Energy Market Authority
Smart Energy, Sustainable Future

CHARTING THE ENERGY TRANSITION TO 2050

ENERGY 2050 COMMITTEE REPORT

MARCH 2022

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FOREWORD

Singapore and Singaporeans depend on energy. It powers our economy, from our diverse manufacturing industries to our growing digital services. It also underpins the quality of modern life for Singaporeans, powering our homes and transportation. Singapore has one of the most reliable electricity systems in the world, thanks to continued investments over the years.

The world is now at an inflection point, with the global imperative of addressing climate change driving a shift towards a low-carbon future. Singapore is committed towards this collective global endeavour, and the energy sector will have to play a significant part in our decarbonisation efforts. The Energy Market Authority (EMA) has laid out an energy transition blueprint to decarbonise Singapore's energy supply based on having "four switches" of natural gas, solar, regional power grids, and low-carbon alternatives.

The energy transition is a long-term, complex endeavour that will require much foresight, preparation, bold action, and agility along the way. It will require many significant changes over time in the energy sector, and will involve concerted action from various stakeholders, including industry, the Government, and the public, as well as international cooperation.

Even as we learn the best practices from countries around the world, we will have to develop strategies and solutions that address Singapore's unique circumstances. We lack natural resources and are renewable energy-disadvantaged. The energy transition will require a clear-minded weighing of the trade-offs across energy security, energy affordability, and environmental sustainability.

EMA had commissioned the Energy 2050 Committee to deliberate on the long-term future of Singapore's energy sector. The Committee, comprising a diverse range of experts from the industry, academia, and the Government, was given the challenging task of examining long-term trends that would affect the energy sector. It was also asked to provide recommendations on how EMA should plan for Singapore's future energy system and enable Singapore to capture the economic opportunities arising from the know-how and capabilities developed along the way.

In this report, the Energy 2050 Committee lays out its views on the key considerations, decision points, and strategic choices for Singapore. These will be invaluable in helping policymakers chart the course for Singapore's energy sector. This will go a long way towards helping Singapore meet its latest ambition of achieving net-zero emissions by or around mid-century. On behalf of EMA, I thank the Committee and all other contributors for this important effort.

Richard Lim Cherng Yih
Chairman, Energy Market Authority

MESSAGE

Action to address climate change is gaining traction around the world even as the devastating impact of climate change becomes increasingly apparent. As a small but advanced urban economy, Singapore will need to do its part to mitigate its greenhouse gas emissions, while hopefully also setting a good example for other cities and countries under similar circumstances. At Budget 2022, the Minister for Finance announced that Singapore will raise its ambition to achieve net-zero emissions by or around mid-century. Decarbonising the power sector is a key part of this quest. The power sector accounts for a sizeable share of Singapore's overall emissions, and decarbonising it will also help other major sectors, such as transport and some heavy industries, become more sustainable through electrification. A meaningful decarbonisation plan for the power sector must also ensure that power remains reliable and affordable, as Singaporeans and the business community here depend on it for their daily lives and livelihoods.

The Energy 2050 Committee embarked on its study more than a year ago, with the aim of putting together a set of recommendations for decarbonising Singapore's power sector. This long-term energy transition will require Singapore to keep abreast of technological and geo-economic changes, navigate uncertainties, and position itself strongly for the future. In its work, the Committee drew on the perspectives of a wide range of experts, policymakers, and stakeholders to better understand the trends that will have implications on power demand, supply, and grid systems of the future.

Our study confirms that the energy transition over the next 30 years will be complex, with uncertainties around the optimal options that will be available to Singapore. Given this, it is not possible to craft a single definitive long-term strategy today. Instead, Singapore will have to stay nimble while adopting a disciplined approach to constantly identify forks in the road and make investments at appropriate junctures to be well-positioned for new pathways as they open up.

This report therefore takes a scenario-based approach to present a few plausible futures of what a decarbonised Singapore power sector in 2050 may look like, depending on how certain global trends pan out. To help policymakers identify key turning points and navigate between these scenarios, the report also lays out signposts and decision points. Finally, the Committee also recommended a set of strategies for Singapore to adopt in the near term as early steps in positioning for this long-term transition.

Overall, the Committee has concluded that it is realistic for Singapore's power sector to aspire to achieve net-zero emissions by 2050 while still maintaining energy security and affordability. To do so, however, it must be prepared to make bold changes along the way based on technology trends as well as other global developments. In addition, the Committee sees good prospects for Singapore to capture economic growth opportunities from the energy transition in the region and beyond. Power sector solutions can become an important pillar of Singapore's green growth engine if it can establish itself as a technology frontrunner and a living lab for sustainable energy solutions.

The journey ahead will be very unlike the global energy sector of the last 200 years, where the transition was slow and the pace conservative. Rather, it will be fast and turbulent, if only because the world realises that there is little time left for irreversible climate effects to be headed off. Here in Singapore, we also need to have the wherewithal in the Government, business, and people sectors to make the needed changes. This will require new structures and new thinking, something that the Government is best-placed to take the lead in, but also critical for the other sectors to embrace as well. As the Committee ends its work with this report, we are optimistic that this can happen and that Singapore will arrive in 2050 with a brighter and greener future!

Choi Shing Kwok
Chairman, Energy 2050 Committee

EXECUTIVE SUMMARY

Changing Energy Landscape

Climate change is an existential challenge to humanity and is driving major shifts around the world. Green growth and climate advocacy have become increasingly salient among businesses, investors, and consumers. As a global citizen doing its part, Singapore needs to take decisive action to combat climate change, and has raised its ambition to achieve net-zero emissions by or around mid-century. The power sector contributes a significant share of Singapore's carbon emissions, and with electricity demand expected to rise further, decarbonising the power sector is one central plank to meeting Singapore's global obligations.

Given Singapore's limited renewable energy potential, reducing the power sector emissions will be more challenging than for many other countries. Nevertheless, the Energy 2050 Committee ("the Committee") assessed that it is **technically viable for the Singapore power sector to achieve net-zero emissions, while maintaining energy security and affordability**. The Committee also believes that it is **realistic for the sector to aspire to do so by 2050**. To achieve this, Singapore needs to step up its decarbonisation efforts across the entire power sector value chain while balancing the attendant trade-offs.

During the transition towards a net-zero carbon emissions world, there will be economic growth opportunities that Singapore can position itself to capture. It can meet the growing global demand for sustainable energy solutions by establishing itself as a technology frontrunner, and becoming a test-bed and living lab for innovative solutions.

Trends and Possible Pathways towards Net-Zero

The Committee studied trends in power demand, supply technologies, and grid development, and summarised the key findings into three predetermined trends and three critical uncertainties that could significantly impact the trajectory of change for Singapore's power sector.

Pre-determined trends: Electricity demand will rise in the coming decades due to economic growth, digitalisation, and electrification of transport and some other sectors. Solar power generation and battery energy storage systems (ESS) are expected to become cheaper and more efficient, driven by ongoing research and development (R&D) efforts and economies of scale. Distributed energy resources (DERs) like solar generation systems, battery ESS, and electric vehicles (EVs) are likely to proliferate within the Singapore energy system, affecting how the grid is to be managed.

Critical uncertainties: The patterns of technology advancement for low-carbon energy technologies, such as low-carbon hydrogen and new geothermal and nuclear technologies, are not clear as they hinge on R&D efforts bearing fruit, the scale of deployment by major countries, and the global price on carbon. The pace of digital technology advancements in the power sector is uncertain as it is contingent upon the affordability of enabling infrastructure such as advanced computing processors, communications infrastructure, sensors, and power controllers. The impetus for collective action on international power and carbon trading is also unknown, given that national interests and priorities may not be fully aligned with the push for decarbonisation.

The Committee has crafted a set of scenarios to describe several possible futures through which Singapore could achieve net-zero emissions by 2050, depending on how the above critical uncertainties pan out. Through these scenarios, they postulate how Singapore can steer its power sector under different circumstances.

In the ***Clean Energy Renaissance*** story, energy and digital technologies develop rapidly and are complemented by strong global cooperation. Singapore is able to achieve a diversified supply mix in 2050 with electricity imports and low-carbon hydrogen as major contributors. A diversified portfolio of sources and local backup capacity make electricity imports a secure and affordable supply option, while global developments make low-carbon hydrogen increasingly cost-competitive. Geothermal and solar add to the mix as two key domestic renewable generation sources. Singapore develops a leading intelligent grid capable of maintaining system stability and reliability amidst the proliferation of DERs. Equipped with smart technologies such as artificial intelligence (AI) and machine learning (ML), the grid harnesses the flexibility of the DERs and optimises the system at a local level, therefore reducing the overall grid capacity and costs. The growth of overall electricity demand is actively managed and the fluctuating demand profile is smoothened, making grid planning and operations more efficient. A greater proportion of end users are self-sufficient and tap on advanced energy and digital technologies to proactively manage their consumption in accordance with their own priorities and needs.

In ***Climate Action Bloc***, countries band together as technology advancements stagnate and come to a virtual standstill. Singapore has to rely heavily on electricity imports from international partners for its electricity needs in 2050. This is achieved through a wider regional grid and trading platform, collectively developed to meet the needs of the entire region while creating widespread economic benefits. Hydrogen accounts for a relatively small share of Singapore's power generation mix due to the relatively high costs. Singapore continues to use some amounts of natural gas with the resultant carbon emissions being offset using international carbon credits. The grid in Singapore remains one of the most reliable and resilient in the world, despite the need to balance and handle a wide array of DERs. The deployment of digital twins and other modelling and simulation tools enables robust grid planning and optimisation of grid assets. The cost savings from this optimisation help to dampen the cost of developing backup capacity to buffer against unpredictability in demand and supply. Micro-grids are commonly used by large end users to enhance system resilience, while at the same time generating cost savings or revenue. Optimisation is done within the micro-grid, allowing the system-level demand profile to be shaped. In some cases, fully self-sufficient micro-grids do not require backup from the utility grid, leading to substantial cost savings for the overall system.

In ***Emergent Technology Trailblazer***, the world is fragmented, and technology advancement is delayed but eventually arrives. Low-carbon hydrogen dominates Singapore's supply mix in 2050, replacing natural gas as the main fuel to power Singapore. The cost of hydrogen continues to fall over time due to increasing global deployment and economies of scale. Electricity imports contribute to the mix but the share is limited due to slow development of the regional grid and interconnections with potential sources of renewable energy. Building on its early investments, Singapore is able to start deploying other low-carbon alternatives, such as nuclear energy, to diversify its supply mix and is well-positioned to scale them up further when they become more commercially competitive. The grid intelligence is highly developed through the use of AI technologies, such that effective forecasts of supply and demand are made, in turn facilitating autonomous decisions that can optimise the use of resources. With AI, the grid is also able to harness the proliferation of DERs by aggregating and managing them as a virtual power plant (VPP) to contribute to system needs. Demand is actively managed and optimised with effective energy efficiency and conservation measures across different end users at all levels. Large industrial and commercial users view energy efficiency as both a commercial benefit and a compliance measure, and they invest in digital solutions to optimise their business processes. Smaller end users gain access to multi-energy solutions and differentiated energy prices, which incentivise them to play a more active role in sustainability efforts.

Navigating the Uncertainties

The scenarios suggest that while the target of net-zero emissions by 2050 is viable, there are different pathways to get there depending on how the critical uncertainties unfold. The Committee has identified key forks along Singapore's decarbonisation journey in the power sector and the critical decisions that need to be made at those junctures. Signposts that provide indications of macro energy trends can be used to guide Singapore's decision-making process along the way.

Recommended Strategies and Planning Paradigms

In order to achieve net-zero emissions for the power sector by 2050, it is clear that there will need to be transformational changes in Singapore's energy landscape.

The desired changes will only come about from the early and deliberate efforts by the Government, industry stakeholders, and consumers. From the three scenarios, it is evident that ***electricity imports***, ***hydrogen***, ***solar,*** and ***ESS*** will be important to the Singapore energy system, while ***new low-carbon supply alternatives*** and ***carbon markets*** may play key roles as well. Efforts to ***manage the growth of energy demand*** and ***shape end user consumption*** provide a longer runway to deploy supply-side measures, while also lowering costs for the system. The proliferation of DERs and other changes warrant a ***multi-layered grid*** with ***digital technologies*** for a secure and optimised system. The different trajectories laid out in the scenarios highlight the need to ***build flexibility into the system***, while offering different opportunities for Singapore to be a ***technology frontrunner***.

The Committee has put together a set of recommended strategies, comprising actions that have clear benefits for Singapore as well as areas that require further study but offer potential benefits. These strategies would maximise the power sector's chances of achieving net-zero emissions by 2050. The Committee also recommends keeping in mind two overarching planning paradigms for the energy transition.

Strategy 1: Pursue the adoption of electricity imports to access cleaner and cost-effective energy sources beyond Singapore's borders. In the near term, electricity imports will be key to the decarbonisation of Singapore's power sector. For long-term sustainability, Singapore will need to prioritise importing electricity generated using renewables. To ensure security of supply, Singapore will need to develop a diversified portfolio of import partnerships supported by a regional grid and trading platform as well as cost-efficient backup supply options.

Strategy 2: Develop the use of low-carbon hydrogen for power generation to decarbonise the power sector. In the medium to long term**,** hydrogen can potentially play a major role in Singapore's supply mix, particularly low-carbon hydrogen**.** Singapore should develop a national hydrogen strategy and work with local and international stakeholders to develop a robust hydrogen supply chain, including investing in infrastructure as needed.

Strategy 3: Maximise solar deployment and use ESS to manage solar intermittency. Even though solar power is unlikely to form a large share of Singapore's energy supply mix, innovative deployment options and utilising the latest solar photovoltaic (PV) technologies can stretch Singapore's solar potential. To address solar intermittency, Singapore should scale up the deployment of ESS. Beyond managing intermittency, Singapore should develop capabilities in different ESS technologies which could potentially meet other system needs.

Strategy 4: Pre-position Singapore for new low-carbon supply alternatives. Given that Singapore has limited options to decarbonise its power sector, it should actively monitor developments in new supply technologies such as carbon capture, utilisation, and storage (CCUS), geothermal, biomethane, nuclear fission small modular reactors (SMRs), and nuclear fusion technologies. Building capabilities in advance will enable Singapore to adopt promising technologies quickly when they become viable.

Strategy 5: Leverage carbon markets to address residual and hard-to-abate carbon. While mitigation should be the primary pathway towards decarbonising the power sector, it may be too costly to eliminate residual emissions if suitable options do not develop in time. Singapore should facilitate negotiations and develop local capabilities and services to support the development of international carbon markets.

Strategy 6: Create a multi-layered grid to manage the growth of DERs and improve grid reliability. The proliferation of DERs will create new challenges for the power system, requiring grid resources and control mechanisms to evolve beyond the transmission level to be deployed at the distribution level. Singapore will need to develop different layers of advanced control and communication systems and introduce physical infrastructure enhancements to achieve oversight and decentralised control of the DERs.

Strategy 7: Leverage digital technologies to enhance grid planning and operations. Singapore should capitalise on digital technologies, such as advanced modelling and simulations, AI, and ML, to improve grid planning and operations for grid reliability and efficiency.

Strategy 8: Actively manage the growth of demand to better manage the rollout of low carbon options and keep energy costs affordable. There is a need to work with key sectors to actively plan and budget the use of electricity in a comprehensive and deliberate manner. Singapore should optimise energy demand at the district level and actively explore other means such as price signals and green standards to drive energy efficiency and energy conservation.

Strategy 9: Shape end user consumption to optimise the power system. Innovative demand-side technologies such as smart energy management systems and the unlocking of demand response potential which is currently untapped due to a lack of awareness can help optimise supply and grid capacities.

Planning Paradigm 1: Build flexibility into the power system to provide optionality for Singapore to pivot across different pathways. The uncertainties that Singapore faces in its decarbonisation journey are significant. Technologies that can be deployed with minimal development time or can switch operations to other fuels quickly will allow the power system to quickly respond to changes.

Planning Paradigm 2: Capitalise on opportunities to position Singapore as a technology frontrunner and living lab for sustainable energy solutions. Singapore should harness its strong R&D ecosystem and ability to invest in nascent technologies in order to seize early mover advantage in areas aligned to Singapore's energy needs. Leveraging its unique dense urban grid, Singapore can become a living lab for innovative sustainable energy solutions.

