1 to 2 hours (and ensure its storage for delivery at the initial hour)	Cooling services • District cooling with thermal energy storage capacity	Commercial buildings with occupancy-based profile in the morning; Households with occupancy-based cooling profile in the evening; Industry
			Cold energy • Phase change materials provide additional cooling that is released to the system to stop peak cooling	Commercial buildings with occupancy-based profile in the morning; Industry; Data centres

* *Figures are for illustration only, where the green line is used to demonstrate the nature of the flexibility service.*

Service*	Service Description	Duration of flexibility need	Clean Cooling Solution	Suitability of solution to sectors
3- Reduce peak power demand 	Considering the shape of the total power demand curve in Singapore, where the peak is spread across about 10 hours, this implies that long-duration storage of energy can reduce the peak: several hours of stored energy is necessary to lower demand during the peak period.	Several hours • Reduce the peak power demand that is currently observed in Singapore, cooling demand needs to be shifted away from the peak hours (7am to 7pm). • This would imply to shift cooling electricity consumption to hours with lower total power demand (such as between 1 and 6am) and store the cold energy (produced through electricity consumption) for several hours to provide the cooling service along the peak hours period.	Cooling services • District cooling	Commercial buildings, Households, Industry
			Cooling services • Super-efficient equipment to reduce cooling load through optimisation of energy use	All sectors
			Cooling services • Control systems that can switch on early or later to support with generational load shifting	Commercial buildings, Industry
			Cooling services • Novel technologies such as liquid cooling, immersion cooling, close-coupled refrigerant cooling	Data centres
4- Smooth small hourly variations in power demand 	Cooling demand can be flexible and used to smooth the variations in power demand on short time. This will need the possibility of the demand interacting directly with the system operator via an adequate technological interface and market mechanisms. Considering the complexities of this interactions between the system operator and the cooling demand, probably sectors or installations with large-scale cooling demand more likely to provide such services, at least in the first phases of the energy transition	Second to hour Quick response from cooling could be undertaken across sectors provided that the cooling demand can be flexible	Cooling services • District cooling with thermal energy storage capacity	Commercial buildings, Households (night time), Industry
			Cooling services • Control systems	Commercial buildings, Industry

Figures are for illustration only, where the green line is used to demonstrate the nature of the flexibility service.

Service*	Service Description	Duration of flexibility need	Clean Cooling Solution	Suitability of solution to sectors
5- Integrate solar PV power 	Cooling demand can also contribute to integrating variable solar PV generation either in the case of onsite generation or at the system level. This can be by mitigating potential quick variations in PV generation, or by absorbing potential excess energy produced avoiding the need for curtailments.	Second to hour • Quick response to PV variations (second to hour) Several hours • Long-duration storage of energy	Cold energy • Phase change materials	Commercial buildings, as they account for a substantial load synchronised with solar PV generation hours. Industry and data centres can provide additional flexibility potential as they also operate through the daytime.
6- Increase power demand in low demand hours to maximise the use of the power infrastructure 	Cooling can provide long-duration storage which could enable energy to be stored during hours of low demand or presence of local generation and distribute it at times of lack of local supply or times of peaks in demand. Such potential service will be determined by the technology used to store energy Energy storage of several hours will smooth daily variations in supply and demand and can reduce the peak demand, by discharging in peak times the energy charged in the energy storage.	Several hours to several days • A cooling demand increase during low power demand hours, associated to storage delivering the cooling service when desired, can optimise the use of the power system infrastructure. For example, excess Renewable Energy (RE) energy present in times of low demand could be used to store energy as cold energy instead of being curtailed. The cold energy stored then can be used for cooling services, or fed back as electricity in hours of peak demand through relevant technologies. This would also optimise the use of the grid infrastructure in time by lowering variations of power flows between high and low power demand hours	Cooling services • District cooling with thermal energy storage capacity	Commercial buildings, Households, Industry
			Cooling services • Control systems	Commercial buildings, Industry
7- Provide storage of low-carbon energy to feed energy during the peak 			Cold energy • Thermal Energy Carrier System to transport cold energy from LNG to supply cooling requirements)	Data centres (store cold energy during the night to feed their daytime needs when power demand is high)
			Cold energy • Heat exchange and phase change materials to reduce energy consumption	Commercial buildings, Industry, Data centres
			Cold energy • Thermal energy storage - LAES systems	Commercial buildings, Households, Industry, Data centres

* *Figures are for illustration only, where the green line is used to demonstrate the nature of the flexibility service.*

4.2. PRIORITISING SECTORS BY THEIR POTENTIAL FOR ADOPTING CLEAN COOLING SOLUTIONS

Based on the assessment completed on (i) the interaction of cooling demand profiles with the grid and of its potential flexibility by sector, and (ii) the capacity of providing flexibility of various types of clean cooling solutions, we propose a prioritisation matrix to determine at a high level which sector should be prioritised for the adoption of clean cooling solutions to support Singapore's power system decarbonisation goals.

The prioritisation matrix in Table 3 aims to classify sectors by considering their potential to adopt and scale clean cooling solutions, based on existing publicly available data and stakeholders' inputs. High priority sectors must see (i) both current and future cooling demand to be significant to indicate that the sector's cooling-related emissions are important to address; (ii) the flexibility of cooling demand to be significant to indicate that there is opportunity to vary the cooling demand profile, including the size and times of the peaks; (iii) that there are various clean cooling solutions capable of adjusting cooling demand to alleviate the grid and with least barriers to their deployment. The prioritisation matrix is built on the criteria noted in Appendix 7.

Based on the assessment of the dependencies between cooling and the energy system, and the potential for cooling solutions to provide grid flexibility in specific sectors, it is concluded that commercial buildings may offer the biggest opportunities for the adoption of clean cooling to provide flexibility services to the grid, and support Singapore's power system decarbonisation goals

Key trends noted in the commercial buildings sector to support its case for prioritisation include:

- Significant contribution of cooling demand to the power demand curve and towards peak demand between the 7am to 7pm window, indicating that addressing cooling in commercial buildings will have a direct impact on total power demand;
- Significant variation of cooling demand on the power system in short periods of time, indicating the potential to introduce flexibility solutions that can smooth ramp ups from cooling demand;
- Alignment of the cooling demand profile to the future generation of decarbonised energy (when solar energy is available), creating an opportunity to absorb significant volumes of variable renewable power;
- Availability of clean cooling solutions already being deployed/tested in the sector that can additionally provide flexibility services to the grid.

Within the commercial buildings sector, the types of clean cooling solutions that can ease the constraint that cooling demand can represent in the power system include district cooling, control systems, and super-efficient cooling equipment. In addition, cold energy solutions and thermal energy storage can be integrated in cooling systems for commercial buildings to contribute to the power system as a flexibility provider alongside other clean cooling solutions such as heat exchange or PCMs for example. A lot of the characteristics of cooling demand in commercial buildings is also noted in the household sector such as the contribution of cooling to peak demand and power demand variability. Industry stakeholders note that while household demand is less predictable, there are increasing opportunities to deploy similar clean cooling solutions in housing districts.

While the commercial building sector provides the clearest opportunity as of today, developments in high cooling demand growth sectors like data centres can also provide opportunities. Other economic sectors where there could be fast growth in cooling demand include the indoor farming sector. Although the size of cooling demand has yet to be quantified and analysed, Singapore's target to achieve 30% food self-sufficiency by 2030 means there is a relatively short timeframe to consider integrating clean cooling strategies.

Table 3: *Examples of Singapore's clean cooling interventions*

Sector*	Cooling demand's impact on the power grid			Clean cooling opportunities			Sector of priority
	Cooling demand/ load	Expected growth in cooling demand	Flexibility potential	Availability of alternative clean cooling solution	Provides flexibility to the grid	Barriers to deployment	
	The percentage of total cooling electricity demand contributed by the sector	*The estimated percentage growth in cooling electricity demand between 2019 to 2030.*	*Cooling demand's ability to shift or adjust demand to different hours of the day*	*Relative range of clean cooling solutions available in Singapore*	*Extent to which clean cooling solutions available in the sector are able to provide flexibility services*	*Degree to which barriers exist in the deployment*	
Household	Medium	Medium	High	Medium	Medium	Low to Medium	High (Score =13.5)
Commercial Buildings	High	Medium	High	Medium to High	High	Medium	High (Score =15.5)
Industry	Medium	Low	Low	Medium to High	Low	Medium	Medium (Score =9.5)
Data Centres	Low	High	Low	High	Medium	Medium	Medium (Score = 12)

** The transport sector has been excluded from the prioritisation exercise as the focus of the study is limited to cooling demand that is supplied by the grid and therefore interacts directly with the grid, which is not the case for cooling demand from the transport sector.*

The final prioritisation of the sector is based on assigning points to each prioritisation level, where High = 3; Medium to High = 2.5; Medium = 2; Low to Medium = 1.5; Low = 1, with the exception of Barriers to Deployment (High = 1; Medium to High = 1.5; Medium = 2; Low to Medium = 2.5; Low = 3) as described in Appendix 4. The sum of the scores indicates the prioritisation of the sector where:
High: 13 – 18 points
Medium: 7 – 12 points
Low: 0 – 6 points
Aside from "Cooling demand/load" and "Expected growth in cooling demand", the other criteria are based on qualitative assessments.

5

CLEAN COOLING SOLUTIONS FOR FURTHER DEVELOPMENT IN SINGAPORE

5. CLEAN COOLING SOLUTIONS FOR FURTHER DEVELOPMENT IN SINGAPORE

Whilst Singapore has been at the forefront of increasing cooling systems energy efficiency and reducing the need for active cooling through passive measures, the listed solutions here further provide grid services through energy storage and enhanced flexibility. In this section, we describe in detail four clean cooling technologies that are applicable to Singapore that could be further developed, highlighting key limitations that surfaced through stakeholder interviews.

Our review suggests that there are several opportunities to harness the grid benefits of clean cooling solutions by extending existing cooling services already being deployed/test-bedded in Singapore further. For example, optimised cooling services are already being deployed at commercial buildings and data centres. In fact, specifically for district cooling, we are starting to see demonstrations of commercial viability of harnessing cold energy storage as part of a district cooling system that can serve as demand-side response to the grid. On the other hand, longer duration cold energy storage systems could bring about additional benefits, but these have yet to be commercialised.

5.1. THE POTENTIAL AND LIMITATIONS OF FOUR CLEAN COOLING SOLUTIONS FOR CONSIDERATION IN SINGAPORE

Four strategic technological clean cooling solutions could be deployed further to achieve material impact in addressing cooling demand, bring flexibility to the grid, whilst limiting the growth of greenhouse gas emissions in Singapore:

1. District cooling[46] for grid flexibility
2. Control systems[47] for demand-side response
3. PCMs[48] providing short-medium duration storage capacity
4. Cryogenic energy storage systems[49] for longer duration energy storage

The first three solutions are prioritised because they are applicable to sectors where the biggest opportunity to adopt clean cooling interventions exist; they can respond to a flexible demand and reduce grid strain through flexibility and have the potential to scale (see Figure 7). District cooling, control systems and PCMs are all applicable to commercial buildings which offers a large opportunity to effectively adopt clean cooling and see its benefits materialise as noted in Table 3. The first three solutions are also most commonly identified as having the necessary characteristics to provide multiple flexibility services to the grid as described in Table 2. The final solution is investigated as there is a need to explore long duration storage specifically to provide storage of low-carbon energy to feed peak demand.

Figure 8: *Prioritisation criteria for clean cooling technologies in Singapore*

- Is the intervention applicable to the sector with the biggest potential to adopt clean cooling solutions? Based on the prioritisation exercise under Section 3.3, the characteristics of the commercial building sector allow it to potentially reap the biggest benefits from clean cooling interventions. As such, any clean cooling solution that can be applicable to the commercial buildings sector to maximise system benefits should be prioritised for deployment.
- Does the intervention have scope for wider scale adoption beyond the prioritised sector? In terms of economies of scale, especially when integrating solutions in districts with a variety of demands on the power system, it will be useful for the intervention to have the malleability to address the cooling needs across several sectors.
- Does the intervention provide multiple benefits to the grid? While there is no 'silver bullet' clean cooling solution, prioritising interventions that offer multiple benefits to the grid such as reducing peak demand, smoothing variations in power demand, providing energy storage solutions etc., will be more impactful in terms of contributing towards an optimal power system that is the backbone of a robust energy transition strategy.

[46] *District Cooling: Central cooling plants supply chilled water to buildings through an underground network of insulated pipes, minimising the use of energy and eliminating the need for buildings to install their own chillers.*
[47] *Control Systems: Use of smart thermostats integrated with building management systems can respond quickly and flexibly to temperature changes and other signals programmed into the system.*
[48] *PCM absorb large amounts of heat when it changes phase from solid to liquid, and the stored heat is released when the PCM solidifies again.*
[49] *A form of phase change material technology that releases energy when specific chemicals are manipulated to change from liquid to gaseous phase, allowing the storage or re-use of wasted cold energy for other needs*

Aside from general technology maturity considerations, stakeholder interviews also highlighted potential limitations for deployment in Singapore that can generally be classified as:

- **Brownfield vs. greenfield deployment:** The considerations raised here include
  - Complexity of land-use decision making and permitting needs given Singapore's land scarcity;
  - Economic considerations like higher capital costs for brownfield projects and potential disruption to business contracts during the retrofit processes;
- **Scale needed:** Most of the technology applications have minimum scale requirements for the economic benefits to be realised, making some less applicable to certain sectors or sites;
- **Safety issues:** Some industry players have been deterred by safety considerations, especially the use of cold LNG as long-term storage;
- **Unclear economic benefits:** Several stakeholders noted that flexibility is not currently systematically valued, making it difficult to build its economic benefits in investment decision making.

