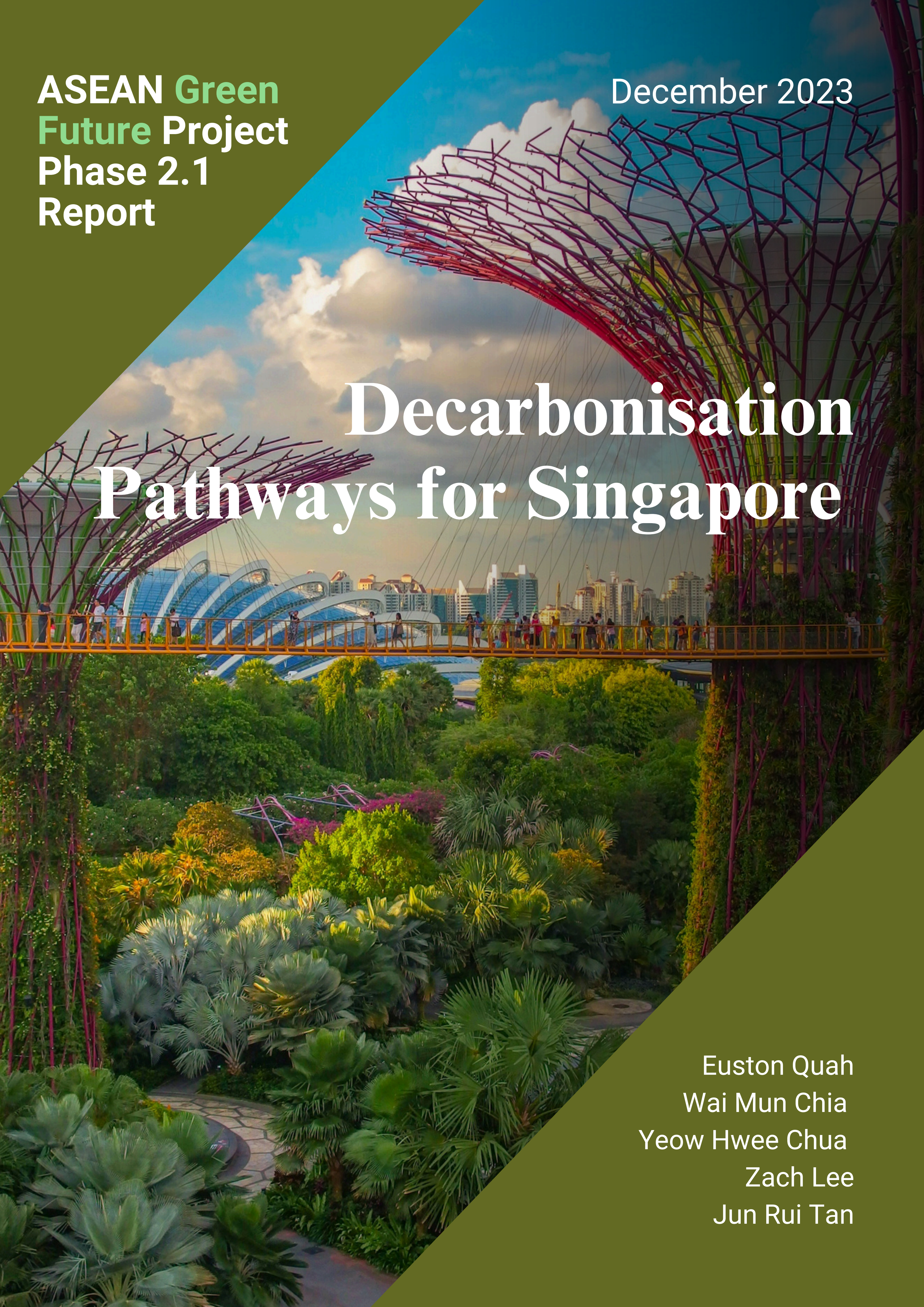
ASEAN Green Future Project Phase 2.1 Report

December 2023

Decarbonisation Pathways for Singapore



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SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK
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About ASEAN Green Future

ASEAN Green Future is a multi-year regional research project that involves the UN Sustainable Development Solutions Network (SDSN), Climateworks Centre and nine country teams from leading universities and think tanks across Southeast Asia (Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, Philippines, Singapore, Thailand and Vietnam). The researchers undertake quantitative and qualitative climate policy analysis and develop net zero pathways to inform policy recommendations and support the strategic foresight of policy makers.

The Phase 1 country reports present priorities and actions to date, and key technology and policy opportunities to further advance domestic climate action. The Phase 1 regional report positions Southeast Asia's low carbon transition pathways within a global context using the country reports and other studies. This series of reports, produced through a synthesis of existing research and knowledge, builds the case for advancing the region's climate agenda. Phase 2 of the ASEAN Green Future project uses modelling to quantitatively assess the different decarbonisation pathways for Southeast Asia.

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Disclaimer

This ASEAN Green Future report was written by a group of independent experts acting in their personal capacities. Any views expressed in this report do not necessarily reflect the views of any government or organisation, agency, or programme of the United Nations.

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1. INTRODUCTION TO SINGAPORE

Addressing the challenges of climate change has consistently been among Singapore's top priorities. While initially committing to a 36% reduction in emission intensity (from 2005 levels) by 2030 in its Intended Nationally Determined Contributions (NDC) to the United Nations Framework Convention on Climate Change, Singapore has continuously refined its strategies to adapt to evolving challenges and aspirations. In 2020, Singapore updated its climate goals, shifting from intensity targets to setting a specific emissions limit of 65 million tonnes of carbon dioxide equivalent ($MtCO_2e$) by around 2030. This was further developed in Singapore's Long-Term Low-Emissions Development Strategy (LEDS), aiming to cut emissions by half to 33 $MtCO_2e$ by 2050. Then, in 2022, Singapore revised its targets again, aiming to reduce emissions to about 60 $MtCO_2e$ by 2030 after reaching peak emissions earlier, with the ultimate aim of achieving net zero emissions by 2050.