Conclusion

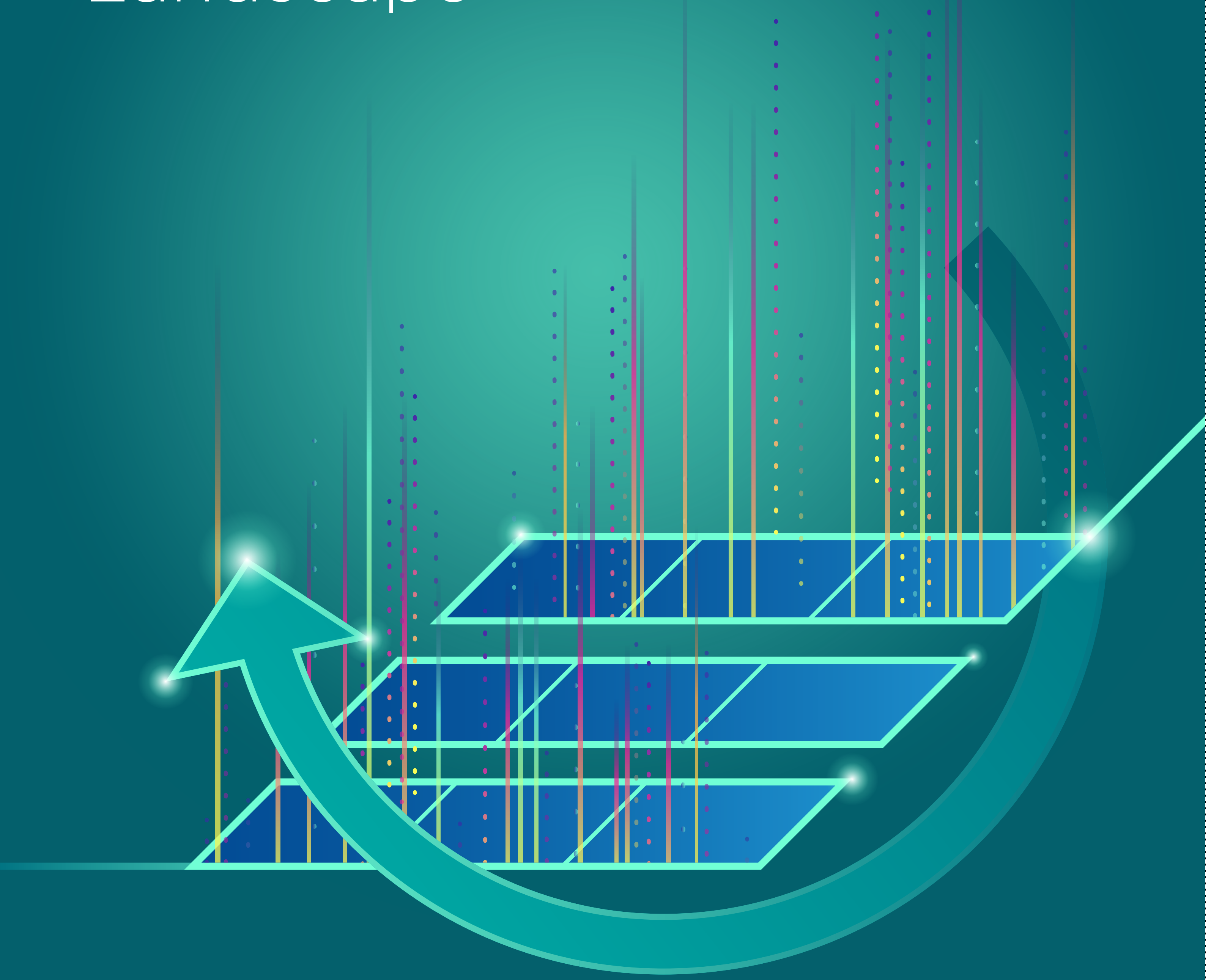
The energy transition will be highly dynamic given the uncertainty of technology and geo-economic trends. It will be especially challenging for a small, densely populated, and alternative energy-disadvantaged country such as Singapore as it balances the energy trilemma to deliver sustainable, secure, and affordable energy.

This major energy transition will invariably involve trade-offs which Singapore has to carefully manage. This would inevitably result in an increase in cost, but it is unavoidable if Singapore wants to make the energy system more sustainable and secure in a carbon-constrained future. Despite the challenges, Singapore should approach this endeavour with hope and optimism.

SECTION 1

Changing Energy Landscape

Climate change is an existential challenge to humanity and is driving major shifts across the world. As climate action gains momentum globally, Singapore, as a global citizen doing its part, has committed to take firm actions to reduce carbon emissions. Decarbonising the power sector is integral to Singapore's global obligations, and concurrently opens opportunities for the country to drive economic growth through sustainable energy solutions.



BACKGROUND

The Urgency of Climate Action

In its most recent climate assessment report[1], the Intergovernmental Panel on Climate Change found that climate change is already affecting various weather and climate extremes across the world. To avert a global catastrophe, urgent action to curtail carbon dioxide (CO_2) and other greenhouse gas emissions is needed.

The global commitment to cut emissions has been gaining traction. More than 130 countries have set or are considering reducing emissions to net-zero by mid-century[2]. More countries are submitting or updating their Nationally Determined Contributions (NDCs), which contain information on targets, policies, and measures for reducing national emissions and adapting to climate change impacts, although countries "must urgently redouble their climate efforts" if they are to prevent temperature increases beyond the goals of the Paris Agreement[3]. Patricia Espinosa, the Executive Secretary of the United Nations Framework Convention on Climate Change (UNFCCC), said that the NDCs submitted in 2021 "clearly represent a commitment to acting on climate change".

Singapore needs to play its part to combat climate change and has given strong indications that it will do so. During the National Day Rally speech in 2019, Prime Minister Lee Hsien Loong said that "although Singapore may not be able to stop climate change by ourselves, we can contribute to solutions, and we must do our fair share. Then we can be credible asking others to reduce their emissions too, and work towards a global solution to climate change".

Given its limited renewable energy potential due to geographical constraints, reducing Singapore's emissions will be more challenging than for many other countries. Nevertheless, Singapore has announced targets and plans to mitigate its emissions. In his speech for Budget 2022, Minister for Finance Mr Lawrence Wong stated that Singapore will raise its climate ambition to achieve net-zero emissions by or around mid-century[4]. The Singapore Energy Transition (SET) was launched in 2021 as a blueprint laying out the broad plans for the power sector to decarbonise and help Singapore achieve its climate commitments. The SET involves using natural gas more sustainably, maximising solar deployment, introducing regional power grids and electricity imports, and preparing for deep decarbonisation using hydrogen and emerging low-carbon alternatives.

Growing Salience of Green Growth and Climate Advocacy

Globally, commitments to green solutions have been gaining traction among businesses, investors, and consumers. More than 300 companies have joined the RE100, a global initiative bringing together the world's most influential businesses committed to 100% renewable electricity. There are also indications that committing to a higher Environmental, Social, and Governance (ESG) position could enhance a company's competitiveness and growth. For example, McKinsey found that customers were willing to pay more to "go green" — upward of 70% of consumers surveyed on purchases in multiple industries said they would pay an additional 5% for a green product if it met the same performance standards as a non-green alternative[5].

The Singapore community is also prepared to do more to combat climate change. In a climate change perception survey commissioned by the National Climate Change Secretariat, about 95% of respondents supported Singapore making a shift to a low-carbon economy.

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[1] Sixth Assessment Report, Intergovernmental Panel on Climate Change, Aug 2021
[2] The Global Coalition for Net-Zero Emissions is Growing, Net-Zero Coalition, United Nations
[3] COP26: Praise for Updated National Climate Plans, but "Nowhere Near" Goal, United Nations, Oct 2021
[4] Under its current enhanced 2030 NDC and Long-Term Low-Emissions Development Strategy (LEDS), Singapore has committed to peak emissions at 65 metric tonnes of carbon dioxide equivalent (MtCO2e), halve emissions from its peak to 33 MtCO2e by 2050, and achieve net-zero emissions as soon as viable in the second half of the century. Singapore will firm up and finalise its plans before making a formal revision of its LEDS.
[5] Five Ways that ESG Creates Value, McKinsey, Nov 2019

In addition, about 78% were prepared to play their part even if they were expected to bear some additional costs and inconvenience as consumers[6]. Youth-led groups such as the Singapore Youth for Climate Action and SG Climate Rally who have the biggest stake in the future have also advocated for more steps to be taken to reduce carbon emissions.

The Power Sector's Carbon Footprint

The Singapore power sector currently contributes a significant share of close to 40% of overall emissions. The demand for electricity is expected to rise further between now and 2050 due to economic growth. In addition, many sectors are aggressively pursuing digitalisation and the trend towards electrification in the transport and industrial sectors will continue. This is expected to cause further growth in the power sector's share of overall emissions. If Singapore is to achieve its committed emissions target, the power sector will need to decarbonise ahead of the economy to support nationwide efforts.

While Singapore has already announced that it will ramp up solar energy deployment, tap on regional power grids, and increase R&D in renewable energy and emerging low-carbon alternatives, it needs to have concrete strategies to step up its decarbonisation efforts across the entire power sector value chain as new technologies become available.

ASPIRATIONS

Net-Zero Emissions for Power Sector by 2050

This is a major energy transition and will not be easy. Policymakers will need to balance the trade-offs across the energy trilemma of energy security, affordability, and environmental sustainability. Nevertheless, following its detailed study of current trends, the Committee assessed that it is technically viable for the Singapore power sector to achieve net-zero emissions, while maintaining energy security and affordability. The Committee also believes that it is realistic for the sector to aspire to do so by 2050.

However, this requires Singapore to overcome its inherent limitations as a small and dense urban city-state. Singapore is alternative energy-disadvantaged and solar power is currently the most viable renewable energy source. However, there is a limit to how much solar power can be deployed in Singapore, due to the limited land and water spaces. Transformational changes are required across the value chain for the aspiration to be achieved. In essence, Singapore must be prepared to pursue the following strategies:

a. Embark on economy-wide energy conservation and energy efficiency efforts to manage total and peak electricity demand;

b. Leverage on a variety of low-carbon supply options while aiming to ensure security and affordability; and

c. Transform the grid using new technologies and storage capabilities to support the decarbonisation of the power sector.

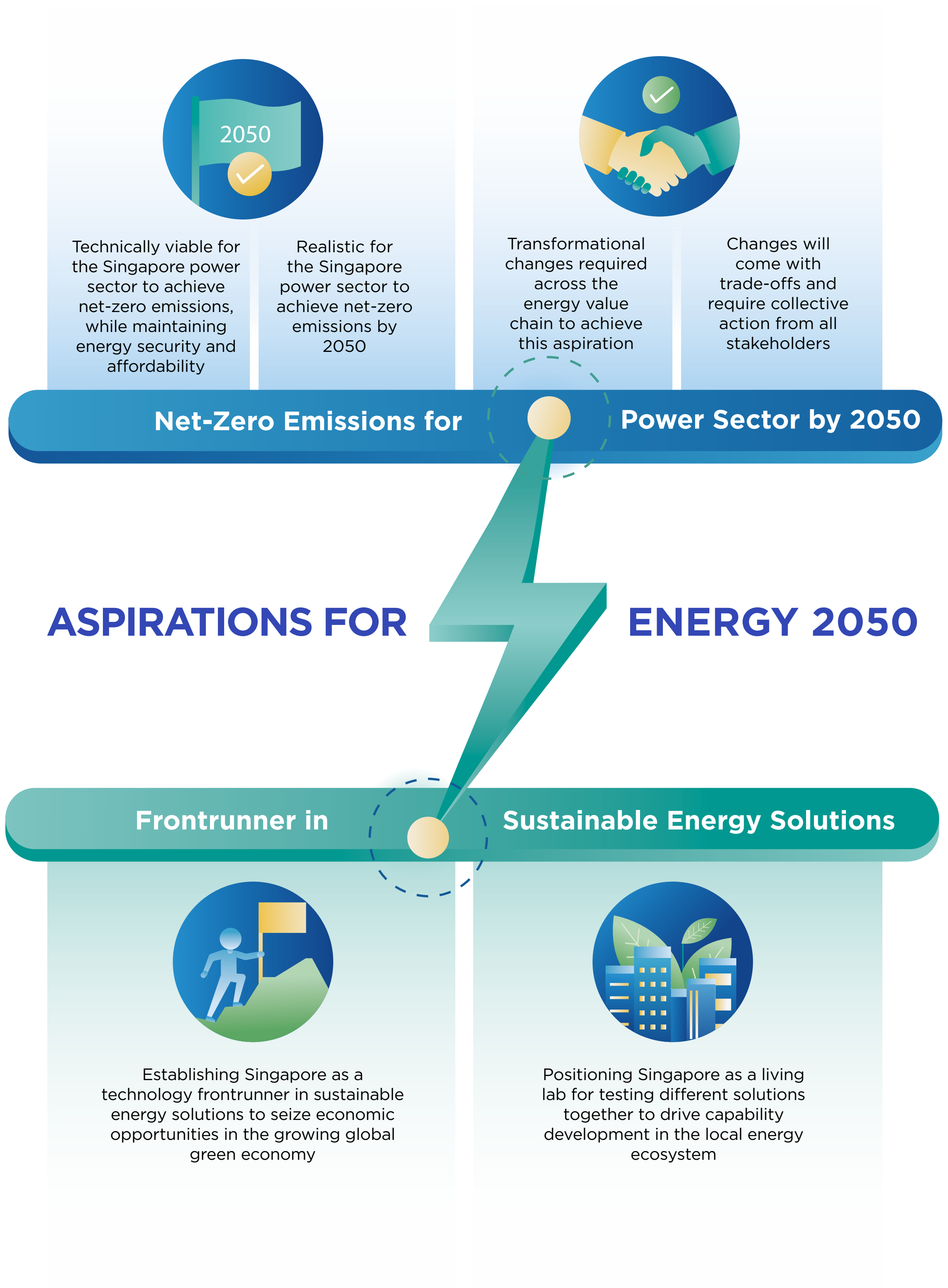
The transformation will come with trade-offs and require collective action from all stakeholders. Consumers and businesses would also need to be prepared to pay higher electricity prices as carbon is underpriced today and support from the Government needs to be provided selectively to ensure inclusion.

[6] Climate Change Public Perception Survey 2019, National Climate Change Secretariat, Dec 2019

Frontrunner in Sustainable Energy Solutions

During the transition towards a net-zero carbon emissions world, many countries and cities will have to grapple with problems similar to those that Singapore faces in achieving sustainability while balancing security and affordability. This would drive global demand for sustainable energy technologies and solutions. In the course of overcoming its own challenges, Singapore could also seize opportunities to meet this growing demand by leveraging on its strong R&D ecosystem and establishing itself as a technology frontrunner in sustainable energy solutions.

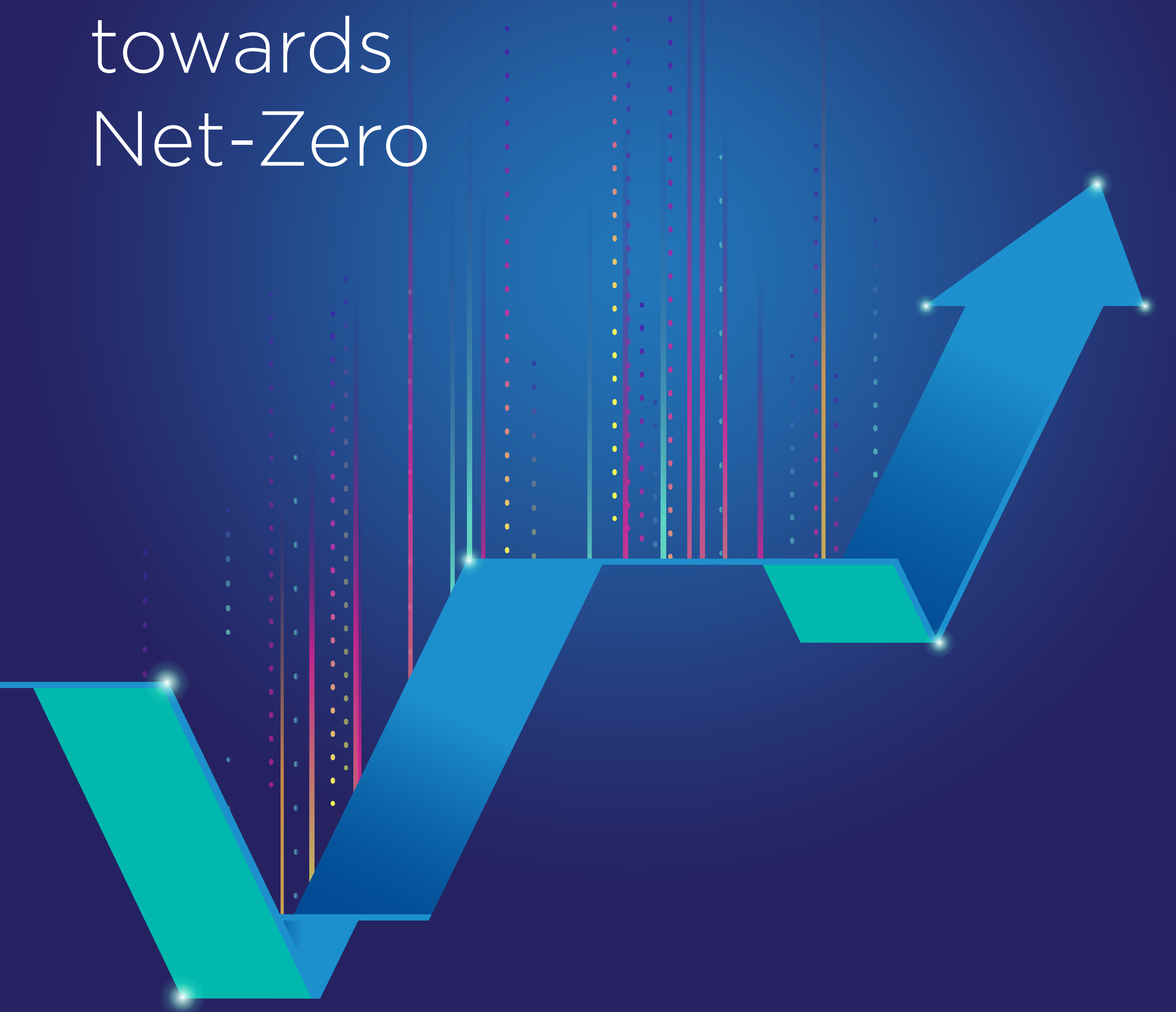
Singapore could also position itself as a test-bed for innovating sustainable energy solutions and a living lab for testing different solutions together by leveraging on its dense urban environment. As Singapore brings together leading companies from around the world in this endeavour, it could drive capability development in the local ecosystem, while also enhancing its offerings to the global marketplace for such solutions.