5.1.1. DISTRICT COOLING FOR GRID FLEXIBILITY

Summary

Technology overview	• Central cooling plants supply chilled water to buildings through an underground network of insulated pipes, minimising the use of energy and eliminating the need for buildings to install their own chillers. • The technology is commercially viable and seeing strong traction in Singapore with SP Group, Keppel Infrastructure and ENGIE leading the design and operations of district cooling systems.
Flexibility potential	• High flexibility potential through the ability to store cold energy to support peak demand and facilitate demand side response from cooling systems.
Potential sector applications	• Commercial buildings, Residential buildings, Industrial buildings
Applicability to brownfield/greenfield	• Typically applied to greenfield sites; a bigger challenge to implement in brownfield sites due to additional effort to minimise disruption to the existing built environment
Limitations	• Space constraints; high upfront capital cost; engineering complexity; logistical challenges; difficulty sizing the capacity of cold storage required to support the power system; disincentivise energy conscious behaviour
Recommendations for wider adoption	• Documenting the energy system and economic benefits of coupling thermal energy storage systems with district cooling in existing cooling networks will build a business case for similar projects to be developed across Singapore.

Technology overview and flexibility potential

A district cooling system consists of central cooling plants that supply chilled water to various buildings through an underground network of insulated pipes. These central cooling plants consume less energy for the same amount of cooling, free up space, and reduce lifecycle costs as buildings do not need to invest in their own chillers. The centralisation of cooling production allows district cooling to reap the benefits in economies of scale of a larger system and to operate at higher efficiency, and this is especially applicable for a warm tropical country like Singapore with high building density.

Some district cooling systems can also provide valuable electricity flexibility services by storing cold energy (usually in the form of ice or chilled water) in thermal energy storage systems and gradually releasing the stored energy during peak cooling demand. Such energy storage systems can facilitate demand-side response from cooling systems and provide services such as distributing cold energy from off-peak to peak hours and managing solar power intermittency. District cooling coupled with thermal energy storage systems could offer several flexibility services stated in Table 2 above, including smoothing ramps from cooling demand, limiting new demand peak emergence, reducing peak power demand, smoothing small hourly variations in power demand, and increasing power demand in low demand hours to maximise the use of the power infrastructure.

CASE STUDY: Contribution of thermal storage in district heating to reduce wind curtailment in China

A UK-China collaborative project developed a commercial demonstration pilot to integrate thermal storage into a district heating in China. By generating and storing decarbonised heat, the facility harnessed excess electricity from local wind generators, reduced curtailment of renewable energy generation and relieved power network constraints. Following this success, 20 plants have been constructed and are in operation across China.[50]

While this case study relies on thermal storage as heat, it illustrates how district thermal storage can provide services to the power system by facilitating the RE integration and reducing curtailment, in addition to enabling low carbon heat generation.

Potential sector applications

Such systems are already being used in Singapore, more prominently in commercial buildings, where more than a dozen buildings in the Marina Bay district including Marina Bay Sands, the Marina Bay Financial Centre, and One Raffles Quay are being cooled via district cooling. It is starting to gain traction in households such as Tengah, which is Singapore's first public housing township with centralised cooling, and 90% of Tengah residents have opted for the technology.[51] In the industrial sector, district cooling will serve high-specification industrial-use buildings in the upcoming Bulim Phase 1 of the Jurong Innovation District.[52]

Applicability to brownfield/greenfield

Given the engineering complexity and the significant upfront infrastructure costs involved, a district cooling system is usually applied in greenfield developments, where they can be more easily introduced into the design of a new development. It becomes challenging to integrate district cooling into built-up or brownfield sites, where there are existing chiller plant systems in the buildings, and any form of retrofit would require navigating the existing built environment while ensuring minimal disruption to existing operations. It is also a challenge to include thermal energy storage systems in brownfield sites, which is a key to the grid flexibility benefit of district cooling. While it is more difficult to introduce district cooling in brownfield sites, a feasibility study showed that if a distributed district cooling network were to be implemented in Tampines Central (a brownfield site in Singapore), it would have the potential to reduce energy consumption and carbon emissions by 17% and 18% respectively and provide economic value of some S$130 million over 30 years.[53] This relies on building a cooling network linking the buildings' cooling systems and existing individual chillers together, before optimising the operation of chillers to answer cooling demand needs.

Limitations

In addition to challenging applicability in brownfield sites, some of the other key barriers to adoption of district cooling include existing space constraint, high upfront capital cost, engineering complexity and logistical issues (e.g., applying for permit for construction and implementation). While district cooling has proven to be applicable and exists across commercial buildings, households and industry in the Singapore's context, its level of deployment could vary widely in these sectors because of economic reasons. According to a 2020 technical report by Cooling Singapore, district cooling is profitable in commercial areas with a mean return on investment of 13%, however, for private and public housing, the cost benefits do not compensate the high investment costs for centralised cooling.[54] For industry, in particular the semi-conductor sector, district cooling is likely to increase in importance given that cooling accounts for a large proportion of its energy consumption, but it needs to overcome some of the implementation challenges mentioned.

Furthermore, cooling systems are designed to be tailored to the cooling needs to avoid oversizing. To provide electricity storage in the form of cold energy, that may later be converted back to electricity to feed the power grid, cold storage capacity sizing must consider the needs of the power system and foresee remuneration streams to justify any potential oversizing. In the absence of clear revenue streams, the assessment of district cooling systems may not include potential services of storage for the power system, and the flexibility potential will be reduced.

50 *International Renewable Energy Agency: Thermal Energy Storage report 2020, from: https://www.irena.org/publications/2020/Nov/Innovation-outlook-Thermal-energy-storage*
51 *SP Group. MyTengah. Retrieved April 6, 2022, from https://www.mytengah.sg/centralised-cooling/*
52 *Keppel Corporation. Keppel DHCS secures $300 million contract to build, own and operate District Cooling System in Bulim Phase 1, Jurong Innovation District. Retrieved April 6, 2022, from https://www.kepcorp.com/en/media/media-releases-sgx-filings/keppel-dhcs-secures-300-million-contract-to-build-own-and-operate-district-cooling-system-in-bulim-phase-1-jurong-innovation-district/*
53 *SP Group and Temasek. Taking The Heat Off Cooling: A Greener Way to Cool. Retrieved April 6, 2022, from https://www.spgroup.com.sg/wcm/connect/spgrp/e9cb79d1-86ea-462f-a69b-c617a6817724/Taking+The+Heat+Off+Cooling+-+A+Greener+Way+to+Cool.pdf?MOD=AJPERES*
54 *Cooling Singapore. Potential of District Cooling in Singapore: From Micro to Mesoscale. Retrieved April 6, 2022, from https://www.research-collection.ethz.ch/handle/20.500.11850/445484*

Finally, increased efficiency and the centralised operation of district cooling systems can lead to a change in the behaviour of consumers, resulting in a rebound effect on cooling demand. The reduced consumption and flexibility services associated with district cooling may therefore be limited.

5.1.2. CONTROL SYSTEMS FOR DEMAND-SIDE RESPONSE

Technology overview	• Smart thermostats integrated with building management systems can respond quickly and flexibly to temperature changes and other signals programmed into the system • Grid-interactive control systems are still nascent in Singapore, although seeing greater adoption in other parts of the world such as the US.
Flexibility potential	• Offers flexibility to the grid and supports it to balance reserves by shifting the cooling load to different times of day by increasing or decreasing the temperature of the building
Potential sector applications	• Commercial buildings
Applicability to brownfield/greenfield	• Applicable to both greenfield and brownfield sites, although integration of control systems is more costly for brownfield sites due to the requirement to design and install new wiring while minimising the disruption to buildings in service
Limitations	• Control systems are unable to improve the efficiency of equipment which may be a barrier to installation for building owners looking to improve efficiency metrics; • Concern that the use case of grid-interactive control systems may not be sustainable; • Limited technical skill-set to implement control system solutions
Recommendations for wider adoption	• Demonstration projects in commercial buildings or industrial facilities can offer an effective way to raise awareness and showcase the benefits of the technology to the grid and instil best practice in terms of effective installation for different use cases.

Technology overview and flexibility potential

Balancing electricity supply to meet fluctuating demand has become a challenge for power system operators due to increasing influx of variable renewable energy sources and large electrical loads. With cooling load being a significant demand for commercial buildings, deploying smart control systems such as smart thermostats integrated with building management systems could be a potential demand-side management strategy and enable adjustments to varying grid requirements. Most commercial buildings are serviced by variable air volume systems where air flow rate can be varied continuously between a low and high value. As commercial buildings are also equipped with building management systems (BMS), the task of implementing additional control algorithms is relatively easier and cost-effective. The technology works best for mechanically ventilated systems as they can respond to quicker temperature change signals thereby allowing the control system to tailor the set point flexibly. Control systems are gaining traction in recent years primarily due to utility-driven energy efficiency programs and simple installation procedures.

Further, the technology can function as a key gateway to enable grid services such as load shifting, complex scheduling and day-ahead service requests while ensuring minimal impact on occupant comfort. As air conditioning systems can contribute to temporary load shedding, most of that load would be essential post curtailment to increase/decrease the temperature, which eventually contributes to load shifting. Further, manufacturer designed control systems could also possibly offer direct control and frequency regulation for balancing reserves.

Potential sector application

Building management systems are a standard component in most commercial buildings offering facility managers to control and operate critical equipment remotely and at desired performance levels. Further, the smart facility management (FM) guide designed by the Smart FM taskforce calls for leveraging data analytics, predictive maintenance, and smart technology solutions. While the total scope of commercial buildings that can be tapped is unknown the solution could be pilot tested and deployed in 4 million sq. m of ready-built facilities developed by JTC corporation. It is also important to note that JTC has deployed its J-Ops command centre which is the first integrated building and estates command centres that offers building optimisation amongst other services across the island thereby offering the necessary infrastructure to integrate smart control systems.

Applicability to brownfield/greenfield

The technology can be deployed across greenfield and brownfield commercial and residential projects. The integration of smart control systems is considerably easier in greenfield projects as the software and hardware can be seamlessly designed and installed along with the whole-building wiring networks. In the case of brownfield projects, these retrofits involve the addition of thermostats to the existing BMS/network. These additions would require the installation of new wiring for connecting these new systems which is a difficult proposal for buildings which are in service. Such costs could be somewhere between 20-80% of the retrofit costs and could also lead to potential delays due to the time required to scope the design and install the new wiring.

Limitations

Technical barriers include limited opportunity for control systems to provide frequency regulation or voltage support as they can only indirectly control the equipment through set points. While such systems can reduce the overall energy consumption for cooling, they may not improve the efficiency of equipment such as improvement to coefficient of performance, electricity use efficiency amongst others. For a building owner, the value they see in any technology upgrade would be the impact on efficiency which may be an inherent barrier in the case of control systems.

Upfront investment costs are still a barrier for uptake of control systems as building owners generally opt for upgrades only at the point of failure. This is especially challenging for owners of small and medium sized buildings as they have limited capital for operational improvements. Further, it is also not known yet whether financial institutions and insurance agencies are willing to accept the valuation of such technology features in their lending appraisal and underwriting.

Other barriers include lack of use-cases for grid-interactive control systems which can be leveraged to run pilot/ demonstration projects. This leads to concerns of premature obsolescence of such new and innovative technologies. Lastly, lack of awareness and gaps in workforce skill to implement such solutions also affect the penetration of control systems. If these technologies are scaled up in the market, it is important for the sector to understand the complete value proposition of control systems while making necessary cultural shifts in the way that buildings are operated.

5.1.3. PHASE CHANGE MATERIALS PROVIDING STORAGE CAPACITY

Technology overview	• PCMs absorb large amounts of heat when it changes from solid to liquid, and the stored heat is released when it solidifies again • With the technology still nascent, R&D efforts and pilot projects are currently focusing on the use of PCM cool coloured coating for building envelopes and PCM in district cooling systems
Flexibility potential	• The use of PCMs in HVAC systems can store low carbon energy and release it during peak demand hours, thereby providing flexibility through demand-response
Potential sector applications	• Commercial buildings, industrial manufacturing facilities, data centres
Applicability to brownfield/greenfield	• Dependent on the type of technology used to deploy PCM. E.g. cool paints incorporating PCM are applicable to both greenfield and brownfield sites, while PCM in thermal storage for district cooling is more suitable for greenfield sites
Limitations	• Awareness of its full technical capability is limited • High investment cost • Risk of flammability
Recommendations for wider adoption	• Pilot projects and further research exploring the integration of PCMs across a wide range of technologies and use-cases will support the development of an evidence base and bring PCMs one step closer to larger scale adoption.