SECTION 2

Trends and Possible Pathways towards Net-Zero

The future energy landscape will be defined by several technology and geo-economic trends. Some of these trends will likely follow stable trajectories that are more predictable, while others continue to remain uncertain going forward. This adds a level of complexity to the aspirations covered in Section 1. How these predictable and uncertain trends interact with each other can lead to different future net-zero scenarios. By studying and preparing for these possible scenarios, Singapore will be able to adopt flexible strategies that will position itself to pivot across the different futures as they play out.



TRENDS AFFECTING THE POWER SECTOR

The Dynamic Energy Landscape

The Energy 2050 Committee engaged many resource persons and examined various data sources over the course of more than a year to build a picture of how Singapore's energy future could pan out. Equipped with these insights, the Committee mapped out the trends affecting power demand, supply technologies, and grid development over the next 30 years.

Demand Trends

Singapore's electricity system demand has increased from about 42 terawatt-hours (TWh) in 2009 to about 53 TWh in 2020 at a compound annual growth rate (CAGR) of 2.2%. The electricity system peak demand grew from 6,041 megawatts (MW) to 7,376 MW over the same period at a CAGR of 1.8%. Over the next decade, from 2022 to 2032, the annual electricity system demand and electricity system peak demand are projected to grow at a CAGR of between 2.8% and 3.2%. These take into account various factors, including changes to population, temperature, projected GDP growth rates, and projected demand from new high-growth sectors[7].

Energy-intensive industrial activities such as advanced manufacturing and energy and chemical activities would likely continue to play a key role in Singapore's economy and will add up to a significant share of electricity demand. Some emerging sectors are expected to drive electricity demand growth even higher. For example, digitalisation trends such as the Internet of Things (IoT) and 5G wireless technologies would result in the deployment of more advanced communication infrastructure and devices that will likely lead to an increase in total energy consumption, notwithstanding that they will be more energy efficient than today. Sectors such as land transport and parts of the industrial sector that are pursuing electrification as a decarbonisation strategy will also add to the load. While electrification could reduce overall carbon emissions through greater efficiency — for example, the use of an EV would generate only half the amount of CO_2 compared to a similar vehicle powered by an internal combustion engine (ICE) — it would contribute to overall electricity demand growth[8].

In order to counterbalance the growth in demand, it is possible to reduce the energy intensity of current and future activities through energy efficiency and energy conservation efforts. These can be achieved by adopting new technologies, improvements in design, and behavioural changes. In the building sector, for example, the future adoption of *Super Low Energy Buildings* could reduce the overall energy consumption of buildings considerably over time as such standards become more widely adopted.

Supply Trends

To achieve net-zero emissions by 2050, Singapore's electricity supply mix will need to evolve over the coming decades towards the "four switches" of natural gas, solar power, regional power grids and electricity imports, and low-carbon alternatives identified by EMA in the Singapore Energy Story.

First switch: While most other advanced economies are switching to gas from other more pollutive fuels as part of their transition, natural gas is already the predominant fuel for power generation in Singapore today and would remain important for some time during the transition to other technologies. Gas turbine manufacturers continue to develop more energy efficient models of natural gas-fired power plants. They are also developing gas turbines that are hydrogen-ready[9]. In the longer term, CCUS technology may be able to help eliminate the carbon footprint of natural gas-fired Combined-Cycle Gas Turbine (CCGT)

[7] Singapore Electricity Market Outlook 2021, Energy Market Authority
[8] Our EV Vision, Land Transport Authority
[9] Siemens' Roadmap to 100% Hydrogen Gas Turbines, Power Magazine, Jul 2020

plants. If this technology becomes viable, it will allow natural gas to continue to play a role in a net-zero power sector.

Second switch: Solar power from photovoltaic (PV) system is currently the most viable renewable energy source in Singapore. The Solar Energy Research Institute of Singapore (SERIS) estimated that Singapore has the technical potential to deploy up to 8.6 gigawatt peak (GWp) in Singapore by 2050 — underpinning this would be efforts in maximising land and space utilisation and managing the trade-offs of competing uses, and in the development of ultra-high efficiency solar cell technologies and innovative deployment solutions[10]. However, even if Singapore deployed 8.6 GWp of solar, this would only represent about 10% of the projected electricity demand then.

Third switch: Regional power grids and electricity imports allow Singapore to overcome its land constraints by importing clean energy from overseas. This would help ensure that the growing electricity demand can be met while longer term low-carbon alternatives are still being developed. Such regional power grids are already in use around the world, for example in the European Union (EU), and between the United States of America (USA) and Canada. There is emerging interest among the Association of Southeast Asian Nations (ASEAN) countries to explore electricity trading, with the Lao PDR-Thailand-Malaysia-Singapore Power Integration Project (LTMS-PIP) being the first multilateral electricity trading project. Singapore, Malaysia, and Indonesia have also kickstarted technical studies to explore the viability of electricity imports by building on existing mutual support arrangements. However, the setting up of regional power grids will require the alignment of market, regulatory, and technical rules to ensure commercial viability. Long-term agreements would also be needed to amortise the cost of interconnection infrastructure such as undersea transmission cables.

Fourth switch: Low-carbon alternatives are needed for Singapore to fully decarbonise the power sector in the longer term. Hydrogen is a promising candidate. To date, 17 countries have published low-carbon hydrogen strategies, and more than 20 have announced that they are working to develop these strategies[11]. Several countries, such as Australia, Chile, and Saudi Arabia are already actively looking to potentially export green hydrogen[12]. Cost projections for low-carbon hydrogen imports vary widely, and are dependent on the costs of renewables that power the electrolysis process and the electrolysers themselves (i.e., green hydrogen), the costs of natural gas and CCUS (i.e., blue hydrogen), and the costs of transportation. Given that the cost of solar and wind power generation technologies has fallen in recent years, there is a high possibility that the cost of green hydrogen may follow a similar pattern and become cost-competitive within 15 to 20 years.

In the longer term, other low-carbon alternatives could be part of the fuel mix when they are more technologically mature and economically viable.

a. While conventional hydrothermal systems are not applicable to Singapore due to its dry rock conditions, next-generation geothermal systems that use fracking or closed-loop system methods are potentially deployable in Singapore's environment. These solutions have been piloted in some countries and are still in the early stages of development[13].

b. As a fuel, biomethane is indistinguishable from natural gas and can be transported and used in the same way. This fuel would allow Singapore to continue using its existing gas infrastructure. It is estimated that by 2040, the production potential of biomethane would amount to be more than 1,000 million tonnes of oil equivalent (Mtoe), with a global average production cost of less than USD 15 per million British thermal units (MBtu)[14]. In comparison, the cost of regasified liquified natural gas in Singapore was about USD 13 per MBtu in 2021.

c. Newer nuclear power plant designs that are being developed and tested have the potential to be much safer than many of the plants that are in operation today. They are being developed by major countries such as China, France, the USA, and Russia. If viable, these safer technologies could provide Singapore with a scalable and carbon-free baseload source of electricity. Nuclear fuel can also be efficiently stockpiled, which would enhance Singapore's energy security[15].

Besides mitigating carbon emissions domestically, some countries are also considering using international carbon credits to offset emissions[16]. It is estimated that demand for carbon credits could increase by a factor of 15 or more by 2030 and by a factor of up to 100 by 2050. Overall, the market for carbon credits could be worth upward of US$50 billion in 2030[17]. However, this hinges on the successful implementation of the Article 6 rulebook, which was adopted at COP26 to establish the rules to govern the use and trading of carbon credits. If the carbon markets become available, Singapore may be able to make use of them to offset any residual carbon emissions in hard-to-abate sectors or as an interim tool while moving towards net-zero emissions.

Grid Trends

The confluence of changes in the future energy system, together with advances in digital tools and reductions in cost of sensor devices, will likely change the way the grid is designed and managed.

The grid network generally comprises the transmission and distribution networks[18]. The increasing deployment of energy resources such as solar PV systems, ESS, and EVs would create more unpredictability at the distribution level and drive the need for more decentralised control of the grid. Having a single Transmission System Operator (TSO) centrally managing the system might result in high costs and compromises in efficiency, as systems would be too complex for the TSO to track and handle[19]. Countries in the EU and the USA are already looking at expanding the role of the Distribution System Operators (DSOs) and improving their coordination with the TSO[20].

As a highly responsive and flexible resource, ESS are expected by many to play a key role in the energy transition. ESS could integrate variable renewables into the grid by regulating frequency, provide backup power, or enable greater demand flexibility by discharging energy to loads during periods of high system demand. Lithium-ion (Li-ion) ESS are becoming more economically viable, and costs are expected to almost halve by 2030[21]. Li-ion ESS could be the dominant technology deployed for grid services with relatively high round trip efficiencies. There have also been efforts to explore other forms of storage technologies such as flow batteries and liquid air that may present Singapore with cost-effective options for energy storage over longer durations[22].

Digital solutions such as VPPs and micro-grid controllers could aggregate DERs such as rooftop solar PV systems and coordinate them in an intelligent and efficient manner using AI and ML technologies. Other digital solutions like digital twins, which could provide a high-fidelity representation of physical assets in the real world, would enhance the work of grid planners and operators by allowing them to perform modelling and simulation before implementing changes in the real system. Faster computing processors and advanced wireless communications that are cost-competitive and deployed at a meaningful scale will help support the implementation of these intelligent digital technologies.

In the longer term, the marriage of decentralised control and grid intelligence could truly revolutionalise today's grid architectures. For instance, the National Renewable Energy Laboratory, a research institute under the US Department of Energy, is undertaking research on the concept of an Autonomous Energy Grid, where scalable cellular blocks that act like micro-grids can self-optimise when islanded and help the main grid when connected to

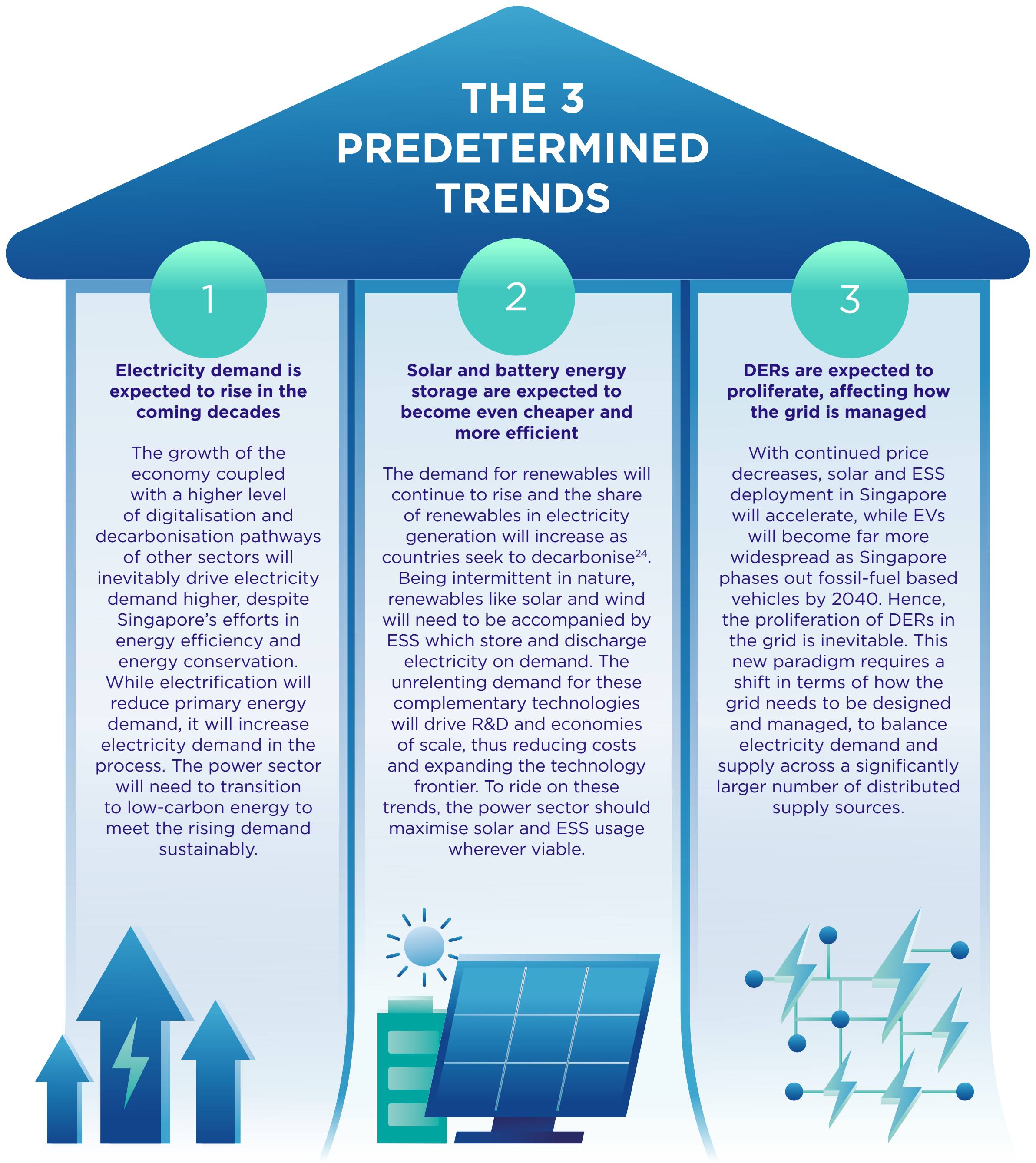
[10] Update of the Solar PV Roadmap for Singapore, SERIS, 2020 – The technical potential considers the use of ultra-high efficiency solar cell technologies such as perovskite silicon tandem cells and innovative deployment solutions such as building applied photovoltaics (PV) and building integrated photovoltaics (PV).
[11] Global Hydrogen Review 2021, International Energy Agency
[12] Australia Backs Desert Project to Export Green Hydrogen to Asia, Financial Times, Oct 2020
[13] Geothermal Well Construction: A Step Change in Oil and Gas Technologies, Journal of Petroleum Technology, Jan 2021
[14] Outlook for Biogas and Biomethane: Prospects for Organic Growth, International Energy Agency, Mar 2020

[15] A pre-feasibility study on nuclear energy done by the Singapore Government had concluded in 2012 that the currently available technologies were not yet suitable for deployment in Singapore.
[16] How 'Article 6' Carbon Markets Could 'Make or Break' the Paris Agreement, Carbon Brief, Dec 2019
[17] A Blueprint for Scaling Voluntary Carbon Markets to Meet the Climate Challenge, McKinsey, Jan 2021
[18] The transmission lines deliver high-voltage electricity to large industrial end users and to substations which step down the voltage level. This lower-voltage electricity is delivered to the bulk of the end users by the distribution lines.
[19] A Tale of Two Visions: Designing a Decentralized Transactive Electric System, IEEE Power and Energy Magazine, Apr 2016
[20] Future Role of Distribution System Operators Innovation Landscape Brief, International Renewable Energy Agency, 2019
[21] In Energy Storage System Costs Survey 2020, BloombergNEF estimates that costs for a large four-hour ESS may fall from US$299kWh in 2020, to US$167kWh in 2030.
[22] The 5 Most Promising Long-Duration Storage Technologies Left Standing, Greentech Media, Mar 2020

it[23]. There is also research on quantum grids that might transmit power via energy packets, similar to the transmission of data packets via the internet. This could allow the flow of electrons to be actively controlled by power electronics, allowing for better resilience and optimisation beyond what can be done today.

Predetermined Trends and Critical Uncertainties That Would Shape the Power Sector

After studying these trends, the Committee has summarised the key findings of the study into three predetermined trends that are expected to play out in a predictable way and three critical uncertainties that could significantly impact the trajectory of Singapore's power sector.



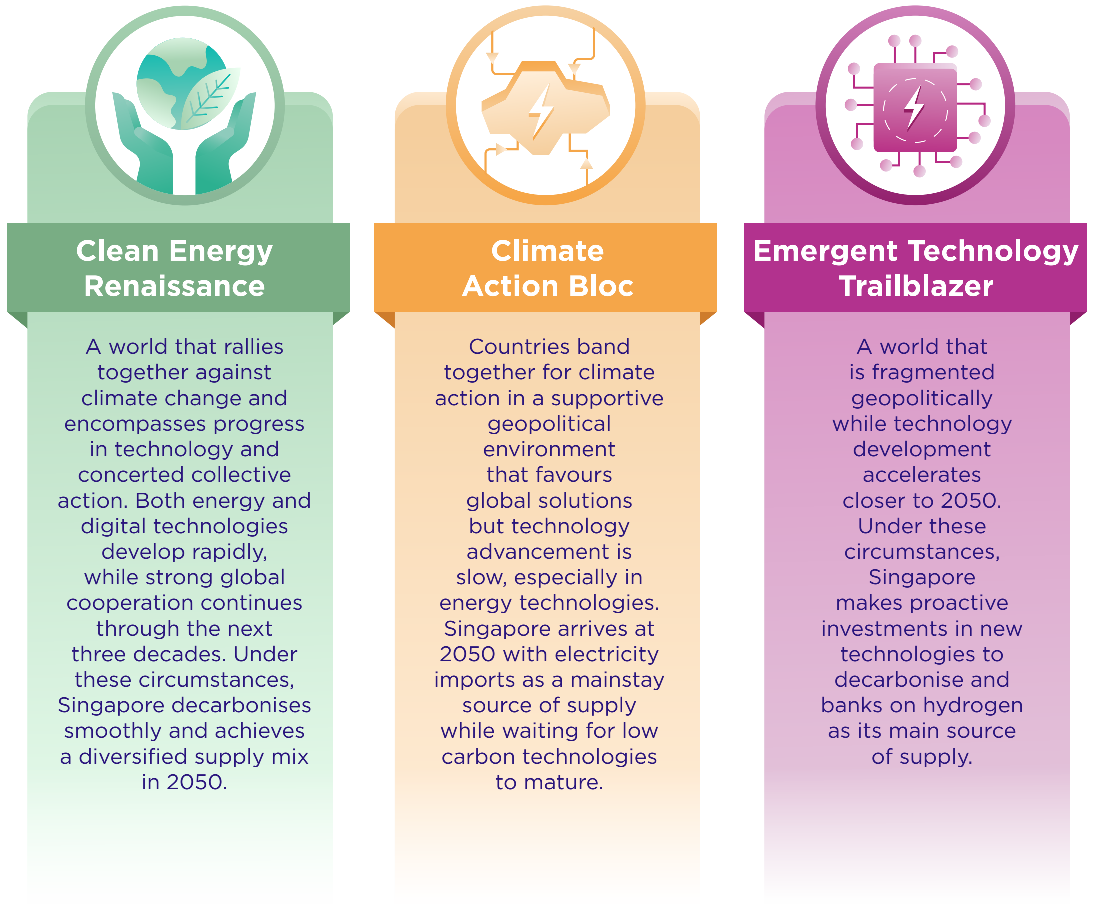
[23] From the Bottom Up: Designing a Decentralized Power System, National Renewable Energy Laboratory

[24] The International Energy Agency estimated in the World Energy Outlook 2021 that global solar capacity would increase almost 20 times from 2020 to 2050, under the Net-Zero Emissions by 2050 scenario. BloombergNEF estimated in the New Energy Outlook 2021 that solar could contribute 12% - 32% of electricity generation in 2050.

Scenario Planning to Make Sense of the Trends

Given the uncertainties outlined, the Committee does not see just one trajectory to achieve the net-zero emissions aspiration in 2050. Therefore, it has designed a set of scenarios to describe several possible futures through which Singapore could achieve net-zero emissions by 2050, depending on how the uncertain trends play out. The scenarios explore different possible outcomes and identify critical branching points between the different scenarios. They are then used as the basis for the development of recommended strategies to navigate the uncertainties better and hence put Singapore in a position to achieve its desired outcome of net-zero emissions as soon as possible.

SCENARIOS FOR ENERGY 2050



The three scenarios are based on different assumptions of how the three critical uncertainties would pan out, and they postulate how Singapore could steer its power sector under changing circumstances. The language employed to describe the scenarios above is deliberately written as vignettes looking back from a hypothetical vantage point in 2050, rather than as forward projections. This brings the potential future scenarios to life and encourages readers to imagine the possibilities in 2050. Assumptions were made to make the vignettes more realistic and complete where necessary. The scenarios are not intended to be exhaustive nor definitive about a future that is still 30 years away, but to serve as tools to focus discussions on the strategies needed to shape Singapore's energy future as it moves towards net-zero emissions.

CLEAN ENERGY RENAISSANCE

Strong Impetus for Sustainability and Digitalisation

Since 2015, global momentum had been building in the fight against climate change, starting from the Paris Agreement[25]. Scientists warned that the global temperature rise for the century must be kept well below two degrees Celsius. There was a growing acceptance of the need to address climate change, and countries and companies started to transform their energy systems and invest in sustainable solutions.

However, in 2019, the world was hit by the Covid-19 pandemic which disrupted the world on many fronts and especially impacted the world economy, public health, and air travel. The development of effective vaccines and implementation of border control and safe management measures by governments worldwide helped bring the situation under control. As a result, the world managed to emerge from the crisis and resume pre-Covid-19 economic activity levels within a few years.

As the global economy recovered, countries were able to re-focus on other serious global challenges. The momentum against climate change picked up from where it left off, while the development of clean energy technologies received renewed vigour through massive injection of capital by institutional investors such as pension funds, insurers, and sovereign wealth funds. Digital technologies, which came to the fore during the pandemic, continued to transform many sectors. Manpower shortages forced firms to reengineer their business processes to ensure business resilience. This digitalisation trend continued strongly post the pandemic and even accelerated in the 2030s and 2040s.

Electricity Imports into Singapore

Singapore started commercial electricity imports in 2022. A trial for 100 MW of electricity imports from Malaysia allowed Singapore to assess and refine its technical and regulatory framework to address the unique characteristics of electricity imports. Singapore also embarked on importing up to 100 MW of renewable electricity via the LTMS-PIP, and another 100 MW of renewable electricity from Indonesia. The success of these trials laid the foundation for Singapore to explore greater electricity imports, not just from its immediate region but further afield as well.

The introduction of electricity imports allowed Singapore to diversify its energy sources, moving away from natural gas which generated about 95% of its electricity in 2020. As more imported electricity entered the Singapore market, the security of supply, especially in the event of prolonged import outages, was a key concern which needed addressing. Local generation capacity from older CCGT plants was retained while various forms of ESS were procured to provide backup capacity. They would be activated to provide the necessary capacity in the market in the event of outages.

By 2035, Singapore had interconnectors with multiple countries, including Australia, Vietnam, Laos, Malaysia, Indonesia, and Thailand. These collectively met over a quarter of Singapore's total electricity needs, enabling it to tap on low-carbon energy resources from beyond its borders and also support the development of renewable energy sources around the region. The success from the electricity import projects encouraged Singapore to pursue more electricity imports from other low-carbon energy sources for diversification.

In adhering to its own sustainability objectives, Singapore ensured its electricity imports were green and beneficial to both Singapore and the exporting country. Cross-border solutions, such as Renewable Energy Certificates (RECs) verified by accredited platforms or providers, enabled Singapore to track the sustainability of the imported electrons. The electricity import projects helped spawn more renewable energy projects in the exporting countries. These renewable energy projects benefitted the local communities as they also contributed to the local needs for clean energy.

[25] A legally binding international treaty on climate change adopted by countries at the 21st Conference of the Parties held in France in Dec 2015, and entered into force in Nov 2016

Hydrogen Emerged as a Key Low-Carbon Fuel

Singapore built its first hydrogen import terminal with sufficient capacity to import hydrogen in small quantities to meet its energy needs in the mid-2030s, thanks to global investments in the previous decade driving costs down substantially. Countries around the world were trying to decarbonise and reduce their dependence on fossil fuels, which dwindled in supply due to the lack of financing. Hence, many countries, including Singapore, had identified low-carbon hydrogen as the fuel to fill the void.

Singapore had already started pre-investing in hydrogen-ready infrastructure in the mid-2020s to ensure that its gas-fired generation plants were ready to adopt hydrogen more quickly as and when it became viable. This was necessary as power infrastructure tends to be long-lived, with CCGT plants typically having a 25-year lifespan. Such investments would have locked Singapore into a certain trajectory if they were not hydrogen-ready.

By the 2030s, a global hydrogen supply chain comprising multiple sources of low-carbon hydrogen began to emerge, and the cost gap between hydrogen and conventional fuels narrowed, as technologies such as water electrolysis and methane pyrolysis became more cost-efficient. Encouraged by these positive signs, Singapore decided to make hydrogen a significant part of its net-zero electricity supply mix by 2050. This strategic decision led to additional investments in hydrogen infrastructure. Singapore's first large-scale hydrogen import terminal commenced operation in 2040 with sufficient capacity to meet more than half of Singapore's electricity needs. Located on Jurong Island, this terminal was connected to nearby generation plants and several industrial facilities. By then, hydrogen costs had fallen significantly and only a slight premium was required for CCGT plants to move away from natural gas and operate fully on hydrogen.

In the 2040s, Singapore continued scaling up the share of hydrogen in its supply mix, as ongoing technology developments continued to bring down the costs of producing, transporting, and utilising hydrogen, while the cost-competitiveness of natural gas deteriorated due to depleting supply and high levels of carbon tax.

Geothermal Became Part of Singapore's Domestic Renewable Energy Portfolio

In the late 2020s, studies confirmed that geothermal energy in Singapore was a serious contender as an important energy source. Geological studies showed that there was significant geothermal resource potential on both Singapore's mainland and its offshore islands. While the lack of heat resources at the surface rendered conventional hydrothermal systems infeasible, next-generation geothermal technologies, which allowed heat to be tapped at depth, renewed hopes of deploying geothermal energy in Singapore.

The first advanced geothermal pilot plant commenced operations in 2030, even as Singapore continued to monitor developments given the high costs to extract energy from deep underground and the concerns associated with seismic risks. In the early 2030s, advanced drilling techniques significantly improved the techno-economic viability of geothermal systems, due to the transfer of expertise from the oil and gas sector. As demand for low-carbon alternatives picked up, oil and gas companies had already pivoted to areas where their exploration and extraction capabilities would be relevant.

Following the success of the first pilot plant, Singapore expanded into commercial-scale geothermal power generation in the late 2030s as costs decreased further. Geothermal energy became another major local renewable resource beyond solar for Singapore, and five geothermal plants were in operation by 2050.

Managing the DERs In a More Refined Manner

In the 2020s, Singapore started to plan for the decentralisation of distribution grid control, as the projected proliferation of DERs connected to the grid would significantly change the way the grid needed to be managed. Solar and ESS were on track to becoming cheaper and more efficient and would thus play an increasing part in Singapore's electricity system. EV adoption also picked up rapidly after Singapore announced that internal combustion engines (ICE) vehicles would be phased out by 2040. These resources had differing generation and consumption profiles. Collectively, they would cause uncertainty and volatility to the grid if they were not coordinated or managed.

The grid system which existed in the early 2020s was mainly designed for a linear flow of electricity from large, centralised generators to consumer loads across the island. Plans were made to develop advanced control systems which would analyse large amounts of grid data, collected via a widely deployed network of sensors, to direct the use of DERs when necessary to maintain system stability. Clear rules and regulations to manage how DERs could be controlled and utilised were put in place and rapidly adjusted when needed.

In the mid-2020s, the Distributed Energy Resource Management System (DERMS) was commissioned to better coordinate the growing number of DERs. The DERMS allowed grid operators to plan and execute when individual DERs would inject electricity to the grid or manage their consumption from the grid. This helped mitigate the volatility that the DERs would otherwise cause to the network and contributed to the stability and reliability of the power system. It also allowed the grid to harness the flexibility of the DERs to meet system needs and helped defer or avoid the need for grid infrastructure upgrades.

Subsequently, the population of DERs continued to soar, making it increasingly challenging for the DERMS to coordinate and optimise the full array of DERs across the entire country. To better manage the system, Singapore evolved the DERMS to segment DERs into different zones in Singapore. This approach improved the workload management for the overall DERMS system.

By focusing on a smaller geographical area, each DERMS segment was able to allow operators to have better cognitive and efficient operation of the increasing DER population. Aided by AI and ML algorithms, each DERMS segment was able to intelligently optimise supply and demand of the DERs within its zone and streamline the support needed from the transmission grid. This contributed towards the optimisation of grid capacity and led to economic savings for the power system.

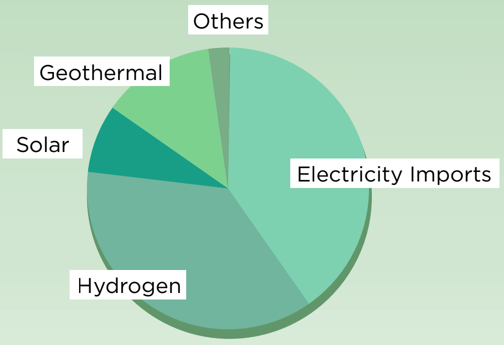
End Users More Empowered and Proactive

On the demand side, many sophisticated end users from the industrial and commercial segments were committed to the sustainability targets. They were no longer passive consumers of electricity and were more empowered through the use of advanced digital technologies to proactively manage their own energy consumption. These end users tapped on ESS and energy management systems to optimise their energy use without disrupting their operations. In this way, they became more self-sufficient and reduced their dependence on the main grid, and could even contribute energy to the main grid at times. Some end users collaborated among themselves to establish micro-grids, which tapped on synergies and resources across different end users for further optimisation.

There was strong adoption of demand response programmes as well as differentiated pricing schemes which reflected the different costs of electricity at different times of the day. These initiatives nudged consumption behaviour and smoothened the demand profile at the system level. AI technologies allowed end users to achieve cost savings and contribute to system needs. The loads were intelligently managed to switch between relying on their local generation or storage and drawing from the utility grid for consumption or charging of storage. AI technologies enabled such users to optimise their consumption autonomously by anticipating load behaviour, forecasting the local solar output and state-of-charge in the ESS, and responding to electricity price signals.

Smaller end users, such as households and EV owners, who had less stringent electricity requirements, also starting monetising the flexibility of their electricity needs. Homeowners leveraged home energy management systems to dynamically respond to price signals and adjust electricity consumption patterns, thereby benefitting from the associated cost savings of reduced electricity usage. Smart EV chargers quickly became the norm as Singapore moved towards its goal of deploying 60,000 EV chargers by 2030, allowing EV charging patterns to be managed based on the needs of the grid. Subsequently, the introduction of bi-directional chargers enabled EV owners to participate in vehicle-to-grid (V2G) programmes to send electricity back to the grid when needed and receive compensation for this service.

Singapore Achieves a Diversified Supply Mix in 2050[26]



Today (in 2050), Singapore has a diversified electricity supply mix with electricity imports and low-carbon hydrogen as the two major contributors, each fulfilling about 40% share of the power generation needs. Through a diversified range of import sources and local backup capacity, electricity imports are a secure and affordable supply option for Singapore. Singapore has also been scaling up low-carbon hydrogen as it continues to become more cost-competitive. Geothermal and solar are two key domestic renewable generation sources that add up to about a fifth of the supply mix. Carbon credits are available but not used, as Singapore's priority is to develop its clean energy options.

Singapore has a leading intelligent grid capable of maintaining system stability and reliability amidst the proliferation of DERs, while harnessing the flexibility of the DERs to benefit system costs. The grid uses the DERMS made up of multiple modules that manage the array of DERs in different zones of Singapore in a refined manner. This is made possible by the collection and transmission of granular data by advanced sensors and communication equipment. Equipped with smart technologies such as AI and ML, the grid harnesses the flexibility of the DERs and optimises their use within each zone to streamline the overall grid capacity and costs.

Electricity demand growth at the system level is actively managed and the fluctuating demand profile is smoothened, making grid planning and operations more efficient. A greater proportion of end users are now self-sufficient and proactively manage their consumption in accordance with system features and needs, using advanced energy and digital technologies such as ESS, AI, and V2G.

[26] The illustrative supply mix is purely for scenario planning purposes. It does not represent the Singapore Government's ambition, target, or projection. "Others" represents waste-to-energy, biomethane etc.

CLIMATE ACTION BLOC

Countries Banding Together

The Covid-19 pandemic in the early 2020s was a trying event across the world. On several occasions, countries thought they had developed an optimal strategy to control the pandemic and a reopening of the economy was in sight. However, they were repeatedly thwarted by the emergence of new variants of the virus that rendered vaccination regimes ineffective and required backtracking on safe management policies, resulting in setbacks for global economic recovery. The protracted Covid-19 battle dragged on for several more years. It strained the economy severely, hollowing out government budgets and driving many smaller businesses into the red. Healthcare and business continuity were overriding concerns. Investments in R&D and development not related to Covid-19 were cut, bringing many technology advancements to a virtual standstill.

It became increasingly evident to countries and international organisations that strategies up till then were not effective enough to counter the global crisis. Given the tendency of this highly infectious and resilient coronavirus to spread between persons and across borders, the rate of recovery from this pandemic was slow. Under the leadership of international organisations, countries began collaborating by sharing medical equipment, personnel, and data. Driving down the infection rate was no longer a target just for any given country, but for entire regions.