Technology overview and flexibility potential

PCMs are substances which absorb or release large amounts of 'latent' heat when the material changes its phase from solid to liquid, and the stored heat is released when the PCM solidifies again. As the energy is stored as latent energy, this takes place without a significant increase in the temperature of the PCM itself, making PCM suitable for thermal energy storage at a constant temperature. The active use of PCMs in HVAC systems could offer the flexibility service of providing storage of low--carbon energy to feed energy during peak load demand, to balance energy demand and supply when needed in an energy-efficient manner.

Potential sector applications

The fields of application for PCMs are broad as they change phase at specific, defined temperatures, making them suitable to control the temperature in a range of applications. Among these areas are thermal building regulations, thermal control of electronic components as well as applications in solar cooling and solar power plants, photovoltaic electricity systems, waste heat recovery systems, and preservation of food and pharmaceutical products.

The use of PCMs is becoming more and more wide ranging in the building sector. PCMs can be used as a passive cooling strategy in building envelopes to minimise indoor temperature fluctuations and peak cooling loads, thus keeping the indoor temperature within the comfort range. The Building and Construction Authority's Super Low Energy Buildings Technology Roadmap has included 'cool paint incorporating PCM as an emerging cooling solution.[55] Application of PCM cool coloured coating in the building envelope has also been studied in Singapore, with the results from quantitative analysis showing

[55] *Building and Construction Authority. Super Low Energy Buildings Technology Roadmap. Retrieved April 7, 2022, from https://www.bca.gov.sg/greenmark/others/SLE_Tech_Roadmap.pdf*

that it could lead to cooling energy savings ranging from 5 to 12% per month.[56] PCM can also be integrated as part of active cooling strategy when used in HVAC systems. For instance, PCM has been trialled to store and release cold energy in a district cooling plant in Singapore to mitigate cooling peak loads in commercial buildings. The trial has demonstrated that it could improve the energy carrying capacity by up to three times as compared to a conventional chilled water storage system and yield at least 10% in annual cost savings.[57]

In data centres, PCM had been used in a novel cooling technology developed in Singapore, which recycles and redeploys the waste heat discharged by servers for refrigerant phase change cycle. Such innovative use of heat exchange and phase change approach was able to reduce energy consumption by up to 50%.[58]

Applicability to brownfield/greenfield

PCMs have a wide field of applications and has demonstrated that it could be used in passive as well as active cooling strategies or technologies. Thus, the applicability of PCMs to brownfield or greenfield sites largely depends on the strategies or technologies that PCMs are used in. For instance, cool paint incorporating PCM can be implemented easily in both brownfield and greenfield sites, whereas PCM that is used as part of thermal storage for district cooling would be more applicable to greenfield than brownfield sites.

Limitations

A key barrier to the usage of PCMs is that the technology is relatively nascent, and their capabilities and achievable performances are not well-known.[59] The costs may be high, resulting in a long payback period to recover the investment cost, and not all construction companies have the knowledge for their use or installations. In some cases, there can be risk of flammability when using PCMs, however this risk can be overcome by using fire retardants. Any land-use implications of PCM would be dependent on the strategy or technology that the PCM is incorporated into.

5.1.4. CRYOGENIC ENERGY STORAGE

Technology overview	• A form of PCM technology that releases energy when specific chemicals are manipulated to change from liquid to gaseous phase, allowing the storage or re-use of wasted cold energy for other needs; • Yet to reach commercial viability, the technology is currently being researched and tested through demonstration projects which include the Cryo-Polygen project developed by Surbana Jurong and Nanyang Technological University
Flexibility potential	• Stores excess supply of renewable electricity at times of peak generation and releases it back to the grid at times of high demand or low renewable electricity generation; • Liquid air energy storage is one type of thermal energy storage that can achieve long duration storage by charging up energy storage during low demand or high generation hours and distribute it at times of lower supply or peak power demand
Potential sector applications	• Commercial buildings, Industrial manufacturing facilities
Applicability to brownfield/greenfield	• Applicable to greenfield sites or existing industrial sites with sufficient available space
Limitations	• Additional land-use planning requirements to accommodate the technology; • Nascent technology with limited solution providers
Recommendations for wider adoption	• Given that solution providers are limited, developers in Singapore could benefit from international research collaboration.

Technology overview and flexibility potential

Cryogenic energy storage systems are a form of PCM technology that use the gas and liquid phases of a chemical, rather than the liquid and solid phases. In cryogenic energy systems, such as those which use air, nitrogen, oxygen, or natural gas, the physical properties of these gases are manipulated to facilitate high volume bulk storage. By liquifying such chemicals, storage space requirements are dramatically reduced to circa one seven hundredth of the volume of the gaseous phase, making them easier to store or transport. A process called liquefaction, which cools the gases to below its boiling point (e.g.–162 to -200 C), is used to liquefy the gas. When gas is required, the process is reversed by adding heat (e.g., ambient

[56] *Lei, et al. Cool colored coating and phase change materials as complementary cooling strategies for building cooling load reduction in tropics. Retrieved April 7, 2022, from DR-NTU*
[57] *Energy Market Authority. New Technology to Boost Energy Efficiency of District Cooling Systems. Retrieved April 7, 2022, from https://www.ema.gov.sg/cmsmedia/News/Media%20Release/2021/141021-Media-Release-New-Technology-to-Boost-Energy-Efficiency-of-District-Cooling-Systems.pdf*
[58] *Singapore Press Centre. A*STAR and local SME develop energy-efficient cooling system for data centres that reduces energy consumption by up to 50 per cent. . Retrieved April 7, 2022, from https://www.sgpc.gov.sg/media_releases/astar/press_release/P-20211125-1*
[59] *Ascione et al. Phase Change Materials for Reducing Cooling Energy Demand and Improving Indoor Comfort: A Step-by-Step Retrofit of a Mediterranean Educational Building. Retrieved April 8, 2022, from https://www.mdpi.com/1996-1073/12/19/3661*

air temperature) to the liquid causing it to boil, returning it to its gaseous phase. During the regassing process, several energy vectors arise:

- Stored cold energy (an absence of heat) draws heat out of the environment. As the cold sink is warmed, the heat source cools (e.g., the local ambient air) – in effect, cold energy is transferred from the liquid to the heat source. In many re-gassing systems this cold energy is wasted (e.g., LNG);
- the circa seven-hundred-fold expansion from liquid to gas provides a significant source of kinetic energy that can drive mechanical work. This mechanical energy can be turned into electricity by passing the expanding gas through a turbine generator. In some cryogenic application the mechanical energy may currently be wasted or not put to productive use (e.g., LNG);
- The gas used for cryogenic storage might be an inert gas (e.g., nitrogen) or a reactive gas (e.g., oxygen, LNG). If it is LNG, then chemical energy is also available to produce heat. If it is nitrogen, oxygen or air, then the cryogenic medium is being used solely as an energy store.

At the core of an efficient cryogenic energy storage system is making best use of these different energy vectors.

Cryogenic energy storage technology, whether based on inert or reactive gases, can be used as an alternative to conventional electric battery storage. It can store excess supply of renewable electricity at times of peak generation and release it back to the grid at times of high demand or low renewable electricity generation. The kinetic energy caused by regasification can be used to drive a turbine regenerating renewable energy. The cold energy which is co-supplied during the regassification processes could be stored for future liquefaction episodes or be supplied to cooling services (e.g., blast chilling, air conditioning).

Research has validated that the round-trip efficiency of using liquid air as a cryogenic energy storage medium is comparable to that offered by conventional electric batteries. There are system losses from using cryogenic energy storage, but these are comparable to the losses observed by using electric batteries. Irrespective of energy storage technology, the electricity being stored is renewably generated and therefore battery system losses have not created GHG emissions.

LAES systems are being extensively researched and demonstrated in the UK, EU and USA. When LAES systems are coupled with use of a source of waste heat, it can achieve an alternating-current round-trip efficiency of 70-80%.

LAES is one type of thermal energy storage that can achieve long- duration storage. Focused on renewable electricity storage, it allows for a direct intersection between cooling- power systems. Long-duration storage can increase efficiencies in the energy system by charging up energy storage during low demand or high generation hours and distribute it at times of lower supply or peak power demand.

Cryo-Polygen

Singapore is already investigating the potential of cryogenic technology. Current research and development have focused on LNG-related processes, including the Cryo-Polygen project developed by Surbana Jurong and Nanyang Technological University, Singapore (NTU Singapore) and being test-bedded at NTU. Other commercial players have also noted active explorations. Given the risks around transportation and storage of LNG, currently its applications are focused on use that can be a safe distance away from high density residential areas, as well as areas/industries where fire risk would be high.

Potential sector applications

There is significant interest from multiple agencies to understand how to harness cold energy, including waste heat/cold processes, to support cooling needs at the district level and for commercial buildings. The International Renewable Energy Agency (IRENA) considers LAES to be a technology that is in demonstration phase and could support the growth of thermal energy storage needs for industries requiring cold chains and data centres in the medium term (5-10 years). Highview Power now has a global project pipeline of more than 5 GWh.[60] Its commercial full-scale pilot plant (5 MW/15 MWh) in the UK is an example of a LAES power station that can provide long duration energy storage. Also in the UK Highview Power is now moving forward with Carlton Power to full scale deployment with the Carrington cryogenic energy storage facility (50 MW/250 MWh).

LAES can accelerate the transition of the energy system to net zero given that it is a source of emission-free power, and has the ability to release energy directly back into the power grid during peak power demand hours. It can also reduce the quantum of new assets that need to be put online to meet additional power demand growth. There is benefit from integrating liquid air energy storage with other industrial processes with waste heat and cold flows.

Applicability to brownfield/greenfield

[60] *Recharge (2021). Highview Power unveils $1bn of liquid-air energy storage projects in Spain. Retrieved 4 April 2022, from https://www.rechargenews.com/energy-transition/highview-power-unveils-1bn-of-liquid-air-energy-storage-projects-in-spain/2-1-1012670*

LAES requires significant design needs to interconnect industrial processes to maximise the efficiency of the energy storage system. This, coupled with its land-use requirements suggests that the technology is applicable to greenfield sites or existing industrial sites with sufficient available space.

Limitations for Singapore

Current systems do have significant land-use implications that would require pre-planning. In the past, some initial research was undertaken in Singapore on liquid air energy storage, and the commercial viability was limited by the energy needs to compress air. However, further research into LAES has occurred since then and the commercial viability of the technology to a Singapore context is likely to have improved. Changing regulations and demands on the grid might improve the economic viability of LAES. For example, the new carbon tax regime announced in Singapore allows for significant commercial considerations in the choice of new power assets. There could also be economic benefits from reducing the quantum of new generation assets on the system.

Furthermore, given new variable demand on the grid, and possible spikes in power at specific nodes in the future, long-duration storage can smooth out demand peaks if located where peaks are expected. Given the technology is only just becoming commercial and the providers are limited, developers in Singapore could benefit from international research collaboration.

6 RECOMMENDATIONS

6. RECOMMENDATIONS

There are certain challenges limiting the growth of clean cooling solutions that have the potential to provide flexibility benefits to the grid. These were noted in the previous section as we explored the potential and limitations of the four clean cooling solutions proposed for further development.

The following policy and research recommendations seek to spur further investigation and investment into the clean cooling technologies described above, to realise the full potential of clean cooling and support the decarbonisation of the grid.

There needs to be policy considerations that will enable the unlocking of demand-side flexibility. This would strengthen the case for clean cooling solutions to be viewed as an important provider of flexibility benefits and economic value. With this as a foundation, a range of incentives that support research, development, piloting, and commercial application of specific technologies can be developed. Singapore's existing cooling collaborative platforms demonstrate it has strong capacity to effectively test-bed cooling technologies in Singapore with the availability of such incentives. This allows for an accelerated pathway towards developing suitable clean cooling solutions that provide energy system benefits. More specific research that studies cooling demand on a standalone basis, at sectoral levels, with an energy systems lens will allow for even deeper explorations, including looking at emerging sectors of cooling demand growth and potential for circularity of cold energy across different sectors.