The significant step-up in international collaboration paid off as the world began emerging from the pandemic in the mid-2020s. It sent a strong signal that collective action was critical in overcoming global challenges. Since then, countries have been determined to band together to plan and implement joint efforts to tackle the ongoing global challenge of climate change.

Electricity Imports Became the Most Significant Option

The success of Singapore's electricity imports trials in the early 2020s laid the foundation for Singapore to explore more electricity imports. In preparation for electricity imports, Singapore had developed backup systems to mitigate potential disruption risks. This backup regime comprised a mixture of short-term fast response solutions such as ESS to cater for instantaneous losses, and long-term backup solutions such as fast-starting open-cycle gas turbines or gas engines to withstand prolonged outages. There were instances where subsea cables carrying electrons from other countries were damaged, requiring backups to be used to maintain the adequacy of electricity supply. Singapore was also able to use spare capacity in its interconnections with other countries to purchase more electricity to fill the shortfall when needed. During instances of serious cable issues, contractors with specialised vessels, marine equipment, and personnel developed the capability to restore the cables within three to six months. As Singapore scaled up electricity imports in the 2020s and 2030s, this strategy continued to deliver electricity reliably to Singaporeans.

Singapore's steady growth in electricity imports and diversification of the sources to ensure security and competitiveness was made possible by a strategic move made in the late 2020s to proactively build interconnector capacity. This gave Singapore the option to scale up electricity imports when needed. The possible alternatives to electricity imports which Singapore had assessed were not promising. At that point, the only other option that could provide a significant amount of low-carbon energy to power Singapore was hydrogen. However, the cut-back in energy R&D investments and weak economic conditions from the Covid-19 pandemic affected the demand for and production of low-carbon hydrogen. While a global hydrogen supply chain was starting to emerge in the 2030s, the use of hydrogen for power generation was still considerably more costly than using conventional fuels, and the number of producers was small. Nevertheless, Singapore introduced a relatively small share of hydrogen into its supply mix to build capabilities and prepare to scale up the use of hydrogen, should hydrogen become more cost-competitive in the longer term.

In the 2040s, Singapore further developed the electricity import system into a commercial-based trading system. This was facilitated by a more connected regional power grid, a transformative evolution of the longstanding ASEAN Power Grid. There was a strengthened sense of collective action in ASEAN to share clean energy resources and develop energy projects to boost the regional economy, especially for the less developed countries in the region. The commercial nature of the trading platform and grid infrastructure elevated the level of energy interdependence among participating parties and enhanced the security and competitiveness of energy supply. Many exporting countries made good returns from their activities in the regional grid and this benefit spilled over into the vibrancy of their domestic economies. For the Singapore power sector, this became the main means for decarbonising its supply mix in a win-win fashion.

Carbon Credits as an Option to Offset Residual Emissions

Besides coming together for electricity trading, countries also started collaborating in the 2020s to set up a functional carbon market for the exchange of high-quality carbon credits. Standards for the measurement, reporting, and verification of carbon credits were established, and clear reporting and auditing processes were put in place. Various governments recognised that this was a win-win situation for countries in the Asian region as they could tap on carbon credits to offset residual emissions. Countries with favourable geographical conditions could play a role in developing natural capital and supplying carbon credits.

Singapore had to tap on carbon credits to offset residual emissions that were difficult to abate, due to the lack of viable low-carbon alternatives. Apart from the renewables, Singapore continued to rely on natural gas to complement its supply mix, while offsetting the resultant carbon emissions using carbon credits.

More Resilient Grid

In the mid-2020s, Singapore developed a full-scale digital twin of the electricity grid to enhance the robustness of grid network planning and the optimisation of grid asset investments. As a high-fidelity representation of the real world, the digital twin allowed detailed simulations of different scenarios to better understand the impact of policy choices and investments. This system was constantly updated based on latest data on the network's condition and situation.

The digital twin played a pivotal role in modelling and simulating the impact of large-scale electricity imports and loads such as EV charging stations. This helped plan the appropriate scale of backup generation and the grid capacity required. Enhanced condition monitoring of assets also allowed Singapore to analyse grid equipment based on their actual performance and state of health. This allowed Singapore to prioritise asset renewal based on actual conditions of the assets, thus improving reliability and cost effectiveness.

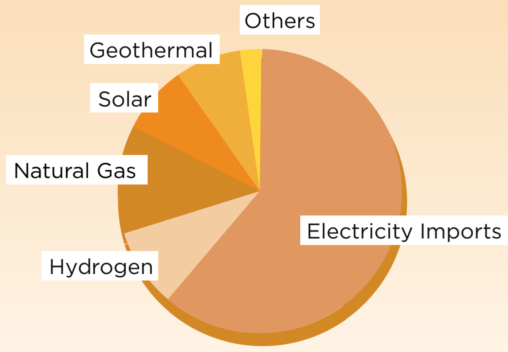
There was an increase in two-way information flows and exchanges as the grid became more digitalised. This exposed the grid to greater cyber risks. Fortunately, several major attacks on the system were foiled by the robust cyber-defence systems in place, and close collaboration between the Government and industry to shore up these defences. Singapore and its regional electricity trading partners also came together regularly to strengthen cybersecurity through strict digital protocols, exchanging cybersecurity intelligence, and conducting regular exercises to uncover the vulnerabilities of their operational and information technology systems.

Micro-Grids for the Large End Users

Large end users began using micro-grids to enhance their energy resiliency, reap cost savings from energy optimisation, and unlock revenue streams through participating in demand response programmes from the mid-2020s. By 2030, micro-grids became a common sight across Singapore. Industrial parks installed onsite generation and storage resources, creating a micro-grid that was connected to the utility grid for themselves, which could disconnect and reconnect as needed. Controllers balanced the micro-grid by drawing on shared resources to meet the demands of individual loads. This smoothened the energy profile the micro-grid was drawing from the utility grid, thus creating savings in grid charges.

Micro-grid owners who became confident of their own setup were able to calibrate their desired reliability levels from the grid and trade off against the payable grid charges. Such arrangements also allowed the grid operator to avoid deploying expensive transmission and distribution infrastructure and reduced the redundancy capacity for individual loads, leading to cost savings which could be shared with the end users.

Singapore is Highly Reliant on Electricity Imports in 2050[27]



Today (in 2050), electricity imports are the main supply source for Singapore's electricity needs, and contribute to about 60% of the supply mix. This is achieved as part of a wider regional grid and trading platform collectively developed to meet the needs of the entire region. This offers greater energy security than bilateral imports and creates economic benefits for the region. Singapore has a relatively small share of low-carbon hydrogen in its supply mix (at around 10%), which remains very costly though there is room for further cost reductions in the future. Singapore continues to use some amount of natural gas to cater for the remaining demand, and the resultant carbon emissions are offset using carbon credits.

The grid in Singapore remains one of the most reliable and resilient grids, despite the need to balance and handle a wide array of DERs. The deployment of digital twins and other modelling and simulation tools enables robust grid planning and optimisation of grid assets. Cost savings from this optimisation help dampen the costs of developing backup capacity to buffer for unpredictability in demand and supply.

Micro-grids are commonly used by large end users to enhance system resiliency and generate cost savings or revenue. Optimisation is done within the micro-grid, allowing the system-level demand profile to be shaped. In some cases, fully self-sufficient micro-grids do not require backup from the utility grid, leading to substantial cost savings for the overall system.

[27] The illustrative supply mix is purely for scenario planning purposes. It does not represent the Singapore Government's ambition, target, or projection. "Others" represents waste-to-energy, biomethane etc.

EMERGENT TECHNOLOGY TRAILBLAZER

Fragmented World Delaying the Energy Technology Boom

Owing to the emergence of a more transmissible and deadly Covid-19 variant, the fight against the pandemic was continually prolonged, badly affecting governments and businesses and detracting their ability to plan for the future. Governments worldwide were under pressure to address unemployment and social unrest problems that were aggravated as the pandemic persisted. Climate action had to be put on the backburner as political pressures made it imperative to prioritise dealing with the virus and its consequences. Unkept promises and unilateral climate change policy U-turns from many parties led to growing mistrust between countries. Gradually, the lack of progress in international engagement eroded the effectiveness of multilateral systems and geopolitical partnerships, and countries became more insular. The new paradigm for governments was to safeguard domestic resources and stockpile key supplies, as global supply chains became more volatile in the midst of the crisis. This paradigm had a negative spill-over effect on other forms of international cooperation.

The world eventually emerged from the Covid-19 pandemic in 2030 and the focus for governments and businesses in the immediate aftermath was on rebuilding efforts and planning for greater business resilience. Most economies bounced back fully only in the mid-2030s, and this allowed for long overdue efforts in climate action to regain momentum. By then, the devastating effects of climate change were manifesting even more clearly around the world. Governments finally buckled down to move on the clean energy transition and tried to make up for lost time. They banked on developing and adopting new low-carbon alternatives to enable this transition, given that hopes of trading electricity or carbon credits were looking bleak in the fragmented world.

Hydrogen Was Late in the Game, But Started Catching Up

Despite the hype in the early 2020s which suggested that hydrogen would play a major role in solving climate change, advancements in hydrogen technologies were frustratingly slow. The pandemic had drawn resources away from energy R&D, hence hydrogen technologies only made incremental improvements, falling short of its perceived potential.

Hydrogen trials in the early 2020s provided key learning points on the requirements to establish a hydrogen value chain in Singapore. However, no decision to move forward was made then as costs were still too high. On the other hand, with electricity imports looking difficult due to a lack of progress on regional grids and power trading, there was increased pressure for Singapore to move forward on hydrogen power.

To allow the flexibility to switch to hydrogen quickly if needed, Singapore made the decision to pre-invest in hydrogen-ready infrastructure, such as CCGT plants that could also operate on hydrogen, while pilots on the use of hydrogen-enriched natural gas were undertaken. Although this raised energy costs in the short term, it was a pragmatic move to prepare for the longer term because this avoided having stranded assets.

By the late 2030s, efforts from a small group of global hydrogen champions showed signs of success as a global hydrogen supply chain started to emerge. Believing that hydrogen costs were likely to become competitive in the foreseeable future, Singapore inked landmark contracts to import hydrogen from around the world, while retaining the contractual flexibility to benefit from future reductions in hydrogen prices. Singapore's new hydrogen import terminal commenced operations by the early 2040s, immediately meeting half of Singapore's energy demand. The benefits of Singapore's early pre-investments in hydrogen paid off, as the fleet of CCGT plants seamlessly pivoted from natural gas to hydrogen. While hydrogen-fired generation costs were still higher than gas-fired generation costs in 2050, cost parity was achieved subsequently within the 2050s.

Mixed Success on Low-Carbon Alternatives

Cutting back of global investments in energy R&D also caused the development of new low-carbon alternatives to be patchy. Bioenergy attracted great interest from sectors seeking to decarbonise, such as the maritime, aviation, and power sectors. Singapore undertook trials to test the use of biomethane for power generation and results showed that it was technically feasible to feed biomethane to the existing natural gas-fired CCGT plants. However, cost reductions of bioenergy proved elusive, and this left the supply chain underdeveloped with only a few niche suppliers of this fuel. More development was needed to ensure a reliable supply chain for Singapore.

With increasing number of countries adopting nuclear energy to decarbonise their economies, Singapore was now ready to assess the viability of nuclear energy for domestic deployment. It had closely monitored the progress of emerging nuclear technologies and had built deep capabilities over the years to assess the safety performances of these technologies. Continuous advancements in small modular reactors (SMRs) had significantly improved their safety performance. Pilot SMR plants that commenced operations abroad from the late 2020s were demonstrated to be safe for deployment in small and dense cities. As a result, several commercial SMR designs and units were progressively developed and deployed globally from the late 2030s. By the 2040s, Singapore had assessed that nuclear energy was viable and began to develop domestic generation capacity.

Several large, developed countries were successful in deploying CCUS to reduce emissions in their industrial and power sectors. In Singapore, however, the use of CCUS was largely confined to the industrial sector (especially energy and chemicals activities) because the relatively low CO_2 concentration levels in the flue gas of natural gas-fired CCGT plants rendered CCUS less economically viable in the power sector. Nevertheless, Singapore continued to actively monitor developments in the CCUS arena as an alternative to tapping on underdeveloped carbon credit markets. From an energy security perspective, CCUS could allow Singapore to continue using natural gas to diversify its supply mix and soften the impact of any shortage in low-carbon hydrogen supplies — without compromising its climate change commitments.

Singapore had tried to explore the potential of harnessing geothermal energy domestically, as this could serve as a new and additional source of domestic energy besides solar for power generation. Exploratory studies were carried out to determine the geothermal resource potential in Singapore. Research was also undertaken to determine the viability and scalability of deploying geothermal systems here. The results of the studies, however, showed that there was limited geothermal resource potential in Singapore. While efforts were made to harness these resources, they were only able to make a small contribution to Singapore's energy mix.

Demand Well-Optimised to Relieve Supply Constraints

Singapore took an active approach in managing the growth of electricity demand in the 2020s by working with high-demand and high-growth sectors to develop sector-specific plans. This was critical as Singapore sought to peak its carbon emissions in 2030, and there was no certainty that new low-carbon technologies would take off in time. Energy efficiency was thus used as an important means to ensure energy affordability, while Singapore awaited the entry of affordable low-carbon options into the power sector.

With incentive schemes and mandatory green standards in place, sectors with high electricity demand such as advanced manufacturing and data centres reviewed their operational and supporting processes to exploit gains in energy efficiency. They upgraded their equipment to best-in-class in efficiency, reengineered their processes to streamline operations, and deployed passive energy efficiency solutions in their infrastructure. These efforts reduced their electricity intensity, allowing them to grow economically while managing electricity demand.

Singapore catalysed energy conservation at the district level by deploying multi-energy systems to meet the needs of end users more efficiently. For example, district cooling systems were deployed in suitable districts to reap economies of scale and they achieved the same level of cooling needs with less electricity. At the individual end user level, the emergence of differentiated retail packages such as energy-as-a-service and tiered pricing models provided end users with cost saving options and the empowerment to contribute to sustainability efforts.

Highly Intelligent Grid to Manage and Harness DERs

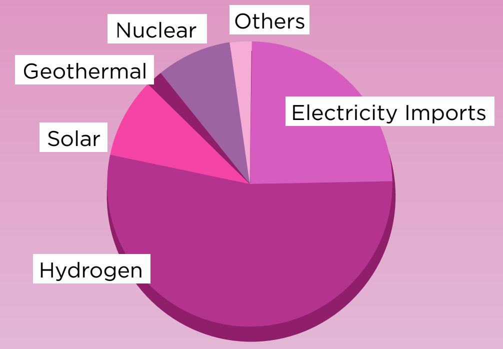
In the 2020s, Singapore was on track towards becoming a frontrunner in intelligent grid systems, extracting greater efficiency from the grid while also charting a new growth area to boost Singapore's economy. A detailed masterplan for a smart grid was developed, featuring advanced controls and high grid intelligence. Riding on the wave of the digital revolution, the Singapore grid started deploying AI extensively in the 2030s.

Singapore began using AI in grid operations to forecast short-term supply and demand. AI was critical in mitigating the intermittency challenges caused by solar in Singapore, which reached 3 GWp by 2030 and was continuing to grow. The AI system learned from historical weather data, real-time measurements of solar irradiance, and satellite images of cloud cover to quickly forecast solar output and guide the planning of dispatch schedules for generation and storage. It was also used to forecast electricity demand by spotting complex patterns based on historical consumption data. The combination of these forecasts allowed finer balancing and optimisation of supply and demand, and supported Singapore's change from a 30-minute dispatch window to a 5-minute window by the mid-2030s, leading to savings in capacity and infrastructure costs for backup generation and storage.

Singapore harnessed DERs in the system by aggregating and controlling them as VPPs. This meant that the DERs were able to provide grid services otherwise unavailable to them and generate revenue for the owners. The AI-enabled VPP could forecast asset performance, electricity demand, and electricity prices, as well as make rapid data-driven decisions about whether each physical asset should throttle its output and contribute towards delivering the grid service.

AI was also infused into grid distribution operations. Grid controllers at the local level leveraged AI to manage clusters of individual substations and connected DERs and optimise the bi-directional flow of energy on a real-time basis. This minimised the adverse impact of DERs on the grid and helped manage infrastructure costs.

Singapore's Supply Mix is Dominated by Low-Carbon Hydrogen in 2050[28]



Today (in 2050), low-carbon hydrogen makes up more than half of the supply mix, replacing natural gas as the main fuel to power Singapore. The cost of hydrogen continues to fall due to increasing global deployment and economies of scale. Electricity imports contribute to the mix but are limited to about 25% due to the slow development of the regional grid and interconnections with potential sources of renewable energy. Building on the investments it made earlier, Singapore is able to start deploying other low-carbon alternatives, such as nuclear energy, to diversify its supply mix and is well-positioned to scale them up further when they become more commercially competitive.

The grid is highly intelligent with the use of AI technologies. It makes effective forecasts of supply and demand as well as autonomous decisions that optimise resources. With AI, the grid is also able to harness the proliferation of DERs by aggregating and managing them as a VPP to contribute to system needs.

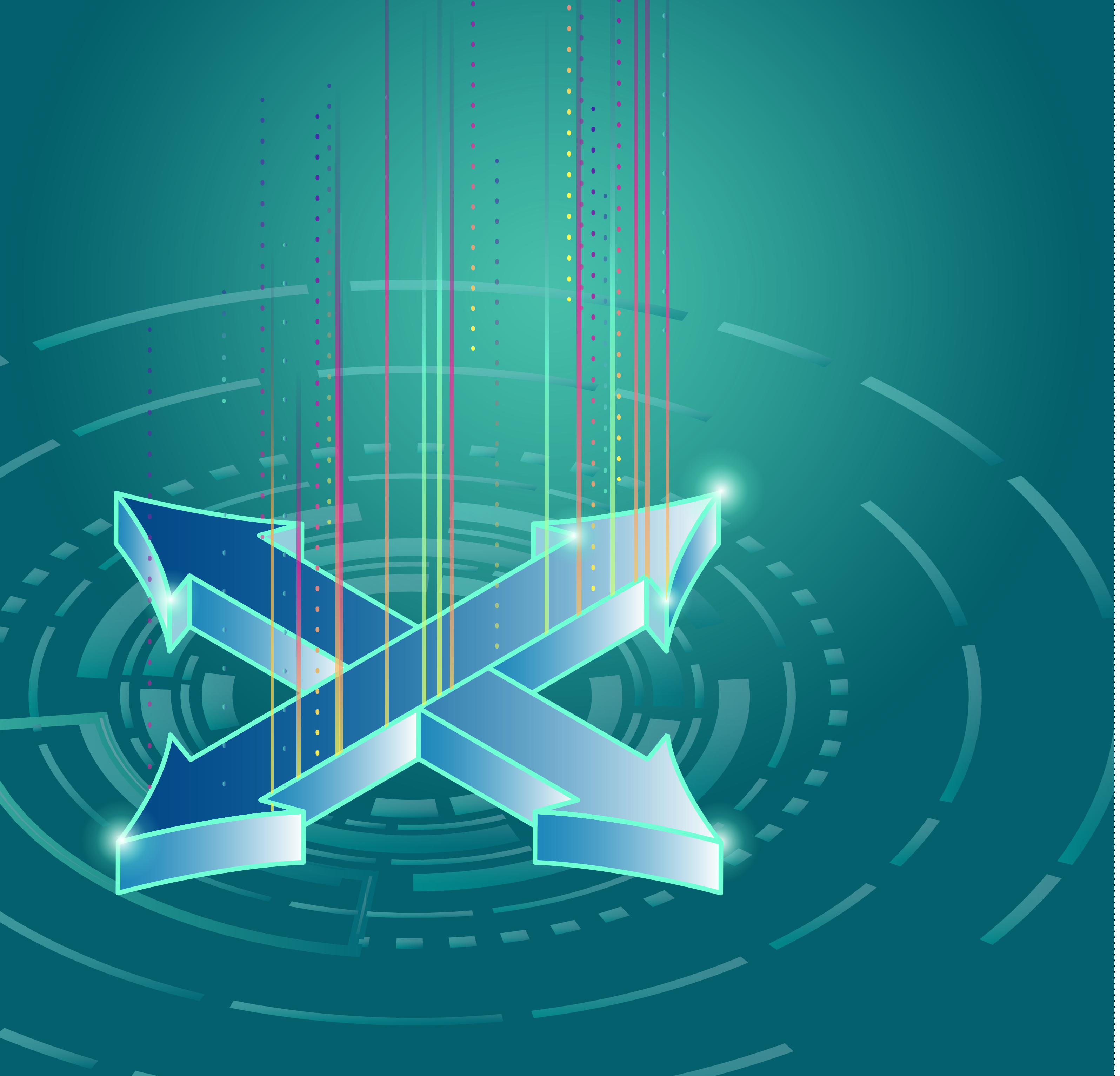
Demand is actively managed and optimised with effective energy efficiency and conservation measures across all end user levels. Large end users from the industrial and commercial sectors view energy efficiency as both a commercial benefit and a compliance measure. This encourages them to invest in digital solutions to optimise their business processes. Smaller end users gain access to multi-energy solutions and differentiated energy prices, which inventivise them to play a more active role towards sustainability efforts.

[28] The illustrative supply mix is purely for scenario planning purposes. It does not represent the Singapore Government's ambition, target, or projection. "Others" represents waste-to-energy, biomethane etc.

SECTION 3

Navigating the Uncertainties

The ways that the uncertainties covered in Section 2 manifest could change the pathway for Singapore to achieve its climate aspirations. Identifying key forks in its decarbonisation pathway and the information required to guide decision making would help Singapore navigate future uncertainties.



The scenarios suggest that while the target of net-zero emissions by 2050 is viable, there are different ways to get there due to the uncertainties in technology advancements and impetus for collective action. How these critical uncertainties develop could significantly alter Singapore's approach and pathway to achieving its net-zero emissions aspiration.

To help navigate through the journey, the Committee has identified key forks along Singapore's decarbonisation pathway in the power sector and the critical decisions that need to be made. Signposts that provide indications of macro energy trends can be used to guide Singapore's decision-making process along the way.

Electricity Imports and Regional Power Grids

Electricity imports and regional power grids enable Singapore to develop regional resources on a mutually beneficial basis to achieve deep decarbonisation and diversify its generation sources. Singapore has already announced the intention to import up to 4 gigawatts of low-carbon electricity (about 30% of its supply mix) by 2035. In the three 2050 scenarios, electricity imports could account for around 25% (in *Emergent Technology Trailblazer)* to 60% (in *Climate Action Bloc)* of Singapore's supply mix, depending on the level of international collaboration.

What are the signposts of how electricity imports will pan out over the next 30 years? One early indicator will come from the success of the electricity import trials from Malaysia, Indonesia, and Laos that Singapore is already embarking upon. Another is the level of interest from regional companies in the requests for proposals (RFPs) for large-scale imports launched by Singapore. In the medium term, the level of cooperation and enthusiasm to build an ASEAN Power Grid and to develop a multilateral market for commercial trading of electricity within the region will be an important signal. A successful regional market with many established buyers and sellers will enable Singapore to rely more on electricity imports as a reliable and secure source of supply over the longer term.

Decision Point for Singapore	How much can Singapore rely on electricity imports for its energy needs?
Signposts to Guide Singapore to This Decision Point	• Outcome of import trials with Malaysia, Indonesia, and Laos • Level of participation in RFPs for large-scale imports • Development of ASEAN Power Grid • Emergence of an international power trading market in the region

Low-Carbon Hydrogen

Low-carbon hydrogen is an option for Singapore to achieve deep decarbonisation. Singapore is already taking steps to build capabilities in low-carbon hydrogen for power generation and there is global interest in exporting low-carbon hydrogen. How much low-carbon hydrogen to use depends on how the technology and industry trends pan out going forward. In the three 2050 scenarios, low-carbon hydrogen could account for around 10% (in *Climate Action Bloc)* to 60% (in *Emergent Technology Trailblazer)* of Singapore's supply mix.

What are the signposts of how low-carbon hydrogen will pan out over the next 30 years? The amount of global investments that go into low-carbon hydrogen, related infrastructure, and R&D of hydrogen solutions will provide an early indication of how fast low-carbon hydrogen will reach technical and commercial viability. The emergence of standards for low-carbon hydrogen carriers will indicate when the adoption of low-carbon hydrogen is likely to accelerate. High global production and shipping capacities of low-carbon hydrogen will suggest that global supply chains are established enough for Singapore to rely on low-carbon hydrogen for its power needs, at an affordable cost.

Decision Point for Singapore	When and how much can Singapore rely on low-carbon hydrogen for power generation?
Signposts to Guide Singapore to This Decision Point	• Global investment levels in low-carbon hydrogen, related infrastructure, and R&D of low-carbon hydrogen solutions • Emergence of modes and standards for low-carbon hydrogen carriers e.g., ammonia, liquid form • Global production capacity for low-carbon hydrogen • Global shipping capacity for low-carbon hydrogen

Grid Decentralisation and Digitalisation

Today, Singapore's grid operates in a centralised manner like most urban systems around the world. With the imminent proliferation of DERs, Singapore's future power system and its grid operations will become more distributed. At the same time, the grid also has the potential to become more digitalised. In the three scenarios, the rate and extent at which the grid decentralises and digitalises vary. In *Emergent Technology Trailblazer*, AI is deployed widely in the grid, allowing Singapore to be a frontrunner in intelligent grid systems. On the other hand, the use of AI is less prevalent in *Climate Action Bloc* which centres on the development of micro-grids.

What are the signposts of how the grid will evolve over the next 30 years? The number and complexity of DERs connected to the grid system will drive the rate at which Singapore needs to decentralise the grid operation to manage the DERs. The establishment of technical standards related to DER controls and communications will smoothen the introduction of decentralised control. The maturity of AI solutions that are developed and deployed for grid management globally will provide an indication on when and how the grid can digitalise and leverage smart solutions to increase efficiency and effectiveness.

Decision Point for Singapore	When and how much should Singapore decentralise and digitalise the grid?
Signposts to Guide Singapore to This Decision Point	• Number and complexity of DERs connected to the system • Establishment of technical standards on the development of microgrid controllers and communications of connected DERs • Maturity of AI solutions developed and deployed for grid management globally

Carbon Credits

While mitigating emissions should continue to be Singapore's priority for the power sector, there may be situations in which there are residual emissions that are inherently difficult to abate. Leveraging carbon credits could be a cost-effective solution to address such residual emissions if needed. In *Climate Action Bloc*, Singapore leverages global carbon markets to offset emissions generated via natural gas combustion, whereas carbon credit markets are underdeveloped and thus unavailable for Singapore to use in *Emergent Technology Trailblazer*.

What are the signposts of how carbon credits and carbon markets will pan out in the next 30 years? The foundation for the use of international carbon credits has been laid at the United Nations Climate Change Conference in 2021. Establishment of clear rules and standards on how carbon credits are recognised internationally for national carbon accounting would be the next critical milestone. The development, depth, and dynamism of these markets would then need to follow. The extent to which mature economies leverage carbon credits would also provide Singapore with an indication of what would be an acceptable amount of carbon credits it could procure.

Decision Point for Singapore	How much can Singapore rely on carbon credits as a means to achieve net-zero emissions?
Signposts to Guide Singapore to This Decision Point	• Establishment of clear rules and standards to recognise carbon credits for national accounting of carbon emissions • Development of international carbon markets trading quality carbon credits • Extent to which mature economies leverage international carbon markets

Next-Generation Technologies Such As Geothermal Energy, Nuclear Energy, and Other Emerging Low-Carbon Alternatives

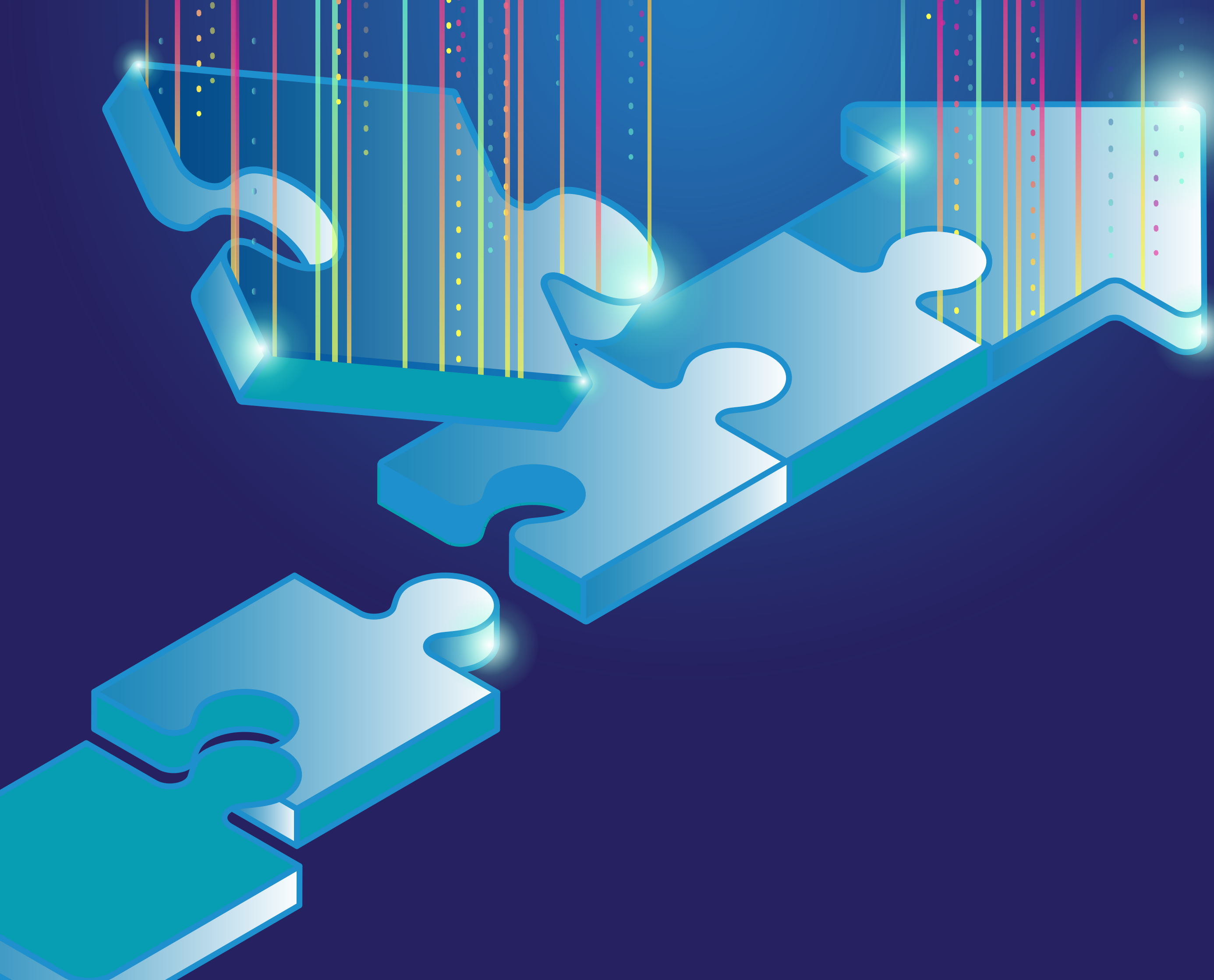
Geothermal energy and nuclear energy have the potential to play a part in Singapore's future energy supply mix. The scenarios leave room for next-generation geothermal energy or nuclear energy to supply around 10% of Singapore's energy needs. While other low-carbon technologies such as biomethane and CCUS do not feature much in the scenarios, Singapore should continue to monitor them given the opportunities that are available should they become viable.

What are the signposts of how next-generation geothermal energy and nuclear energy will pan out in the next 30 years? The development and successful application of advanced drilling technologies in geographical conditions similar to Singapore's will provide an early indication of whether next-generation geothermal energy technologies will be viable here. The global deployment capacity of next-generation geothermal technologies as well as nuclear technologies such as nuclear fission SMR and nuclear fusion will suggest when these options are sufficiently mature for Singapore to adopt. Singapore should likewise monitor investment trends and technology developments to guide the decisions for other low-carbon alternatives like biomethane and CCUS. For example, the development and deployment of technologies overseas like carbon capture for gas turbines can indicate whether such options are possible in Singapore.