6.1. POLICY IMPLICATIONS

While there has been significant development in the direction of policy to support the decarbonisation of Singapore, a whole-systems approach that considers all interactions between all energy vectors and the possibility of enabling demand-side flexibility can present new decarbonisation pathways for the whole system. Clean cooling solutions can be a means to provide this flexibility. To ensure that the benefits from the clean cooling solutions noted above fully materialise and contribute to Singapore's energy transition, the following policy recommendations can be considered:

- **Unlocking demand-side flexibility as part of the power system transition:** There is increasing recognition that demand-side flexibility will play and increasing role in Singapore's energy system planning. This is an important transition as grid flexibility will need to be addressed as future renewable energy sources for power generation are added to the system, bringing new challenges,, notably the increase of the need for flexibility given the increased presence of variable and inflexible generation technologies. Going beyond energy efficiency and total demand management to promote the need for grid flexibility can be supported by a suite of activities that anchor flexibility as a core part of the energy system, including considering the potential for clean cooling to contribute to flexibility. These could include a whole-system assessment of flexibility requirements, refining tariff mechanisms, and developing the ancillary service market through open tender of grid services where storage could facilitate the provision of those services at a competitive price compared to generation technologies. These market incentives can be tailored across the range of service benefits outlined in Table 2 based on the key system needs for the future (for example, incentivising solutions that ease power system constraints caused by cooling demand or incentives that promote grid flexibility by storing or shifting cooling demand).
- **Coordinating a whole of government approach to flexibility, including clean cooling:** Our study demonstrates that while clean cooling can support flexibility services to the grid, realising the full economic value of the technologies involved will require strong coordination across multiple agencies as the issues can be cross-cutting. For example, existing building efficiency incentives can be enhanced to also support clean cooling technology adoption, and with a market for grid services, providers of flexibility can be suitably remunerated. Furthermore, large-scale implementation of clean cooling solutions across multiple sectors could require urban planning decisions related to land-use and co-location that require inputs from multiple stakeholders such as the Land Transport Authority, the Housing Development Board, the Ministry of Trade and Industry, the Urban Redevelopment Authority among others.

- **Developing a clean cooling roadmap considering the role of cooling in providing services to the energy system:** The potential flexibility benefits for the energy system that could come from the adoption of clean cooling are currently not seen as a driver for retrofits and investment decisions by industry players. Given its wider energy system benefits related to providing grid flexibility and maximising the use of imported renewable energy, along with the requirement to be deployed at a sector level, it would be beneficial to start developing a roadmap on how each different sector can potentially support the transition towards clean cooling. This roadmap will require inputs from market players (including industry, data centres, utilities, building facilities management, and infrastructure developers) on existing technology, design, and behavioural changes that are already providing benefits to the system, how to enhance these, as well as where investment into innovation can play a role.
- **R&D and demonstration investment support:** Clean cooling solutions noted in Section 4 are pathways to providing flexibility to the grid, as well as reducing total power demand. Some of the key technologies with potential such as liquid air energy storage are still in the pilot demonstration phase globally. Investment support targeting industry players with existing cooling-related R&D initiatives can encourage them to further assess the additional energy systems and flexibility benefits arising from the pilot solutions. Similar demonstration platforms can be applied to public government buildings to assess the energy system benefits of clean cooling retrofit projects. This direct approach can help alleviate the risk perception of investing in novel technologies and accelerate their adoption.
- **Expansion of financial incentive schemes:** As the economic viability of novel technology solutions is often the deciding factor for the adoption of clean cooling, the use of subsidies, grants or investment support mechanisms for building owners or project developers can improve the business case of these opportunities and accelerate their implementation. While BCA's Green Mark scheme is currently technology-agnostic, it only focuses on accelerating efficiency improvement. Retrofit grants like the Green Mark Incentive Scheme for Existing Buildings can specify technologies that not only bring about efficiency gains, but also support the provision of demand-side flexibility; for example, the use of control systems and PCMs. Current grants that are evaluated based on performance (carbon abatement) would be able to support the implementation of the specific innovative cooling technologies. Supporting district cooling for brownfield sites through financial incentives is another lever to accelerate the transition to clean cooling where clear system benefits exist.
- **Implementing market mechanisms for flexibility:** Utilities should consider adopting time-of-use tariffs to incentivise demand-side flexibility and reduce utility bills, especially pertinent in the view of rising carbon taxes. Time-of-use tariffs can help shift cooling demand to the time of day when power from renewable energy sources is being generated. In addition, market mechanisms that specifically remunerate flexibility (such as ancillary services) can be made accessible to the use of clean cooling solutions so that they can promote demand-side response and benefit the broader energy system. Several pilots and voluntary mechanisms have been put in place in Singapore and can be further expanded upon.

Market incentives make flexibility benefits economical

In Singapore, a preliminary trial was conducted at Temasek Polytechnic (TP) to explore how electricity consumption can be reduced in response to real-time system conditions, such as high prices or contingency events. Results demonstrated that the electricity load of chillers – amounting to about 13.5% of total consumption – can be curtailed for up to half an hour with minimal impact on comfort level of users.[61]

In addition, Red Dot Power (an initiative part of EMA's Smart Energy Challenge grant) launched a pilot incentive scheme in which participating institutions were paid to voluntarily reduce consumption during peak periods. This project successfully completed the development of a virtual power plant providing 40 MW of DSM, in which customers curtailed their loads without affecting operations. Participating customers included Keppel DHCS, curtailing the load of chillers backed up by thermal storage.

The Marina Bay District Cooling Services operated by SP Group also directly participates in the power system operation in Singapore to provide demand-side response against remuneration.

[61] *Energy Market Authority (EMA), Demand Side Management, from: https://www.ema.gov.sg/Demand_Side_Management.aspx*

6.2. RESEARCH IMPLICATIONS

The emphasis for research on energy use in Singapore has a strong focus on efficiency and the reduction of overall demand. To harness all aspects of clean cooling potential, it would be beneficial to understand cooling demand characteristics in a more granular manner and establish a focus on variability both on the demand and supply side of cooling, as well as develop a whole-systems approach to cooling.

Understand future cooling demand holistically

There is a lack of data to understand and characterise the cooling sector. Data to estimate the cooling demand profile from the commercial and residential buildings sectors is available, but this is not the case for industrial and transport sectors, especially cold chain logistics. A more granular view on commercial building types, cooling technologies used, and their demand profiles can help establish where opportunities to manage cooling demand per sector exist. To reduce concerns of building owners, this data could be collected, anonymised and aggregated.

In addition, it is notable that there is expected growth in cooling demand from sectors that were not traditionally as critical. Further studies on the expected cooling demand load of new growth sectors such as indoor farming and electric vehicles[62] will allow for a more holistic picture of future cooling demand load, and understanding their demand profiles will allow for the identification of suitable clean cooling solutions that can alleviate the source of new strains on the power grid.

On the other hand, strategies that could reduce or induce a time-shift in cooling demand have not been analysed.

Understand future variable power demand's growth and profile

Another aspect to focus on in the characterisation of the cooling demand profile is its variability. As Singapore explores demand-side response as a potential contributor to a net zero energy grid, it is important to develop a detailed understanding of the various power demand profiles, including location profiles to understand where nodes for variable demand will emerge in the future. Increased research and the explicit assessment of cooling and energy plans is recommended to support the adoption of clean cooling solutions that promote demand-side response, as well as cold storage solutions that provide flexibility services to the grid.

Size the potential of solutions to replace traditional cooling, considering grid services and circularity

While several strands of research have brought some clean cooling technologies into the pilot phase and beyond, it is notable that a holistic view of the potential deployment of clean cooling across sectors has yet to be consolidated. Gaps that can be filled include:

- For technology that is already commercially deployable (e.g. district cooling, control systems in commercial buildings): It is important to size the potential to replace traditional cooling across major greenfield and brownfield sites, consider the barriers in technology adoption by facility owners, analyse how responsive different clean cooling technologies could be to the power grid's signals, and identify the different grid services they can support. This can set the stage for more refined financial incentive schemes to support demand response.
- For technology that is still in pilot phase (e.g., cold energy storage): More in-depth techno-economic analysis can be undertaken by industry. This could include a mapping of waste cold and waste heat energy flows from different industries, that can support land-use planning decisions at the district or island-wide level to achieve maximum energy system efficiency for these technologies.

Clarify safety issues and mitigation techniques across new potential energy assets

As Singapore explores new energy asset types to achieve a net zero power sector, it will need to gain clarity on the range of safety considerations across the different assets. Assets that can support increased flexibility in the grid can be comprehensively reviewed for safety concerns, with mitigation steps to establish consistent decision-making criteria.

Accelerate clean cooling technology demonstrations with international collaborations

Singapore has established important international platforms where research, demonstrations and test-bedding of cooling technology have been conducted. Extending these international platforms to explore the intersection of cooling and the energy system can ensure we are accelerating the search for solutions that can address the increasing need for flexible energy systems in a tropical climate.

[62] *In an EV car, the power electronics and the electric battery in an EV needs to be kept within a certain temperature range. [The Economist, Cooling: Transporting us to net zero. Retrieved January 24, 2022, from https://impact.economist.com/perspectives/sites/default/files/cooling_transporting_us_to_net_zero.pdf]*

7

CONCLUSION

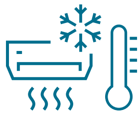
7. CONCLUSION

Given Singapore's increased ambition to achieve economy-wide net zero emissions by or around 2050, it must explore ways to both reduce total power demand growth as well as decarbonise its power grid. Cooling, as a large and rapidly growing source of power demand can be seen as a constraint to Singapore's energy transition ambitions and meeting net zero emissions target. Singapore has already implemented a range of cooling related policies as described in Appendix 9.

On the other hand, the challenges presented by business-as-usual cooling on Singapore's energy transition goals can be directly addressed via clean cooling solutions, whereby:

Replacing conventional cooling loads with passive cooling, behavioural changes, high efficiency equipment, low-carbon technologies, cold energy storage and low GWP refrigerants can reduce cooling's contribution to total emissions;

Investing in cold energy storage solutions may offer greater system flexibility. Cold energy storage can play a breakthrough role supporting the changing dynamics of the grid as greater intermittency is introduced as more renewables come online;



The profile of cooling demand and its correlation with renewable energy generation can support the integration of renewable energy and manage its intermittency.

However, the full potential of cooling can only be realised when flexibility is seen as integral and providing clear value to the grid, along with a more granular understanding of cooling demand and supply.

APPENDIX

APPENDIX 1: ESTIMATING SINGAPORE'S COOLING DEMAND IN 2019

Singapore's overall electricity consumption was 51.7 TWh in 2019. The Industrial-related sector is the largest consumer of electricity (41.3% or 21.0 TWh), followed by Commerce & Services-related (36.4% or 18.5 TWh) and Household (16.1% or 8.2 TWh) sectors.

Total final energy consumption in 2019: 16,134.80 ktoe
Total electricity consumed in 2019: 51.70 TWh

Cooling Estimation Data Sources

Sector	Equipment (if available)	Source	Year	% of sector's energy/ electricity consumption by cooling systems	Remarks	Any missing data?
Commercial buildings	Cooling system	Ecosperity	2021	40% to 50% of energy consumption	% energy consumed by cooling systems in commercial buildings applies to hotels, office and retail buildings. Supermarkets are included under the retail building category.	No disaggregated data by types of cooling system available.
Household	Air conditioner	NEA household energy consumption study	2017	24% of energy consumption	-	No, main cooling systems covered by the study
Household	Refrigerator/ Freezer	NEA household energy consumption study	2017	17% of energy consumption	-	No, main cooling systems covered by the study
Industry	Chilled water systems	NEA	2019	16% of electricity consumption	The 16% value refers to energy used by chilled water systems for process and space cooling in energy-intensive facilities. Total % of cooling energy use is expected to be higher than 16%.	Energy used by other cooling systems in industry is not available. However, it is noted that chilled water systems are the second highest electricity consuming system in the industry
Data centres	Cooling system	Ecobusiness	2020	37% of energy consumption	-	No disaggregated data by types of cooling system available.
Transport	Mobile air conditioning system	International Council on Clean Transportation (ICCT)	2019	20% of energy consumption	ICCT estimates that mobile air conditioning systems installed in vehicles typically consume 3-7%, and up to 20% in very hot, humid regions with traffic congestion. Since no Singapore specific data is available, is used 20% as a proxy of fuel consumption by vehicles.	Proxy data rather than actuals is used, and this is only specific to mobile air conditioning (AC). Data for refrigeration systems in transport is not included in this data point.

Estimation of cooling energy/electricity demand

Grid emissions factor:[63] 0.4085 kg CO2/kWh (source: EMA energy statistics, 2019 estimate: EMA: Singapore Energy Statistics | Energy Transformation)

	Electricity consumed 2019 by Sector (TWh)	Energy consumed 2019 by Sector (ktoe)	% of the Sector's energy consumed by cooling	Energy consumed by cooling (ktoe) - 2019	% of Singapore's total energy consumption from cooling	Electricity consumed by cooling (TWh) - 2019	% of Singapore's total electricity consumption from cooling	Emissions 2019 (MtCO2e)
Commerce & Services related	**19.3**	**1,818.90**						
Commercial buildings		1,345.99	45%	605.69	3.75%	7.05	13.64%	2.88
Household	**7.68**	**747.2**	**41%**	**306.35**	**1.90%**	**3.57**	**6.90%**	**1.46**
Air-conditioners			24%	179.33	1.11%	2.09	4.04%	
Refrigerators			17%	127.02	0.79%	1.48	2.86%	
Industry	**21.4**	**10,960.90**	**16%**	**288.62**	**1.79%**	**3.42**	**6.62%**	**1.40**
Data Centres	**3.6**	**305.46**	**37%**	**113.02**	**0.70%**	**1.34**	**2.59%**	**0.55**

Based on the assumptions above, our estimate for electricity consumed to power cooling in 2019 amounts to 15.3TWh (considering households, commercial buildings, the industry and data centres).

In order to estimate the average capacity that would be used to power this demand, this volume can be divided by the number of hours in the year, which results in 1.75GW of power on average dedicated to cooling every hour in Singapore.

Current Cooling Demand by Sector

Commercial Buildings

The Energy Benchmarking Report 2021 of the Building and Construction Authority (BCA) noted that the overall energy use intensity in commercial buildings has decreased by 25% between 2008 to 2020. However, data in Table 4 suggests that there are existing inefficiencies in retail buildings that, if addressed, can further reduce the energy intensity of the sector. That is, the energy intensity of air conditioning use is the highest in retail buildings compared to hotels and office buildings.

Table 4: *Cooling system characteristics in Singapore Commercial Buildings (2020)*

Building Type	Building Size	% of air-conditioned floor area	Common Types of Air-conditioning System	Average age of Chiller (years)	Average Centralised Air-conditioning Plant Efficiency (kW/RT)	Average 2020 Energy Use Intensity (kWh/m2.yr)
Office	Small (GFA < 15,000m²)	87%	Water cooled chilled water plant; Air cooled chilled water plant	7.81	0.89	195.89
Office	Large (GFA > 15,000m²)	76%	Water cooled chilled water plant; Air cooled chilled water plant; District cooling plant	7.54	0.72	195.74
Hotel	Small (GFA < 7,000m²)	85%	Water cooled chilled water plant	6.43	0.75	248.60
Hotel	Large (GFA > 7,000m²)	86%	Water cooled chilled water plant	5.47	0.65	188.61
Retail	Small (GFA < 15,000m²)	82%	Water cooled chilled water plant	4.6	0.68	214.83
Retail	Large (GFA > 15,000m²)	80%	Water cooled chilled water plant	5.36	0.65	376.79
Mixed Development	Small (GFA < 15,000m²)	75%	Water cooled chilled water plant; Air cooled chilled water plant	7	0.88	218.17
Mixed Development	Large (GFA > 15,000m²)	85%	Water cooled chilled water plant; Air cooled chilled water plant	6.54	0.69	219.23

Source: BCA; Note: GFA = gross floor area

[63] *Comparing the grid factor to a similar geography such as Hong Kong, in terms of its city-state status and land constraints, notes that Singapore's grid emissions factor is lower than Hong Kong's which is 0.71 tCO2/MWh[63] given that natural gas comprises of 48% of Hong Kong's fuel mix followed by 24% of coal[63].*

Households

In a study by the International Energy Agency (IEA) on cooling in South East Asia,[64] which was based on information from CLASP, the Kigali Cooling Efficiency Program and the national registration database of Singapore, it was noted that air conditioners with an efficiency level between 3.08 W/W to 4.3 W/W are the most widely available (representing more than 60% of the sample) in Singapore. Meanwhile, air conditioners with a higher efficiency of 5 W/W to 6.2 W/W are available but not widely used (less than 60% of the sample) in Singapore.

Indeed, the NEA has recently raised the Minimum Energy Performance Standards (MEPS) for window air conditioners from COP100% ≥ 2.9 to COP100% ≥ 3.78, and for split-type air conditioners from $COP_{100\%} \geq 3.78$ to $COP_{100\%} \geq 4.04$.[65] While the enhanced MEPS are higher than the market average energy performance noted in the IEA study, it is still below the energy performance of the best available air conditioning technologies in the market.

Industry

Based on the analysis conducted on the industrial sub-sector data provided by the NEA, and the proportion of energy use by sub-sectors relative to total industrial energy consumption noted in the NCCS 2010 study,[66] chilled water systems in the electronics and semiconductor sub-sector consume the most energy at 3.11% of Singapore's total electricity consumption in 2019. This is followed by the chemicals sector which contributed towards 0.86% of Singapore's total electricity consumption in 2019.

Data Centres

Singapore accounts for about 60% of the data centres in Southeast Asia. There are approximately 60 data centres in Singapore, which consumed almost 7% of the country's total energy needs in 2020, which is significantly higher than the average of 1% to 2% in the rest of the world.

In Southeast Asia, between 35% to 40% of total energy usage goes towards cooling a typical data centre, whilst the global average is 30% to 35%.[67]

Transport

For vehicles with internal combustion systems, the energy demand for cooling results in CO2 emissions as a result of more fuel burned. For electric vehicles, the cooling demand results in indirect emissions of CO2 from the electricity generated at fossil-fuel plants. The role of cooling demand, on to the grid, from electric vehicles will increase in importance for Singapore with plans to phase out all internal combustion engine vehicles and replace them with vehicles running on cleaner energy by 2040.

64 *IEA (2019). The future of cooling in Southeast Asia. Retrieved January 24, 2022, from https://iea.blob.core.windows.net/assets/dcadf8ee-c43d-400e-9112 533516662e3e/The_Future_of_Cooling_in_Southeast_Asia.pdf*

65 *NEA (2021). NEA To Enhance Minimum Energy Performance Standards (MEPS) For Refrigerators, Clothes Dryers And Air-Conditioners. Retrieved January 24, 2022 from, https://www.nea.gov.sg/media/news/news/index/nea-to-enhance-minimum-energy-performance-standards-(meps)-for-refrigerators-clothes-dryers-and-air-conditioners*

66 *Source: National Climate Change Secretariat (2010). Industry Energy Efficiency Technology Roadmap. Retrieved 14th January 2022, from https://www.nccs.gov.sg/docs/default-source/default-document-library/industry-energy-efficiency-technology-roadmap.pdf*

67 *Eco-Business (2020). The future of data centres in the face of climate change. Retrieved January 13, 2022, from https://www.eco-business.com/news/the-future-of-data-centres-in-the-face-of-climate-change/*

APPENDIX 2: ESTIMATING SINGAPORE'S COOLING DEMAND IN 2030

% Growth in Cooling Energy Demand between 2020-2030			
Sector	**Cooling System**	**% Growth in unit sales (2020 – 2030)**	**Source**
Transport	Transport Refrigeration	18.90%	Green cooling initiative
	Transport Mobile Air Conditioning	24.20%	Green cooling initiative
Industry	Industrial Refrigeration	19%	Green cooling initiative
	Chiller	19.70%	Green cooling initiative
Commercial Buildings	Commercial Refrigeration	19.40%	Green cooling initiative
	Unitary air conditioning	45.50%	Green cooling initiative
Household	Room Air Conditioner	43% (growth in energy consumption)[68]	UNEP
	Residential Refrigerator	20% (growth in energy consumption)[68]	UNEP

Data centres are expected to account for 12% of Singapore's total electricity needs by 2030 (up from 7% in 2020). Cooling systems consume 37% of the total energy used in data centres.

Demand Type	Value	Unit	Remarks
2019 Singapore Electricity Demand:	51.70	TWh	
2030 Singapore Electricity Demand[69]:	73.85	TWh	Average based on EMA's projection of 71.3 – 76.4TWh
2019 Data Centre Electricity Consumption	3.619	TWh	7% of Singapore's electricity consumption[70]
2030 Data Centre Electricity Consumption	8.862	TWh	12% of Singapore's electricity consumption[71]
2019 Data Centre Cooling Demand	1.34	TWh	37% of total energy used in data centres is for cooling
2030 Data Centre Cooling Demand	3.28	TWh	Assume that the proportion of cooling demand (37%) remains constant
% growth in data centre cooling demand from 2019 to 2030	**145**	**%**	

Growth projections in cooling service demand are based on unit sales of cooling equipment (e.g., refrigerators, chillers and air conditioners). Projections do not account for potential efficiency gains possible for these technologies because (i) much of the cooling equipment installed today will still be in use in 2030 and (ii) the time lag between the average efficiency of equipment being positively influenced by the efficiency of the best equipment on the market. Therefore Figure 3 projects growth in cooling demand without short term efficiency gains. Electricity demand grows in line with the demand for cooling units.

Projected Cooling Demand by Sector

Commercial Buildings

According to estimates by the Green Cooling Initiative,[72] the use of unitary air conditioning is expected to grow by 45.5% from 2020 to 2030 from 1.34 million units to 1.95 million units. Unitary air conditioning includes ductless split, ducted split and rooftop AC as well as variable refrigerant flow systems and self-contained units, which are movable ACs and window/through-the-wall units. The use of commercial refrigeration is expected to grow by 19.4% from 71,000 units to 84,800 units between 2020 to 2030.

[68] *UN Environment Programme (2022). Singapore Policy Savings Assessment. Retrieved 22 June 2022, from https://united4efficiency.org/country-assessments/singapore/*

[69] *Energy Market Authority (2021). Singapore Electricity Market Outlook. Retrieved 14 January 2022, from https://www.ema.gov.sg/cmsmedia/PPD/Singapore-Electricity-Market-Outlook-2021.pdf*

[70] *Channel News Asia (2021). Singapore puts 'temporary pause' on new data centres: Why and what it means for the industry. Retrieved 14 January 2022, from https://www.channelnewsasia.com/business/new-data-centres-singapore-temporary-pause-climate-change-1355246. The article noted that "In Singapore, data centres accounted for about 7 per cent of the country's total electricity consumption last year, said the MTI in a recent written answer to a parliamentary question.*

[71] *NUS News (2021). NUS and NTU launch first-of-its-kind tropical data centre testbed. Retrieved 14th January, 2022, from https://news.nus.edu.sg/nus-and-ntu-launch-first-of-its-kind-tropical-data-centre-testbed/#:~:text=Data%20centres%20in%20Singapore%20consume,12%20per%20cent%20by%202030*

[72] *Green Cooling Initiative. Singapore. Retrieved 14th January, 2022, from https://www.green-cooling-initiative.org/country-data#!country-data-sheet/702/all-sectors*

Households

According to estimates by the UN Environment for Singapore, total energy consumption of room air conditioners and residential refrigerators are projected to increase by 43% and 20% respectively from 2020 to 2030.

Industry

Based on estimates by the Green Cooling Initiative, the number of industrial refrigerators in use are projected to increase by 19.0% between 2020 and 2030 from 200 units to 238 units. Similarly, the number of chiller units in use are expected to increase by 19.7% from 1,880 units in 2020 to 2,250 units in 2030.

Data Centres

Data centres are projected to contribute to 12% of the total energy needs in Singapore by 2030.[73] In the past five years, 14 data centres with a total IT capacity of 768 megawatts were approved, compared to 12 data centres carrying 307 megawatts in the preceding five years. With the industry being an intensive user of energy and water, in 2019, the government had decided to moderate the growth of data centres with a temporary pause on the release of state land for data centres, as well as the development of data centres on existing state land. However, in 2022 the moratorium on data centres was lifted with the caveat that new data centres will have to meet more stringent efficiency and capacity conditions.

Transport

Estimates from the Green Cooling Initiative note that the number of refrigerator units in use in transportation is projected to grow by 18.9% from 942 units in 2020 to 1,120 units in 2030. Similarly, the use of mobile air conditioning systems that are installed in cars are forecasted to grow by 24.2% between 2020 to 2030 from 2.19 million units to 2.72 million units.

[73] *NUS News (2021). NUS and NTU launch first-of-its-kind tropical data centre testbed. Retrieved 14th January, 2022, from https://news.nus.edu.sg/nus-and-ntu-launch-first-of-its-kind-tropical-data-centre-testbed/#:~:text=Data%20centres%20in%20Singapore%20consume,12%20per%20cent%20by%202030.*

APPENDIX 3: COOLING DEMAND PROFILES

Following the estimation of cooling demand, the cooling profile through the hours of the day provides further insights to better characterise the dynamic impact of this demand on the power system.

The figures below show the profiles of residential and commercial cooling loads in Singapore for two use cases: a continuous cooling demand through the day (where cooling is operated from 00:00 to 24:00), and an occupancy-based use of cooling (where the cooling system is operated from 7:00 to 18:00 in commercial buildings and 22:00 to 7:00 in residential buildings).[74]

The profiles show that:

- Occupancy-based cooling behaviour can lead to significant variations of demand on the power system in short periods of time when cooling systems are turned on and off. In addition, indoor air temperature can increase beyond the desired temperature range while cooling systems are turned off. This translates into a significant cooling load during initial hours of operation to reach the set range. Consequently, a substantial increase of demand is expected around 10pm for the residential sector and 7am for the commercial sector.
- The commercial cooling load is mainly used during daytime hours while the residential demand profile substantially varies depending on the continuous or occupancy-based profile.