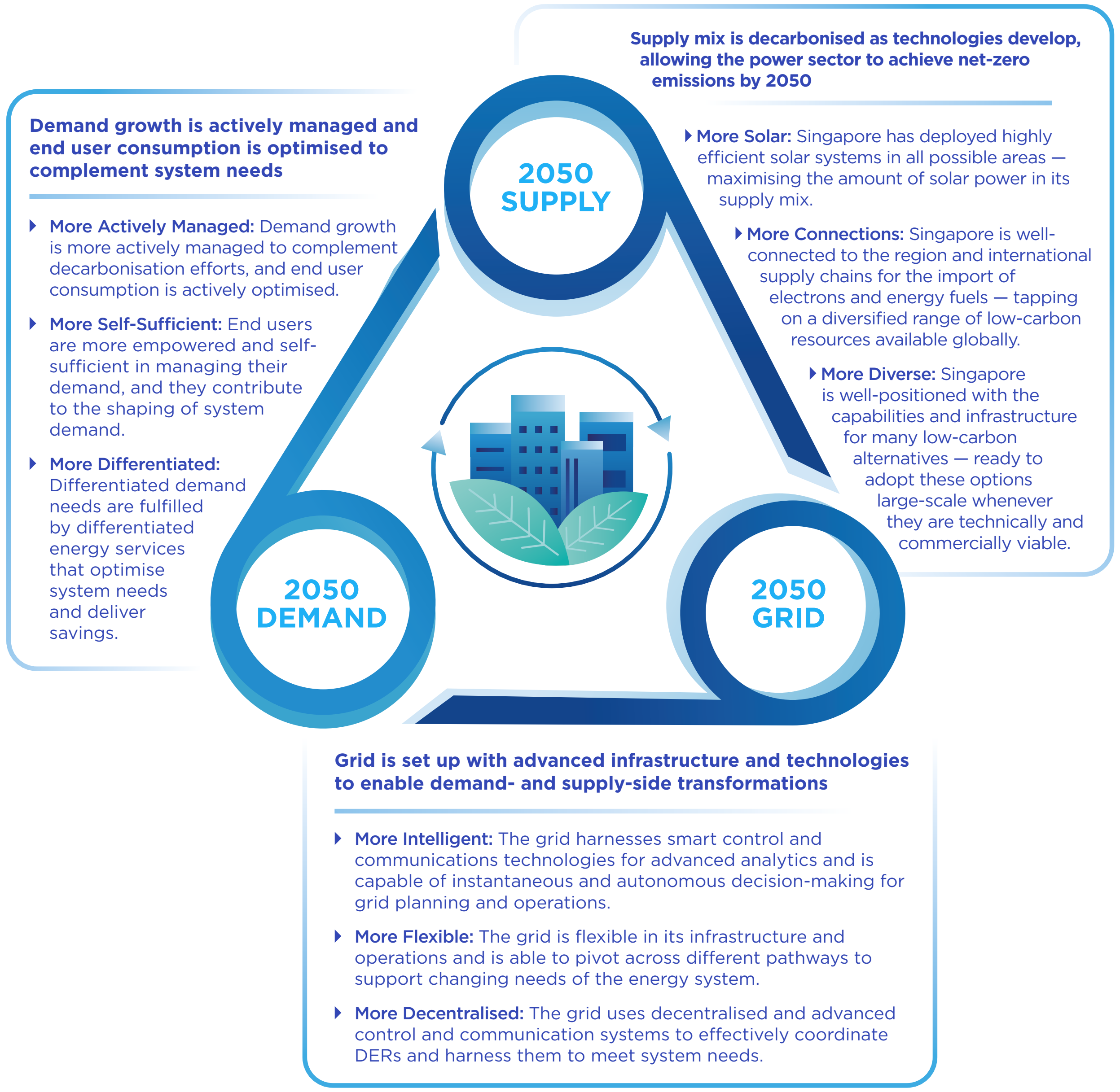
Decision Point for Singapore	When should Singapore deploy next-generation technologies such as geothermal energy, nuclear energy, and/or other low-carbon alternatives?
Signposts to Guide Singapore to This Decision Point	• Development and application of advanced drilling technologies in next-generation geothermal energy projects • Global deployment capacity of next-generation geothermal technologies as well as nuclear technologies such as nuclear fission SMR and nuclear fusion • Global investment trends and technology developments related to other low-carbon alternatives like biomethane and CCUS

Recommended Strategies and Planning Paradigms

While it might not be possible to predict precisely how the trends and uncertainties for the power sector described in Sections 2 and 3 would pan out, Singapore should adopt these strategies and planning paradigms now to position itself for the upcoming transition and achieve its energy aspiration.



In order to achieve net-zero emissions for the power sector by 2050, it is clear that there will need to be transformational changes in the supply, grid, and demand components of Singapore's energy landscape. Various technology trends and global developments must also take place.



The desired changes will only come about if there are deliberate efforts on the part of the Government and industry stakeholders. From the three scenarios, it is evident that electricity imports, hydrogen, solar, and ESS will be important to the Singapore energy system, while new low-carbon supply alternatives and carbon markets may play key roles as well. Efforts to manage the growth of energy demand and shape end user consumption provide a longer runway to deploy the supply-side measures, while also lowering costs for the system. The proliferation of DERs and other changes warrant a multi-layered grid with digital technologies for a secure and optimised system. The different trajectories laid out in the scenarios highlight the need to build flexibility into the system, while offering different opportunities for Singapore to be a technology frontrunner.

The Committee has put together a set of recommended strategies tied to supply, grid, and demand. Each strategy consists of "Implement" steps which represent actions that have clear benefits for Singapore, and "Explore" steps which represent areas that require further study and offer potential benefits. These strategies would stand Singapore in good stead as it arrives at the key decision points discussed in Section 3 of this report, and maximise the power sector's chances of achieving net-zero emissions by 2050. Besides these strategies, the Committee also recommends keeping in mind two overarching planning paradigms for this energy transition. These are needed to keep Singapore flexible and nimble vis-à-vis the uncertain environment, and to seize green growth opportunities for the Singapore economy.

STRATEGY 1: PURSUE THE ADOPTION OF ELECTRICITY IMPORTS

In the near term, electricity imports will be key to the decarbonisation of Singapore's power sector. The technologies for transmitting electricity over long distances are mature and well-established. Electricity imports would allow Singapore to access cleaner and cost-effective energy sources beyond its borders while catalysing a broader ASEAN power grid. It would also improve Singapore's energy resilience by reducing its dependence on natural gas.

"Implement"

Strategically develop a diversified portfolio of electricity import partnerships to ensure the security of supply and avoid over-reliance on a small number of import sources. Similar to Singapore's approach to the import of natural gas, the Government should seek to engage multiple countries and companies with the aim of strategically diversifying Singapore's electricity import sources. However, having a diverse import portfolio might entail trade-offs. For example, in order to import from a wide range of sources, Singapore might need to trade off source diversity with cost.

Prioritise the development of renewable sources to ensure the long-term sustainability of electricity imports[29]. Singapore should aim to tap on low-carbon energy resources such as wind, large-scale solar, and hydropower that are abundant in some parts of the region. These sources should be verified using accredited RECS or other similar mechanisms which take into account the assessment of life cycle emissions and cost.

Develop backup supply to mitigate supply disruptions and ensure that energy security is not at risk. Singapore should develop a mixture of backup solutions, ranging from fast-response technologies (e.g., battery ESS) that cater for instantaneous losses, to long-duration technologies (e.g., open-cycle gas turbines and gas engines) that could tide the system over prolonged outages. Some of these backup systems could be deployed at source while others are in Singapore. These backup systems are important as repair works for damaged interconnections may take three months or more. To manage the cost of such backup measures, Singapore could pace the deployment of these backup solutions with the scaling up of electricity imports and take advantage of the falling cost of such technologies.

"Explore"

Work with regional partners to promote the development of a regional grid supported by commercial electricity trading to enhance competitiveness and security. Singapore could work with governments and companies in the region to promote the setting up of a commercial power trading exchange that would manage and operate cross-border electricity markets. This would provide clear and common rules for participants to drive investments and encourage market competition and efficiency across the region. This could start with the LTMS-PIP, a potential launchpad for the realisation of a larger ASEAN power grid in which power is traded commercially on a region-wide basis.

[29] Based on the UNFCCC carbon accounting guidelines today, national inventories include greenhouse gases (GHG) emissions taking place within national territory and offshore areas over which the country has jurisdiction. The interpretation is that GHG emitted for electricity imports should be factored within the exporting country's inventory and not within the importing country's inventory to avoid double counting.

STRATEGY 2: DEVELOP THE USE OF LOW-CARBON HYDROGEN FOR POWER GENERATION

In the medium to long term, low-carbon hydrogen will also be key to decarbonise the Singapore power sector as it can potentially play a major role in the future supply mix. Hydrogen can be stored in a carrier such as ammonia or in liquid form and transported globally. While production of low-carbon hydrogen today is still costly, that cost is expected to fall with increments in scale. Singapore should collaborate with international partners to accelerate the development of hydrogen supply chains, while developing local capabilities and infrastructure to be ready to integrate hydrogen when it becomes commercially viable.

"Implement"

Develop a national hydrogen strategy, including for power generation, to provide clarity to potential companies and investors. Singapore should identify and aggregate the demand for hydrogen for different sectors, such as the industrial, maritime, transport, and power sectors, and establish a clear direction on how and when Singapore would start using hydrogen for power generation. The announcement of a national low-carbon hydrogen target would help send a clear economic signal to potential investors and help build demand for the international hydrogen market.

Work with Singapore companies and international partners to develop a robust and competitive hydrogen supply chain that Singapore can tap into. Singapore should work with international organisations and potential exporters and importers of hydrogen to develop the technical and regulatory frameworks to facilitate large-scale adoption of hydrogen. This will include establishing common standards and institutions for the setup of an efficient hydrogen market.

Work towards utilising only low-carbon hydrogen. Singapore should import hydrogen from countries which produce hydrogen sustainably, for example, using renewable electricity or using fossil fuels coupled with CCUS. However, hydrogen produced from fossil fuels may be necessary in the initial years to kickstart the deployment of hydrogen in an affordable manner.

Embark on R&D to develop hydrogen solutions that meet Singapore's specific needs to enhance flexibility and energy security. Singapore could trial the transmission and use of hydrogen enriched natural gas for power generation to leverage its existing natural gas ecosystem, avoid stranded gas infrastructure, and streamline the transition to hydrogen. Singapore could also explore new technologies, such as methane pyrolysis, to produce blue hydrogen domestically, and potentially diversify from imported hydrogen for energy security.

Prepare Singapore's infrastructure early so that the system can quickly move to hydrogen when it becomes viable. Singapore should make pre-investments where viable and ensure that new infrastructure developments today, such as gas-fired power plants, are designed to be hydrogen-ready and can be adapted quickly.

STRATEGY 3: MAXIMISE SOLAR DEPLOYMENT AND USE ESS TO MANAGE SOLAR INTERMITTENCY

Both solar power and ESS will continue to become cheaper and more efficient over time. Solar PV is currently the most viable renewable resource in Singapore. Even though solar power is unlikely to form a large share of Singapore's energy supply mix, it is important for Singapore to explore innovative deployment options and utilise the latest solar PV technologies to maximise solar output. ESS has the capability to respond instantaneously to fluctuations in solar power output and is crucial in getting more output from the solar deployment in Singapore.

"Implement"

Deploy solar power in innovative ways to overcome Singapore's land constraint. Besides deploying solar PV on rooftops and water spaces, Singapore should develop innovative deployment solutions such as integrating solar PV into building facades and noise barriers. Singapore should also push the technology frontier and develop ultra-high efficiency solar cells that can offer the best possible output within Singapore's limited land area.

Promote regular upgrade of solar PV infrastructure to exploit the efficiency gains from technology advancement. Singapore should maximise the solar power generation potential in any given space, by promoting the use of the most efficient solar panels. While solar panels typically have a useful life of 25 years or more[30], the pace of technology development will justify replacing existing installations with more efficient panels well before they reach end-of-life, perhaps even every 5-8 years.

Scale up the deployment of ESS to address solar intermittency and maintain system stability and reliability. Li-ion ESS is the most viable storage solution today and its price is expected to drop further with more advanced technologies and economies of scale by around 2025. Singapore should proactively work with the industry to grow the ESS ecosystem and refine regulations to facilitate ESS deployment. To build a more competitive local ESS ecosystem, Singapore should also develop adjacent capabilities, such as in testing, inspection, and certification, as well as repurposing and recycling of used batteries.

"Explore"

Develop capabilities in different ESS technologies which could also meet Singapore's needs. Despite the current dominance of li-ion ESS, EMA should continue to track emerging ESS technologies such as solid-state batteries and develop capabilities and partnerships to harness these technologies when they become competitive. Other forms of storage technologies such as flow batteries and liquid air batteries may present Singapore with cost-effective options for energy storage over longer durations.

Explore different frameworks to best manage intermittency so that solar power is deployed in a sustainable manner. Singapore should study different approaches to manage solar intermittency to determine the most cost-effective and efficient framework.

[30] Useful Life – Energy Analysis, National Renewable Energy Laboratory

STRATEGY 4: PRE-POSITION SINGAPORE FOR NEW LOW-CARBON SUPPLY ALTERNATIVES

Singapore has limited options to decarbonise its power sector and should stay open to all emerging low-carbon alternatives. Technologies such as CCUS, geothermal, biomethane, nuclear fission SMRs, and nuclear fusion have the potential to play a significant role. Singapore should establish the necessary enablers to become a fast adopter of these technologies when it decides to deploy them.

"Implement"

Actively monitor developments in new supply technologies to stay abreast of latest trends that might open new opportunities for Singapore. Singapore should continue to participate actively in international platforms and deepen its engagements with industry and research partners on low-carbon solutions. Singapore should develop capabilities to track global technology developments, forecast commercialisation and cost trends, and continually update its assessment of these emerging technologies.

Build capabilities in advance to enable Singapore to adopt promising technologies quickly when they become viable. New technologies such as geothermal and nuclear will require highly specialised expertise for them to be deployed, regulated, and operated. To assess the viability of these technologies in the local context, Singapore should map out the required capabilities, regulations, resources, and timeline for the respective technologies, and identify the areas that should be developed in advance.

Embark on R&D to test and demonstrate the viability of emerging technologies to build knowledge and operational experience. Singapore should conduct research and testbeds for technologies that show promise of being feasible in Singapore. For example, should Singapore ascertain that there is good underground heat resource, it should undertake pilot studies to test next-generation geothermal technologies in Singapore's local context. Embarking on R&D in these technologies helps Singapore build operational capabilities, gain insights, and potentially accelerate the pace of wider deployment in the future.

STRATEGY 5: LEVERAGE CARBON MARKETS TO ADDRESS RESIDUAL AND HARD-TO-ABATE CARBON

While mitigating Singapore's emissions should be the primary pathway towards achieving a net-zero emissions power sector, it may be too costly if suitable options do not develop in time. If global carbon credit markets develop before 2050, they can provide an avenue for Singapore to address hard-to-abate emissions in a cost-effective manner.

"Implement"

Support the development of international carbon markets to help alternative energy-disadvantaged countries like Singapore meet climate targets. Singapore should leverage its status as an honest broker to facilitate negotiations among international parties to implement the Article 6 rulebook adopted at COP26, and establish rigorous, robust, and credible carbon markets[31].

Develop local carbon market capabilities and services which could be a high value industry that also benefits the Singapore economy. The Government should collaborate with the private sector to scale up the voluntary carbon market and support the growth of the carbon services ecosystem in Singapore. These could cover low-carbon project development, carbon trading, and measurement, reporting, and verification of emissions reductions and carbon credits. Achieving this would strengthen Singapore's position as an international trading hub.

"Explore"

Explore the use of carbon credits for offsetting carbon tax liabilities, to promote the trading and use of carbon credits. The Government should assess whether it will be feasible to allow the industry to use credits purchased from international carbon markets to offset part of their carbon tax liabilities. Such economic incentives could contribute towards the growth of a carbon market while developing carbon trading capabilities.

Facilitate the development of a commercial carbon market to trade credible international carbon credits. Singapore should build on the existing private sector interest in developing commercial carbon markets, such as the Climate Impact X marketplace, as a key avenue to establish robust carbon credit standards and rules[32]. Southeast Asia has good nature-based resource potential that could be tapped to kickstart the market.

[31] COP26 Reaches Consensus on Key Actions to Address Climate Change, United Nations, Nov 2021
[32] DBS, SGX, Standard Chartered and Temasek to Take Climate Action Through Global Carbon Exchange and Marketplace, May 2021

STRATEGY 6: CREATE A MULTI-LAYERED GRID TO MANAGE THE GROWTH OF DERS AND IMPROVE GRID RELIABILITY

The proliferation of DERs will create new challenges for the power system. Traditionally, generation resources and their control mechanisms are concentrated at the transmission level. Going forward, system operators will need to manage a rising number of DERs and increased activity at the distribution level. Singapore will need to develop different layers of advanced control and communication systems to effectively manage the DERs. This could also help mitigate the possible impact of DERs on system reliability, while also harnessing the flexibility of DERs to improve grid operations and optimise the infrastructure for cost savings.

"Implement"

Leverage advanced control and communication systems to achieve oversight and control of the DERs. Singapore should enhance the control and communication infrastructure and protocol for DERs across multiple levels of the grid for effective coordination. The development of DERMS would allow the control centres to have a comprehensive view of the array of DERs. In combination with the deployment of edge control systems, this allows operators to effectively control the DERs. The energy management system at the transmission level should also evolve to include new functionalities and capacity for overseeing a growing number of energy resources and a massive store of real-time data.

Harness DERs to optimise the respective zones of the distribution network to enhance overall grid efficiency. The grid should dynamically manage the DERs at the zonal level to meet local needs, for example, by coordinating demand response and bi-directional electricity flow. This efficient balancing of supply and demand within each zone optimises the support needed from the transmission grid, thus streamlining the large-scale power flows across the transmission network. This defers or avoids the need for grid infrastructure upgrades and creates savings for the power system.

Enhance the physical infrastructure of the grid to allow for more decentralised control of the DERs. Singapore should exploit advanced power electronics technologies to enhance the capabilities of the grid. For example, solid-state transformers and energy routers can enable the control of bi-directional electricity flow.

"Explore"

Study the feasibility of segmenting grid services to meet differentiated needs of different end users. Different end users would have different reliability requirements. For example, customers with onsite generation and storage may be less reliant on the national grid for energy services. With a more decentralised and refined grid, Singapore could potentially provide differentiated grid services that more accurately match customer needs, delivering savings for both the system and end users.