Figure 9: *Residential Cooling Load in Singapore*

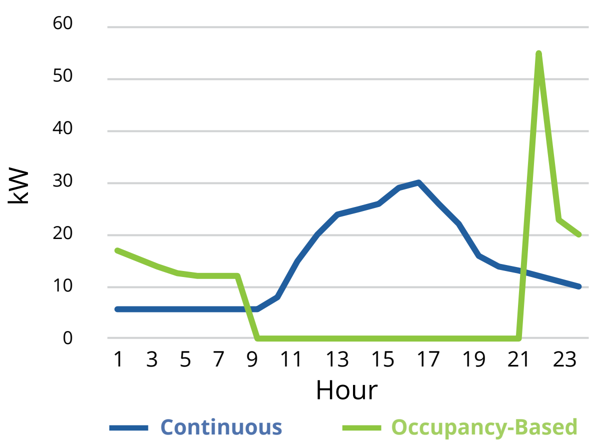
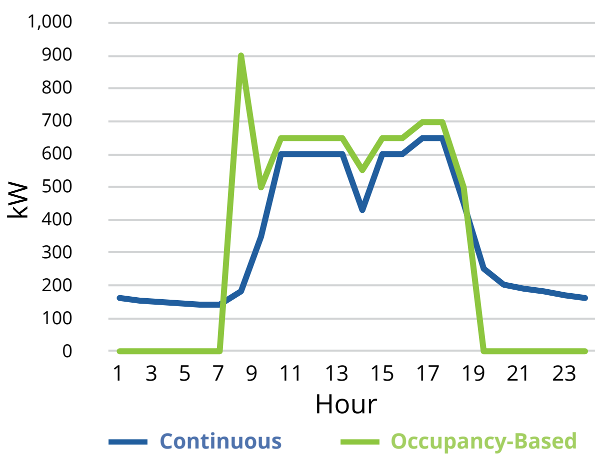


Figure 10: *Commercial Cooling Load in Singapore*



Source: derived from: Effectiveness of cool walls on cooling load and urban temperature in a tropical climate - ScienceDirect

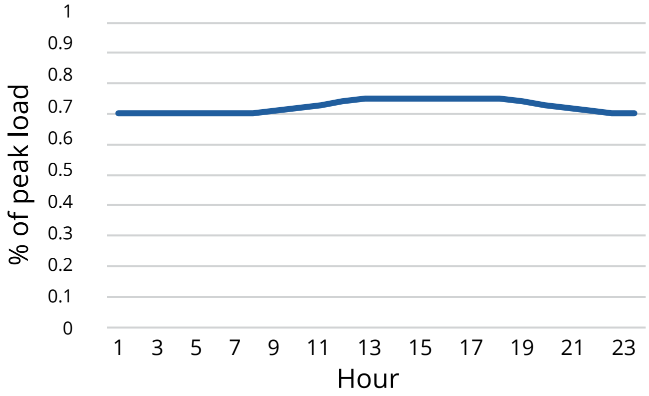
In the absence of information regarding the operation of cooling systems in the commercial and residential sectors, it is assumed that 50% of cooling demand follows a continuous schedule and 50% follows an occupancy-based schedule in these sectors.

For the industrial sector, as no information specific to Singapore is available, an estimation from a study in Hong Kong[75] is used, which shows a steady demand for cooling through the day. As the study used data during the hot and humid months of May to October in Hong Kong, it is assumed to present a realistic hourly cooling demand profile for the industrial sector in Singapore.

[74] *These profiles are derived from simulations of the HVAC schedule in the 2019 study: Effectiveness of cool walls on cooling load and urban temperature in a tropical climate from the Massachusetts Institute of Technology. In the simulations, these cooling systems work as a dual set-point thermostat with dead-band between minimum and upper set-points. For occupancy-based schedules, the maximum set-point is set to 24 degrees Celsius. For the continuous operation, it is increased to 26 degrees Celsius to lower unnecessary energy consumption in low occupancy periods.*

[75] *Seung Jin Oh, Kim Choon Ng, Kyaw Thu, Wongee, Chun, Kian Jon Ernest Chua (2016). Forecasting Long-term Electricity Demand for Cooling of Singapore's Buildings Incorporating an Innovative Air-conditioning Technology, Energy and Buildings. Retrieved January 11th 2022, from http://dx.doi.org/10.1016/j.enbuild.2016.05.073*

Figure 11: *Industry Cooling Load (proxy from Hong Kong data)*



Source: [Forecasting long-term electricity demand for cooling of Singapore's buildings incorporating an innovative air-conditioning technology - ScienceDirect]

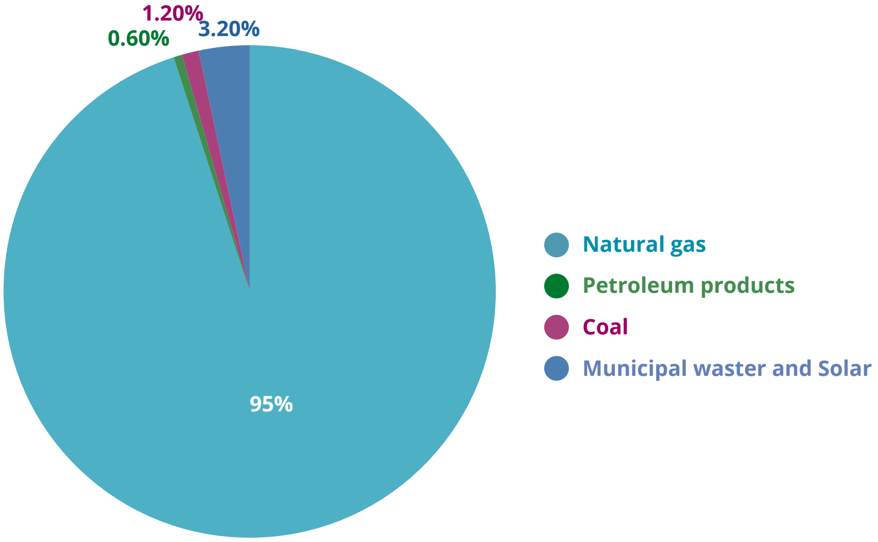
For **data centres**, interviews with relevant stakeholders in Singapore indicated that the cooling demand from data centres is currently steady – in the absence of a publicly available cooling demand profile for data centres in Singapore, an even distribution of demand for cooling in data centres through time is thus assumed.

APPENDIX 4: POWER SYSTEM CHARACTERISTICS

Power Generation Mix

Singapore's power generation (Figure 12) is primarily through use of natural gas assets, with minor contributions from municipal waste, solar energy, petroleum products, and coal. Singapore does not import electricity from neighbouring countries.

Figure 12: *Power Generation Mix 2021 (estimated as of June 2021)*

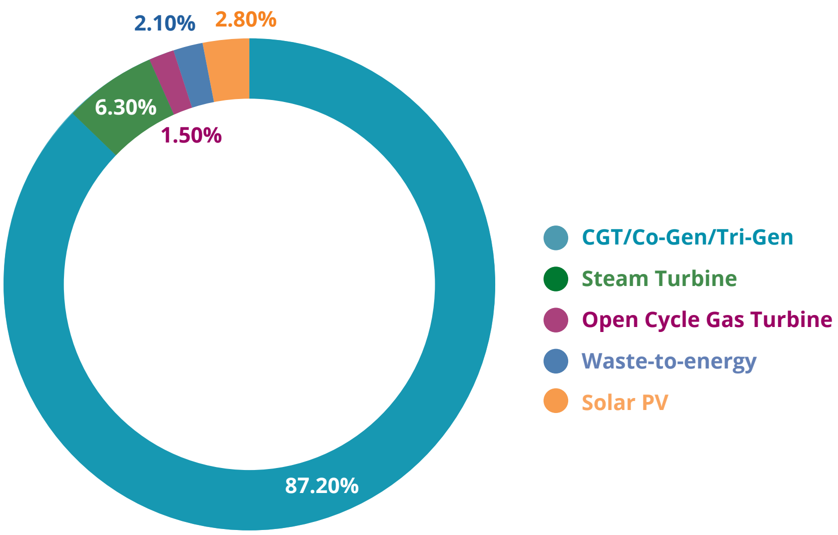


The 2020 Grid Emission Factor, which measures average CO2 emissions per MWh of electricity generated in Singapore, was estimated at 0.408 tCO2/MWh. This figure, largely driven by the dominance of natural gas in Singapore's generation mix, is one of the lowest in South East Asia due to the region's larger reliance on oil or coal for power generation.[76]

Installed Capacity

In terms of installed capacity (Figure 13) for electricity generation, 87.2% of capacity is from combined cycle gas turbines, co-generation plants and trigeneration plants, while an additional 6.3% comes from steam turbines. The remainder includes PV, waste-to-energy plants, and open cycle gas turbines.

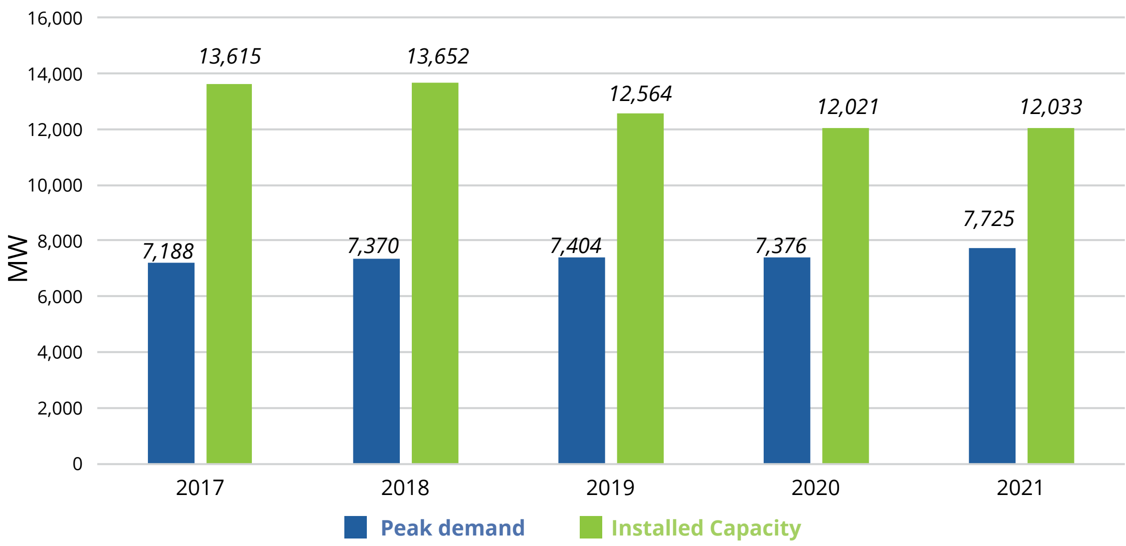
Figure 13: *Installed Capacity 2021 (estimated as at March 2021)*



[76] *Institute for Global Environmental Strategies (2022). List of Grid Emission Factors version 10.12. Retrieved 1 March 2022, from https://pub.iges.or.jp/pub/iges-list-grid-emission-factors*

Peak Demand

Figure 14: *Peak Demand and Installed Capacity in Singapore*



Merit Order

Each asset will display technical parameters which will impact its operation schedule and short-run power generation costs. Assets relying on fossil fuels are dispatchable with the generation determined based on demand. The heat rate[77] of each installation will determine how much fuel is needed to generate each unit of electricity, directly impacting the generation cost and associated CO2 emissions.

Different technologies of power generation plants will display different heat rates. The United States Energy Information Administration provides the following average annual heat rates for gas combined cycles, steam generators and turbines in 2020:[78]

- Combined Cycle: 7,604 British Thermal Unit (BTU)/kWh (translating into a 45% efficiency: the amount of energy output in the form of electricity equals 45% of the energy input in the form of gas)
- Steam Generator: 10,368 BTU/kWh (translating into a 33% efficiency)
- Gas Turbine: 11,069 BTU/kWh (translating into a 31% efficiency)

The heat rate of each installation per category also varies as a function of the installation age for example.

In Singapore, according to a study by Deloitte[79] (Figure 4), the largest share of assets displays relatively homogeneous heat rates, up to 8,000 MW of installed capacity. Between 8,000 and 9,600MW, heat rates increase, and above 9,600MW, assets display substantially higher heat rate levels.

This depiction of Singapore's installed capacity as a function of heat rate illustrates the order in which assets are likely to be called upon to satisfy power demand needs. The merit order ranks electricity generation assets based on the short-run marginal costs of production and the amount of energy generated. For power generation plants relying on fossil fuels, the short-run marginal cost is mostly determined by fuel costs and potential greenhouse gas emission costs (if there is a price on GHG emissions). The heat rate, in combination with the fuel and emissions price, determines the marginal costs as it quantifies the amount of fuel needed to produce electricity. The most efficient units, which display lower heat rates, will have lower short-run marginal costs and will be called first to answer power demand.

77 *Heat Rate is a metric to characterise the efficiency of an asset, calculated as the amount of energy used by an electrical generator/power plant to generate one kilowatt-hour (kWh) of electricity.*

78 *U.S. Energy Information Administration (2020). Form EIA-860, 'Annual Electric Generator Report. Retrieved 4 April, 2022, from SAS Output (eia.gov)*

79 *Deloitte, 2021. Electrifying Singapore. Retrieved February 24th 2022, from https://www2.deloitte.com/content/dam/Deloitte/sg/Documents/finance/sea-fa-rsi-electrifying-sg.pdf*

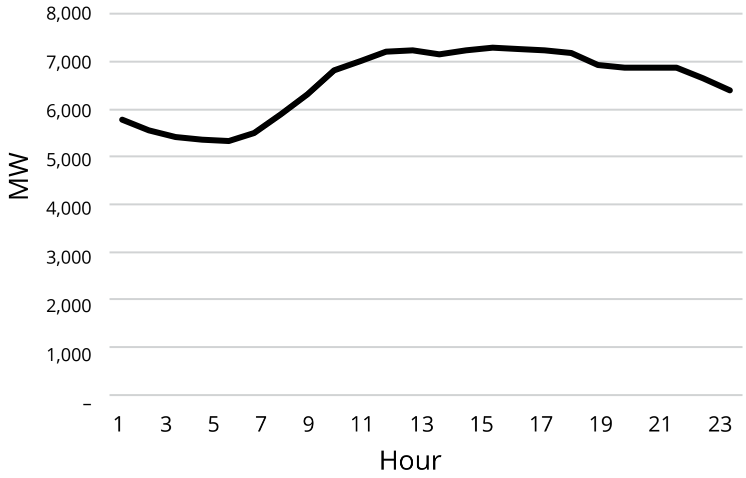
Based on Figure 4, installed capacity of the most efficient assets (below and around 7,000BTU/kWh) is high enough to satisfy Singapore's peak demand. Should availability of these assets decline (through maintenance, outages, or retirements) or power demand rise to higher levels, less efficient assets will be needed to meet demand. This would result in higher fuel consumption per unit of electricity produced, and thus higher GHG emissions (as long as these units are not coupled with carbon capture, utilisation and storage (CCUS) technologies).

This figure also reveals that both the peak demand and reserve margin are significantly lower than installed capacity in Singapore.

Total Power Demand

The Energy Market Authority of Singapore publishes the total power demand in Singapore on a half-hourly basis. A representative day of 2019 (prior to Covid-19) has been used to illustrate the profile of total power demand in Singapore through the day in the figure below.

Figure 15: *Total Power Demand - Typical Day in Singapore*



Source: EMA

APPENDIX 5: SINGAPORE'S ENERGY TRANSITION TARGETS

- Net zero target: Singapore has announced plans to accelerate its long-term climate ambition and aim to reach net-zero emissions by or around 2050.[80]
- 2030 Emissions target: Singapore updated its Nationally Determined Contributions (NDC) in March 2020, formalising its first NDC intensity target in absolute terms, as 65 MtCO2e in 2030. However, these 2030 targets will be reviewed in 2022 to align with the latest net zero target.
- Power generation mix: By 2035, the remaining supply of Singapore's electricity will continue to come from various sources, including the current natural gas-fired power plants, solar and waste-to-energy sources. Natural gas will continue to play a role in meeting the country's energy needs for the next 50 years.
- Phase out unabated coal power by 2050: Singapore's current reliance on coal is less than 2% of its power generation capacity. However, the country has committed to continue phasing out the use of unabated coal in its electricity mix by 2050, and to restrict direct Government finance of unabated coal power internationally, having joined the Powering Past Coal Alliance at the 26th Conference of Parties (COP26).
- Solar Energy Target: A new 2 GW target for solar energy by 2030 has been set. According to EMA chief executive,[81] this solar capacity could power about 3% of the country's total electricity demand in 2030.
- Renewable energy imports: Singapore expects to increase renewable electricity to 8% of peak power in 2030. Singapore plans to import 30% of energy from low-carbon sources, such as renewable energy plants by 2035 (up to 4GW). This includes importing (i) 100MW of low-carbon or clean electricity from Malaysia, (ii) 100MW of non-intermittent electricity from solar farms in Indonesia, and (iii) 100MW of hydropower from Laos via Thailand and Malaysia. If additional projects like the Australia-Asia Power Link are fully implemented and scaled by end 2028, then the plans to dispatch solar energy from a 12,000 hectare solar farm in Australia to Singapore through an undersea cable will be able to satisfy 15-20% of Singapore's total electricity needs, and exceed Singapore's solar energy target.
- Hydrogen: Emerging low-carbon alternatives such as green hydrogen are being considered but these are at very early pilot stages. This includes exploring various supply pathways for price-competitive low-carbon hydrogen (including importing hydrogen via shipping, piping from neighbouring countries).
- Carbon Capture and Storage: Singapore plans to add 2 million tonnes of carbon capture capacity in the energy intensive Jurong Island with options to scale up the technology to capture 6 million tonnes of carbon per year by 2050.
- Transmission and distribution network plans: Singapore's Smart Grid 2.0 is planned to be the next generation grid system that will transform how energy supply and demand are managed, by consolidating gas, solar, thermal, and other sources of energy into a single intelligent network that is more efficient, sustainable, and resilient.
- Transportation plans: Singapore plans to increase access to public transportation by increasing the length of the rail network and targets 75% of all trips to be on mass public transport by 2030 compared to 64% in 2020. In addition, Singapore aims to phase out all internal combustion engine vehicles and replace them with vehicles running on cleaner energy by 2040. With electric vehicles, the country is targeting 60,000 charging points to be installed by 2030.
- Green building plans: There are three main targets for green buildings for 2030 – (i) to have 80% of buildings by gross floor area to be certified as green, (ii) to have 80% of new buildings qualify as "super low energy" which means pursuing best-in-class standards, and (iii) to have green buildings see an improvement of 80% in their energy efficiency compared to 2005 levels.
- Other power system goals: While wider goals outside of energy transition are not explicitly stated, it is expected that complementary objectives for Singapore will include limiting the cost of power system build out and ensuring system reliability.

[80] *Announced as part of Singapore's Budget 2022 and is not part of the official NDC. Business Times (2022). Budget 2022: Singapore to target net zero 'by or around mid-century'. Retrieved 21 February, 2022, from https://www.businesstimes.com.sg/government-economy/budget-2022-singapore-to-target-net-zero-by-or-around-mid-century*

[81] *Announced at the Singapore International Energy Week 2021. Business Times (2022). Solar shines as Singapore's energy alternative; international collaboration is key. Retrieved 4 April 2022, from https://www.businesstimes.com.sg/government-economy/solar-shines-as-singapores-energy-alternative-international-collaboration-is-key*

APPENDIX 6: MAPPING THE IMPACT OF COOLING DEMAND AGAINST SINGAPORE'S ENERGY TRANSITION

Energy transition goal	Is there a direct impact from cooling?	Quantifying the direct impact from cooling	Is there an indirect impact from cooling?	Quantifying the indirect impact from cooling	Is there a role for clean cooling?
Carbon neutrality and 2030 emissions target	Yes, increased cooling demand contributes towards increased emissions due to the energy consumed by cooling technologies.	Estimation of emissions from cooling power in 2019 (excluding transport) was 6.28 MtCO2e (in 2018, total emissions were 52 MtCO2e). Emissions from hydrofluorocarbons (HFCs) were 0.47MtCO2e or 0.92% of the country's total emissions.	N/A	N/A	Yes, passive cooling, behavioural changes, high efficiency equipment, low-carbon technologies, cold energy storage and low GWP refrigerants can reduce cooling's contribution to total emissions.
Power generation mix targets	Yes, the mix will be sized and operated as a function of power demand, including demand for cooling.	In 2019, the total electricity consumed was 51.70 TWh. Of this, cooling consumed ~15 TWh of electricity (30% of total electricity).	Yes, there is an impact on the operation of power generation assets in terms of which assets are online and when.	The availability of power generation as the mix includes more variable renewable energy will be affected by the cooling demand profile which peaks during the day for commercial sectors, and peaks at night for the household sector.	Clean cooling initiatives that offer system flexibility can play a role to support the changing dynamics of the grid once more intermittency is introduced through renewables.
Solar energy target	No, as this refers to the build out of solar which is independent to cooling demand.	N/A	Yes, if cooling is flexible or cold energy storage is developed, it can ease solar generation use. Solar panels also act as roof shades which reduce the temperature of the rooms below the roof, reducing the need for air conditioning.	A 2 GWp solar energy target by 2030 would support the fulfilment of the estimated 1.75 GW of current average hourly cooling energy demand, leaving little capacity to support wider electricity demand.	Clean cooling initiatives that offer system flexibility can play a role to support the changing dynamics of the grid once more intermittency is introduced through renewables.
Renewable energy imports	Cooling demand can impact the target to increase renewable electricity to 8% of peak power in 2030. That is, reduced cooling loads can reduce the peak demand, making it easier to reach the 8% target.	A 4GW renewable energy import target by 2030 would support the fulfilment of the estimated 1.75 GW of current average hourly cooling energy demand.	N/A	N/A	Yes, clean cooling technologies can reduce the need for power plants to meet peak demand, especially at night.

Energy transition goal	Is there a direct impact from cooling?	Quantifying the direct impact from cooling	Is there an indirect impact from cooling?	Quantifying the indirect impact from cooling	Is there a role for clean cooling?
Hydrogen	Impact will depend on the definition of the target	N/A	Hydrogen has the potential to be used for district cooling and can also provide energy storage capacity for cooling demand. The profile of cooling demand – and its correlation with RE generation – can impact the need for electricity storage, including through power-to-gas-to-power, and thus impact the amount of hydrogen	N/A	Hydrogen can support the move towards low energy intensive, cleaner forms of cooling.
Transmission and distribution network plans	Cooling demand will play a role in the way the energy supply and demand are managed by the Grid 2.0. A lower and/or more flexible cooling load will support the smart grid operation and could lead to lower operation and infrastructure costs.	N/A	N/A	N/A	Yes, clean cooling technologies reduce electricity demand and offer system flexibility, contributing towards the objectives of the Grid 2.0.
Transport electrification plans	Yes, as the transport fleet becomes electrified, the high cooling load as a result of Singapore's tropical climate will put a strain on batteries and the distance travelled before recharging. This may affect the adoption of electric vehicles.	The power requirement to cool the cabin of an electric vehicle and the battery in 30°C temperatures reduces the battery range by 25%.[82]	Yes, if cooling demand is managed then the constraints on the grid will be reduced to support the demand from electric vehicle. In addition, the transfer of cooling demand from the transport sector to the electricity system in case of electrification of transport would translate into a substantial additional amount of power to be produced to satisfy cooling needs.	It is estimated that mobile air conditioning systems in internal combustion vehicles use up to 20% of fuel consumption in hot and humid regions.[83] Applying this proxy to the total energy consumed by Singapore's transport sector, results in 516 ktoe of energy consumed by cooling. If electric vehicles replaced the existing fleet and it is assumed that the fuel consumption by cooling shifts to electricity consumption, then this is translated to 6TWh or 12% of Singapore's total electricity consumption in 2019.	Yes, innovations in cooling technologies in electric vehicles that reduce the impact on the battery storage and energy consumption will improve the adoption of electric vehicles and lower the demand transfer to the power grid.

[82] *The Economist, Cooling: Transporting us to net zero. Retrieved January 24, 2022, from https://impact.economist.com/perspectives/sites/default/files/cooling_transporting_us_to_net_zero.pdf*
[83] *International Council on Clean Transportation, Mobile Air Conditioning. Retrieved January 24, 2022, from https://theicct.org/sites/default/files/publications/ICCT_mobile-air-cond_CBE_201903.pdf*

Energy transition goal	Is there a direct impact from cooling?	Quantifying the direct impact from cooling	Is there an indirect impact from cooling?	Quantifying the indirect impact from cooling	Is there a role for clean cooling?
Green buildings	Yes, as cooling is the biggest consumer of electricity, it will directly impact the targets related to improved energy efficiency, and the classification of more buildings as "green" or "super low energy".	District cooling is being scaled up across Singapore as a way to improve the efficiency of cooling systems in buildings. A recent feasibility study for a district cooling system in Tampines noted a 17% reduction potential in electricity consumption.[84]	N/A	N/A	Yes, passive cooling, behavioural changes, high efficiency equipment, low-carbon technologies, and low GWP refrigerants can reduce cooling power demand.
Other goals					
Cost of the energy system	The volume and profile of cooling demand and potential cold energy storage technology will impact the energy system dimensioning and thus the costs of future system build out.	N/A	N/A	N/A	Yes, passive cooling, behavioural changes, high efficiency equipment, low-carbon technologies, and low GWP refrigerants can reduce cooling power demand.
System Reliability	Yes, cooling's substantial share in power demand and potential dynamic variability can affects the grid operation.	The share of flexible cooling demand is required to size the potential impact on the grid.	N/A	N/A	Yes, clean cooling solutions, both by reducing demand and increasing flexibility, can ease the system operation.

[84] *Channel News Asia. Greener system of cooling buildings may be set up in Tampines, paving the way for more eco-friendly towns, 2021. Retrieved on 25 February 2022, from: https://www.channelnewsasia.com/sustainability/tampines-cooling-buildings-eco-friendly-towns-2122426*

APPENDIX 7: PRIORITISATION MATRIX CRITERIA

I. Cooling demand's impact on the power grid: This refers to the current and future cooling load of the sector and how this affects the energy system in terms of its flexibility potential. Here thresholds are defined as follows:

   a. Cooling demand/load: The percentage of total cooling electricity demand contributed by the sector, where,

      - High demand refers to sectors contributing towards more than 30% of Singapore's total cooling demand;
      - Medium demand refers to sectors contributing towards 10 – 30% of Singapore's total cooling demand;
      - Low demand refers to sectors contributing towards less than 10% of Singapore's total cooling demand.

   b. Expected growth in cooling demand: The estimated percentage growth in cooling electricity demand by sector between 2019 to 2030 (taken from Section 1.2), where,

      - High growth refers to sectors projected to experience more than 100% growth in cooling demand;
      - Medium growth refers to sectors projected to experience between 50% - 100% growth in cooling demand;
      - Low growth refers to sectors projected to experience less than 50% growth in cooling demand.

   c. Flexibility potential of cooling demand: This refers to the qualitative assessment of flexibility potential in a sector's cooling demand in terms of the ability to shift or adjust demand to different hours of the day (section 2.3), where,

      - High flexibility is when there is significant variation in the cooling demand profile of the sector along with a strong opportunity to influence the interaction of cooling demand with the power system;
      - Medium flexibility is when there is some variation in the cooling demand profile of the sector along with a few opportunities to influence the interaction of cooling demand with the power system;
      - Low flexibility is when there is minimal variation in the cooling demand profile of the sector and limited opportunity to influence the interaction of cooling demand with the power system.