STRATEGY 7: LEVERAGE DIGITAL TECHNOLOGIES TO ENHANCE GRID PLANNING AND OPERATIONS

Advances in digital technologies have transformed many parts of the economy and will continue to do so in the coming decades. Singapore should capitalise on the opportunities offered by these emerging technologies to enhance grid planning and operations. These improve grid reliability and efficiency, while keeping digital threats at bay.

"Implement"

Improve grid planning and operations using advanced modelling and simulation. Singapore should perform advanced modelling and simulation, for example, through digital twins for the grid network and grid assets, to better design and manage the grid. Simulating the impact of future changes to the grid can help guide informed decision-making on upgrading plans and the connections of new energy sources or end users. Data on the assets' condition allows the grid planner to maximise the lifespan of these assets and maintain or renew them only when necessary, thus optimising grid costs. Data on the performance of the assets can also help grid operators identify risks in advance to enhance grid reliability.

Enhance the intelligence of the grid using AI and ML. Singapore should harness the use of advanced computing and sensors to unlock the potential of data analytics in its future grid. AI and ML solutions could analyse real-time and historical data to enhance grid operations and optimise grid resources. This augments the grid operator's role via autonomous decision-making and the identification of trends that may not be immediately apparent to the operator. This could allow finer and more accurate projections of supply and demand, potentially leading to savings in capacity and infrastructure costs for backup generation and storage.

Ensure robust cybersecurity protections. While digital technologies have great upside potential, they could also expose the grid to cyberthreats. Singapore must develop adequate cybersecurity measures to defend against the latest threats and secure commitment from partners in the regional grid to collaborate and adopt these measures.

STRATEGY 8: ACTIVELY MANAGE THE GROWTH OF ENERGY DEMAND

Electricity demand typically increases with economic growth. The need to rapidly decarbonise would inevitably put the Singapore power sector under immense pressure. Therefore, Singapore should increase its emphasis on demand management to actively control demand growth. This will help Singapore better manage the rollout of low-carbon options and keep energy costs affordable.

"Implement"

Work with key sectors to actively manage the growth of electricity demand in Singapore. With carbon, and by extension electricity generated from fossil fuels, becoming a critical constraint for Singapore, the Government should actively plan and budget the use of electricity in a comprehensive and deliberate manner. When necessary, Singapore should pace the growth of energy demand, particularly for high-growth and energy-intensive sectors. This provides greater scope for Singapore to capture high value-add economic opportunities when they come along subsequently, without sacrificing its climate action objectives. The Government should also work with energy-intensive sectors that are key to Singapore's economy, such as advanced manufacturing and data centres, to develop deployment roadmaps in advance wherever possible.

Optimise energy demand at the district level to exploit synergies. While many existing energy conservation efforts, such as green building standards, are targeted at end users, Singapore should also harness district-level opportunities to improve energy efficiency. Co-locating end users with complementary energy requirements, for example, end users who produce waste heat and end users with heating needs, would set the stage for greater synergies at the district level. This could lead to a lower total energy demand than if end user requirements were separately met.

Continue building on energy efficiency and energy conservation efforts. Singapore should build on existing energy efficiency efforts, such as incentive schemes and green standards, and actively explore other means to influence and encourage greater energy conservation. These would include providing price signals via incentives or penalties and promoting the growth of energy service companies to offer energy efficiency solutions.

STRATEGY 9: SHAPE END USER CONSUMPTION PATTERNS TO OPTIMISE THE POWER SYSTEM

The expected adoption of digital technologies by end users opens possibilities for them to manage their consumption patterns and power requirements from the grid. More active management on the demand side reduces the need to continuously upgrade generation or grid capacities to meet peak demand levels. This will optimise the overall system utilisation.

"Implement"

Enhance the market design to provide price signals and incentivise behavioural change among end users. Currently, most end users purchase electricity on fixed pricing contracts that provide price certainty but dampen time-of-use price signals to end users. Singapore should review its market design such that adequate price signals flow through to end users, complemented by more active education and engagement efforts. This incentivises behavioural changes to shift consumption away from periods of high system demand, through the adoption of technologies like smart energy management systems and ESS that enable greater demand flexibility.

Develop the flexibility of demand to optimise supply and grid capacities. Singapore should increase the use of innovative technologies, such as smart vehicle-to-grid technology and smart energy management systems, to augment the amount of demand response in the market. These technologies can intelligently manage electricity demand and allow end users to shape their consumption patterns. The Government could work with the industry to develop digitalisation roadmaps to guide the adoption of these demand-side management solutions.

Unlock areas where demand flexibility can be tapped for end users to play a bigger role in demand-side management. A significant amount of demand flexibility is yet to be tapped today, due to asymmetry of information and inertia to adoption. For example, many end users have backup generation sets which are largely underutilised. These could be leveraged to provide demand response to support the grid under stressed conditions. The Government could promote the growth of energy-as-a-service providers who can help end users identify, operationalise, and monetise these untapped resources to improve demand flexibility.

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PLANNING PARADIGM 1: BUILD FLEXIBILITY INTO THE POWER SYSTEM TO PROVIDE OPTIONALITY FOR SINGAPORE TO PIVOT ACROSS DIFFERENT PATHWAYS

The uncertainties that Singapore faces in its decarbonisation journey are significant. It is crucial that Singapore builds flexibility across its entire energy value chain to allow for the scope to pivot across different pathways nimbly.

"Implement"

Increase speed-to-deployment to allow the power system to quickly respond to changes. Singapore should increase its ability to deploy new supply and grid capacities quickly to meet increased demand. Solutions such as mobile power plants have a relatively short development time and could be activated quickly to add capacity to the system. Singapore should also be ready to deploy new supply technologies quickly when the conditions are favourable, for example in the transition to hydrogen for power generation. This could be achieved by investing in plug-and-play generation technologies that can operate on a variety of fuels such as natural gas and hydrogen.

Use plug-and-play infrastructure to achieve the flexibility to pivot to different pathways and minimise hefty investments. Conventional power infrastructure often entails heavy and long-tailed investments that extend over several decades. With greater uncertainties during this energy transition, Singapore should explore pre-investing in cost-effective plug-and-play solutions that can provide short-term capacity and can be removed when they are no longer needed. One example is leasing floating power plants for a few years to boost capacity when there is a short-term requirement for additional generation capacity. This allows Singapore to remain nimble to fluctuating demand and new technologies, while minimising costly long-term infrastructure investments that could become stranded later.

Adopt modular solutions to pace investments and reduce the risk of stranded assets. Singapore should adopt modular solutions, where possible, to space out investments. This reduces the size of each investment, thus lowering the risk and cost of stranded assets. Technologies like solid state transformers and gas engine generators are generally smaller than conventional transformers and CCGTs respectively. They could provide the advantage of expanding the infrastructure capacity in a more incremental fashion.

PLANNING PARADIGM 2: CAPITALISE ON OPPORTUNITIES TO POSITION SINGAPORE AS A TECHNOLOGY FRONTRUNNER AND LIVING LAB FOR SUSTAINABLE ENERGY SOLUTIONS

Amid the transformation of the energy sector, there are also economic opportunities Singapore can seize by leveraging its unique traits. Being both a city and a nation, Singapore should move nimbly towards developing solutions suited to its urban environment, with minimal conflicting interests that other federal or larger jurisdictions may have. With a strong academic and research ecosystem in place, Singapore can build on existing strengths, such as systems integration, to develop exportable solutions and capabilities.

"Implement"

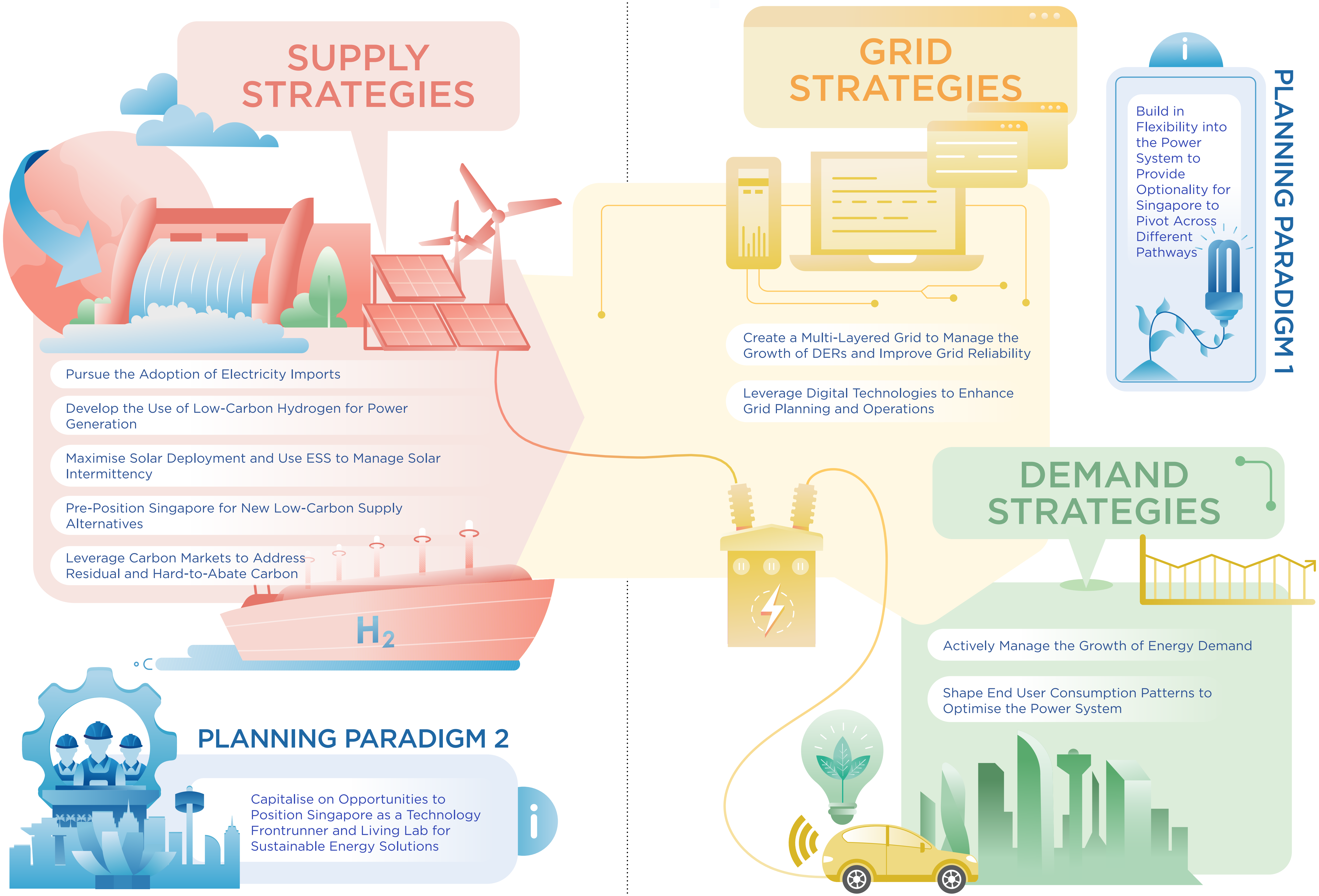
Seize early mover advantage in areas that could benefit Singapore's economic growth. In light of Singapore's limited resources, Singapore should consider how to play to its strengths of a strong R&D ecosystem and ability to attract investments from technology companies and select the right opportunities. Singapore should conduct research and experiment with innovative ideas early, for example on developing a smart grid in a dense urban environment and using membrane technologies for carbon capture. Singapore's national Research, Innovation, and Enterprise (RIE) plan, which lays the groundwork for Singapore's science and technology efforts every five years, can synergise use cases across various sectors and direct the research focus towards the identified areas.

Invest proactively in nascent technologies to develop niche strengths. Singapore should invest proactively in nascent technologies that have clear upsides in Singapore's context. This would allow Singapore to gain an early advantage and develop niche strengths ahead of other larger countries. For example, nascent technologies such as packet-based electrical power systems could be ideal for Singapore's dense urban environment.

Utilise Singapore as a living lab to test different ideas together and promote the co-creation of solutions. Singapore should leverage its unique dense urban grid to encourage the development of large-scale test-beds to test different solutions together and assess how they interoperate with one another in the grid. This would be a valuable platform to test the effectiveness of new technologies in a real-world environment. Nevertheless, there need to be safeguards and boundaries in place to ensure that the overall system is kept reliable and resilient.

"Explore"

Develop platforms to facilitate the access to and sharing of data to catalyse innovation in the industry. Beyond strengthening its engineering and technological capabilities, Singapore should also aim to leverage the power of data to drive innovation and growth. Singapore should explore developing platforms that allow for easy access to and sharing of data across the energy industry to support data analysis and co-creation of new solutions.


SUPPLY STRATEGIES
Pursue the Adoption of Electricity Imports
Develop the Use of Low-Carbon Hydrogen for Power Generation
Maximise Solar Deployment and Use ESS to Manage Solar Intermittency
Pre-Position Singapore for New Low-Carbon Supply Alternatives
Leverage Carbon Markets to Address Residual and Hard-to-Abate Carbon
H2
PLANNING PARADIGM 2
Capitalise on Opportunities to Position Singapore as a Technology Frontrunner and Living Lab for Sustainable Energy Solutions
GRID STRATEGIES
Create a Multi-Layered Grid to Manage the Growth of DERs and Improve Grid Reliability
Leverage Digital Technologies to Enhance Grid Planning and Operations
PLANNING PARADIGM 1
Build in Flexibility into the Power System to Provide Optionality for Singapore to Pivot Across Different Pathways
DEMAND STRATEGIES
Actively Manage the Growth of Energy Demand
Shape End User Consumption Patterns to Optimise the Power System

SECTION 5

Conclusion

The evolution of the global energy landscape over the next three decades is expected to be highly dynamic as the world takes steps to tackle climate change. Technology and geo-economic trends remain uncertain, and could lead Singapore down a range of different decarbonisation pathways. This transition will be especially challenging for a small, densely populated, and alternative energy-disadvantaged country like Singapore. In this journey, Singapore will also need to balance its energy trilemma to deliver sustainable, secure, and affordable energy to Singaporeans.

Despite this, the Committee concluded that it is technically viable for the Singapore power sector to achieve net-zero emissions, and that it is realistic for the sector to aspire to do so by 2050. To do this, Singapore will need to effectively navigate the uncertainties and implement strategies to strongly position itself for the transition at every stage.

Achieving this aspiration will require transformational shifts. Singapore's power system has achieved high levels of reliability, mainly through the provision of ample reserves and buffers. However, the current approach of continuously expanding supply and grid capacity to keep up with demand growth will become increasingly inefficient and costly as demand increases significantly. The grid needs to change its approach of maintaining system reliability through a more finely tuned and balanced system instead of building more capacity and redundancies to cater for different contingencies. Demand needs to be actively managed. End users must be brought in to play a more active and constructive role in the power system through more concerted energy management and conservation.

Achieving the energy 2050 aspiration is possible, but there will be unknowns and potential derailers. Hence, it is important for Singapore to introduce flexibility into the power sector to provide optionality to pivot across different pathways. Investing in digital technologies that contribute to improving agility and intelligence will allow supply, grid, and demand to operate more seamlessly and optimally together, while mitigating the need to constantly expand the system. Infrastructure pre-investments can also enhance flexibility by incorporating plug-and-play capabilities to accept new standards and technologies. A systematic way of taking stock of these uncertainties and investments is necessary. Clear decision points guided by a set of signposts to help sense make along the way will help Singapore navigate through the various issues.

This major energy transition will invariably involve trade-offs. Singapore will need to carefully manage these trade-offs and make tough decisions when necessary. In some instances, Singapore may need to deploy new energy technologies that are more economically costly, yet are overall beneficial after considering the positive impact to energy sustainability and security. Despite Singapore's best efforts, there may still be residual carbon emissions that are hard to abate, and Singapore might need to use negative emissions strategies such as carbon credits to help meet its aspirational goal of net-zero emissions. The energy transition would inevitably result in an increase in cost, but it is unavoidable if Singapore wants to make the energy system more sustainable and secure in a carbon-constrained future.

Despite the challenges, Singapore should approach the energy transition with hope and optimism. Singapore is not alone in this endeavour. The rest of the world is also undergoing an energy transition to fight climate change, and this presents opportunities to collaborate on technology development, carbon markets, and energy trading. This global movement also brings about economic growth opportunities. Singapore businesses can ride on this momentum and develop green solutions that meet the needs of this global energy transition. Singaporeans can also look forward to new and exciting job opportunities in this burgeoning green power economy.

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Land Transport Authority

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National Environment Agency

National Research Foundation

Public Sector Science and Technology Policy and Plans Office

Urban Redevelopment Authority

This report represents the collective view of the Committee. This report is not meant to be definitive or comprehensive. Rather, it postulates future pathways for the energy system and outlines possible measures that Singapore could implement over the next 30 years to decarbonise the power sector, using the current and projected state of technological and industrial trends and different geopolitical outcomes as its basis.

ENERGY MARKET AUTHORITY

Smart Energy, Sustainable Future