II. Clean cooling opportunities: This assessment looks at the availability of clean cooling opportunities in each sector, their respective ability to provide flexibility services to the grid, and any barriers to their effective deployment as noted in Section 3. Here thresholds are defined as follows:

   a. Availability of alternative clean cooling solution: This refers to a qualitative review of the relative range of clean cooling solutions available in Singapore based on their relevance to each sector, where,

      - High availability is where there are multiple clean cooling solutions characterised as passive, cooling services and/or cold energy that are already being adopted or explored in the sector relative to other sectors (i.e., the sector with the largest range of relevant clean cooling solutions is characterised as high);
      - Medium availability is where there are a few range of clean cooling solutions characterised as passive, cooling services and/or cold energy that are already being adopted or explored in the sector relative to other sectors;
      - Low availability is where there are minimal clean cooling solutions characterised as passive, cooling services and/or cold energy that are already being adopted or explored in the sector relative to other sectors.

   b. Provides flexibility to the grid: This refers to the qualitative assessment of the extent to which clean cooling solutions available in the sector are able to provide flexibility services to the grid, where,

      - High flexibility potential is where the types of cooling solutions available in the sector are able to adjust or shift cooling demand quickly and effectively, or there are a variety of cooling solutions with different features that enable cooling demand to be managed more effectively;
      - Medium flexibility potential is where the types of cooling solutions available in the sector are able to adjust or shift cooling demand to an extent, or there is a limited number of cooling solutions with different features that are able to address some elements of cooling demand;
      - Low flexibility potential is where the types of cooling solutions available in the sector do not have a material impact on shifting cooling demand, or there are minimal cooling solutions that can shift demand.

c. Barriers to deployment: This refers to the qualitative assessment of the degree to which barriers exist in the deployment of clean cooling technologies in a given sector, where,

- High barriers to deployment of clean cooling solutions exist when the solution relies on nascent technologies that are yet to be commercialised, requires high capital expenditure, is logistically challenging to implement, adoption results in significant interruptions to business operations, market players are not empowered to adopt the solution, or there is a lack of market or regulatory incentives for adoption of the technology in the given sector;
- Medium barriers to deployment of clean cooling solutions exist when the solution relies on new technologies in the process of being commercialised, requires significant capital expenditure, is logistically difficult to implement, adoption results in some interruptions to business operations, market players have limited independence to adopt the solution, or market/regulatory incentives for adoption of the technology are limited in the given sector;
- Low barriers to deployment of clean cooling solutions exist when the solution relies on recognised, commercial and scalable technologies, requires minimal capital expenditure, is logistically straightforward to implement, adoption results in minimal interruptions to business operations, market players are empowered to adopt the solution, or there are effective market/regulatory incentives for adoption of the technology in the given sector

APPENDIX 8: USE CASES OF NOVEL COOLING TECHNOLOGIES

Technology	Technology Description	Potential Savings	Use Case
Air-cooled Tropical Data Centre 2.0 *(Cooling service)*	This research investigates the raising of data centre air-cooling temperatures and relative humidity levels to reduce energy consumption.	-	Applies to data centres as the technology aims to preserve the reliability and performance of IT equipment while raising the temperature.
Direct Chip Hybrid Cooling *(Cooling service)*	This research examines a heat sink design with two modes of cooling, i.e. air and liquid cooling, in a single integrated piece which eliminates the connectors and ducts.	-	This can serve as an alternative air-cooling solution during water-loop maintenance to significantly reduce the server downtime.
Direct liquid cooling/ immersion cooling *(Cooling service)*	Immersion cooling is where hardware is cooled by directly immersing it in a non-conductive liquid. Heat generated by the electronic components is directly and efficiently transferred to the fluid.	Liquid cooling is estimated to cut down electricity bills by 40% in hot locations like Singapore.[85]	Immersion-cooling systems use less power as a result of removing server fans, air handling units, and chilled water systems. Lower-power consumption for thermal management means reduced annual energy costs. Additionally, with fewer moving parts in an immersion-cooling solution, maintenance costs are also reduced.[86]
Desiccant-coated heat exchanger *(Cooling service)*	This allows the simultaneous removal of adsorption heat and dehumidification in air flow.	-	Desiccant cooling systems have been considered as an efficient method of controlling moisture content in supply air. They do not use any ozone-depleting coolants and consume less energy as compared with the vapour compression systems.[87]
Semiclathrate Thermal Energy Carrier System *(Cold energy)*	The use of semiclathrate hydrates slurries, which are water-based phase-change fluids, replace chilled water as a cooling medium.	It can potentially enable data centres to improve their power usage effectiveness by 20 per cent.[88]	It can be used to transport cold energy from LNG to supply cooling requirement of data centre.
KoolLogix *(Cooling service)*	An energy efficient data centre heat removal solution that offers on-demand cooling solutions, leveraging on the strengths and benefits of rack-based and row-based cooling.	Uses an innovative heat exchange and phase change approach that can reduce energy consumption at data centres by up to 50%.[89]	Based in Singapore, their solutions handle a high-density environment both as primary and secondary system for DC racked IT equipment cooling. It improves the power usage effectiveness, lowers cooling cost, economises chilled water use and increases productivity.
Thermal Energy Storage *(Cold energy)*	Thermal storage is needed to hinder the effects of cooling system failure. Using a thermal storage tank in data centres can ensure a longer duration of chilled water supply.	-	It can provide support cooling and the ability to run chilling systems whilst the power supply is interrupted, which can save on energy costs that would otherwise occur if the whole cooling system was allowed to turn off and start up again.[90]

85 *Data Centre Dynamics (2021). Liquid cooling can cut power costs by 40 percent, states Iceotope CEO David Craig. Retrieved June 21, 2022, from https://www.datacenterdynamics.com/en/marketwatch/liquid-cooling-can-cut-power-costs-by-40-per-cent-states-iceotope-ceo-david-craig/*

86 *Dell'Oro Group (2021). Is Immersion Cooling the Answer to Data Center Sustainability? Retrieved June 21, 2022, from https://www.delloro.com/is-immersion-cooling-the-answer-to-data-center-sustainability/*

87 *Minaal Sahlot, Saffa B. Riffat, Desiccant cooling systems: a review, International Journal of Low-Carbon Technologies, Volume 11, Issue 4, 15 December 2016, Pages 489–505, https://doi.org/10.1093/ijlct/ctv032*

88 *NUS News (2019). NUS, Keppel and SLNG join forces to develop new energy-efficient cooling technology for data centres. Retrieved June 21, 2022, from https://news.nus.edu.sg/nus-keppel-and-slng-join-forces-to-develop-new-energy-efficient-cooling-technology-for-data-centres/*

89 *Koollogix. Greener DC Heat Removal. Retrieved June 21, 2022, from https://www.koollogix.com/*

90 *Masterflow Solutions (2021). Why Data Centres Need Thermal Storage Tanks. Retrieved June 21, 2022, from https://masterflow.net.au/why-data-centres-need-thermal-storage-tanks-masterflow-solutions/*

Technology	Technology Description	Potential Savings	Use Case
Cognitive Digital Twin *(Cooling service)*	A key feature of next-generation data centres is the ability to operate new cooling solutions which are digitalised to enable real-time monitoring and AI-based optimisation.	A combination of these innovative cooling technologies, when they are successfully developed and tested, could significantly reduce energy consumption as well as greenhouse gas emissions up to 25 per cent, as compared to conventional data centres which are traditionally air-cooled.	

APPENDIX 9: THE SINGAPORE CONTEXT

Overview of Singapore's climate priorities

In 2020, Singapore submitted its enhanced NDC and Long-Term Low-Emissions Development Strategy (LEDS) document to the United Nations Framework Convention on Climate Change (UNFCCC). The enhanced NDC updated Singapore's climate pledge previously submitted in July 2015 under the Paris Agreement, and stated an absolute emissions target to peak emissions at 65MtCO2-e around 2030. Singapore's LEDS built on the enhanced NDC by aspiring to halve emissions from its peak to 33 MtCO2-e by 2050, with a view to achieving net zero emissions as soon as viable in the second half of the century.

To enable Singapore's low-carbon transition, the LEDS had three thrusts:

i. Transformations in industry, economy and society, e.g. more renewable energy, greater energy efficiency, reducing energy consumption;

ii. Adoption of advanced low-carbon technologies, e.g. CCUS, and use of low-carbon fuels; and

iii. Effective international collaboration, e.g. international climate action, regional power grids, market-based mechanisms.

Following the LEDS, Singapore raised its ambition to achieve net zero emissions by or around mid-century as part of the country's Budget 2022 announcement. This revision has been based on the advancement in green technologies alongside new opportunities for international collaboration within carbon markets, and will be formally included in an updated LEDS by end-2022. As part of this increased ambition, Singapore will raise carbon taxes from Singapore dollar (SGD) 5 per tonne of emissions at present to SGD 25 per tonne in 2024 and 2025, with a view of reaching SGD 50 to SGD 80 per tonne by 2030.

Existing cooling related policies

Singapore has been a party to the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol) since 5 January 1989. Since then, Singapore has acceded to four amendments made under the Montreal Protocol – the London Amendment on 2 March 1993; the Copenhagen Amendment and the Montreal Amendment on 22 September 2000; and subsequently the Beijing Amendment on 10 January 2007.

More recently, the Kigali Amendment to the Montreal Protocol has countries phasing down potent greenhouse gases used as refrigerants while simultaneously pushing for improvements in energy efficiency in cooling appliances. The goal is to achieve over 80% reduction in hydrofluorocarbon (HFC) consumption by 2047. The impact of the amendment will avoid up to 0.5 °C increase in global temperature by the end of the century.

Singapore has ratified the Kigali Amendment in June 2022 and will be phasing down the consumption of HFCs by 80% over the next two decades to meet the obligations.[91] Since 1 January 2019, HFCs imported into Singapore have been subjected to licensing controls. In 2020, the Climate-friendly Label was introduced to help consumers choose household refrigerators and air-conditioners that use climate-friendly refrigerants. The Grant for low GWP, Refrigerant Chillers was also introduced to support companies that want to make an early switch to more climate-friendly commercial water-cooled chillers. As HFCs can leak into the atmosphere if RAC equipment is not handled properly, the NEA has launched a training course to train and certify technicians to handle refrigerants properly. Below are policies that are in placed to regulate and control HFCs refrigerants.

- Restriction on supply of RAC equipment that use high-GWP refrigerants: From 1 October 2022 onwards, a restriction will be imposed on the supply of commercial water-cooled chillers and household refrigerators that use refrigerants with GWP above 15, and household air-conditioners that use refrigerants with GWP above 750.
- Mandatory collection and proper treatment of spent HFC refrigerants: Spent refrigerants are sometimes vented into the atmosphere during equipment disposal, resulting in HFC emissions. Under the Resource Sustainability Act, e-waste recyclers, who take in household RAC equipment for recycling, are already prohibited from venting spent refrigerants. NEA will also mandate the collection and proper treatment of spent refrigerants from decommissioned RAC equipment under the Environmental Public Health Act.

[91] *National Environment Agency (2020). Singapore Ratifies Kigali Amendment To The Montreal Protocol. Retrieved June 20, 2022, from https://www.nea.gov.sg/media/news/news/index/singapore-ratifies-kigali-amendment-to-the-montreal-protocol*

In addition to regulating HFCs refrigerants, there are also policies to improve the energy efficiency of cooling systems and appliances.

- Minimum Energy Efficiency Standards (MEES): NEA is introducing MEES for Cooling Systems in Industrial Facilities to improve the energy efficiency of water-cooled chilled water systems in new and existing industrial facilities. Water-cooled chilled water systems in existing energy-intensive industrial must conform to MEES by 1 December 2025, while those in other industrial facilities must conform by 1 December 2029. Grants are available to support companies to upgrade their water-cooled chilled water systems before the mandatory requirements kick in.
- Mandatory Energy Labelling Scheme (MELS) and Minimum Energy Performance Standards (MEPS): There are energy labels to help consumers make informed decisions when buying energy intensive appliances, and MEPS to raise the average energy efficiency of household appliances by removing the least energy efficient appliances from the market. From 1 January 2022, MEPS levels for refrigerators and certain types of air-conditioners are raised.

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