To achieve these goals, there is a need to have a comprehensive and integrated approach. One crucial strategy is outlined in the Singapore Green Plan 2030. This plan includes initiatives targeting green spaces, enhancing household resource efficiency, promoting cleaner transportation and transitioning to a greener energy mix. In fostering a green economy, all economic players would need to work collaboratively towards these objectives. While the Singapore government can take the lead in facilitating this transition, industries and individuals need to contribute through their own actions. Due to the interconnected nature of climate change impacts, addressing this global challenge requires concerted efforts from all sectors of society. This is best illustrated in the power sector.

In this study, we focus on an important aspect, the power sector. The power sector is critical as it is the foundational pillar of the entire economy's transition to a net zero economy. Moreover, there is the presence of the energy trilemma, highlighting the need to balance environmental sustainability, energy reliability and affordability. This underscores the significance of conducting a comprehensive study within the region. Through this study, we aim to assess potential pathways to decarbonising Singapore's power sector within the ASEAN Green Future project. Currently, the 2050 Energy Committee Report by the Energy Market Authority (EMA) has described a set of potential scenarios through which Singapore could achieve net-zero emissions in the power sector by 2050 (EMA, 2022a). We add on to the discussion by examining different pathways and linkages within the region. We would like to underscore that these simulations are hypothetical and serve as an academic exercise which do not necessarily reflect our position on the best way to achieve net zero. The goal of this paper is to explore different possibilities that can facilitate policy discussions. As such, we clearly lay out all definitions and assumptions used.

Through the Low Emissions Analysis Platform (LEAP), we also model historical energy demand and supply data, including the current green trajectory and more ambitious pathways which explore future developments in low-carbon alternatives such as hydrogen, geothermal and nuclear, as well as pushing the boundaries of solar energy deployment. Regarding the more ambitious pathways, we also examine greater interconnectivity of the regional renewable power grid and the potential phasing out of fossil fuels. This academic exercise, while basic at the current stage, allows us to simulate the future energy security, reliability and environmental implications of such policies.

2. SINGAPORE'S ENERGY SUPPLY PROFILE

Singapore faces several challenges in its energy landscape. Due to limited alternative energy resources, the nation has historically relied heavily on imported fossil fuels to meet its escalating energy demands. Nonetheless, it is acknowledged that this continued dependence on fossil fuels poses environmental risks and undermines long-term sustainability goals. Coupled with the energy trilemma of sustainability, energy security, and affordability, Singapore has recognised the need to invest in renewable energy sources and diversify its energy mix to avoid over-reliance on any single one. Looking ahead, central to the Singapore's national energy policy framework are the four 'energy switches': natural gas, solar power, low-carbon alternatives, and integration with the regional power grid.

2.1 Natural gas and other fossil fuels, including waste-to-energy

Natural gas constitutes about 95% of Singapore's electricity generation mix with a small amount of oil and coal since 2014. Currently, natural gas is piped from neighbouring Malaysia and Indonesia and shipped as liquified natural gas (LNG) from distant countries such as Australia, the United States, Qatar, and Angola. Natural gas produces the least amount of carbon emissions per unit of electricity among all fossil fuels and is seen as an important bridge fuel for a more sustainable energy portfolio in the future. The switch from oil to primarily natural gas in electricity generation contributed significantly to mitigating emissions of around 7.6 $MtCO_2e$ in the past decade (Su et al., 2017). However, greenhouse gas (GHG) emissions from gas energy generation attributed in Singapore has increased over the years from 16.26 to 24.65 $MtCO_2e$ between 2012-2021 (Ember, 2022).

In general, power generation units can be deployed through the use of open cycle gas turbine (OCGT) and combined cycle gas turbines (CCGT). To strengthen energy security, EMA is building two OCGT generation units, which are less efficient but has faster startup time compared to CCGTs to respond to gas supply disruptions. Producing 340 MW of electricity each, these units run on natural gas as the primary fuel and diesel as a backup similar to existing generation units (Hong, 2023a). Moreover, industry sources have also suggested that Singapore should consider setting up a strategic reserve facility for diesel as an important alternative fuel for power generation even if it is not cost-effective to mitigate global energy supply risks (Pachymuthu, 2022). Singapore is set to shift toward LNG to meet the bulk of its gas demand in the coming years as piped natural gas supply contracts are discontinued and LNG import capacity is expanded.

Enhanced energy efficiency is one way to reduce emissions from electricity generation using OCGTs and CCGTs, which have an economic lifespan of around 25 years. Singapore's electricity grid emission factor (average operating margin) was 0.417 tCO_2e/MWh in 2022. EMA plans to introduce emission standards for new and repowered fossil fuel-fired generation units of 0.355 tCO_2e/MWh based on 75% Plant Load Factor (PLF) and advanced CCGTs[1] for baseload generation units. Advanced CCGTs are expected to be about 10% more efficient than existing CCGTs deployed for electricity generation (Tan, 2023b). For OCGTs, the emissions allowance limit for OCGTs will be equivalent to a Tier 1 advanced CCGT but running at a lower PLF of 50% (EMA, 2023). Even though coal constitutes just 1% of Singapore's energy mix, Singapore has pledged to phase out the use of unabated coal in its electricity mix by 2050 under the Powering Past Coal Alliance (PPCA)[2].

Singapore has traditionally relied on incineration to achieve the dual objectives of reducing up to 90% of waste volume and converting the heat energy produced as a by-product of the incineration process into electricity. Since 1986, there have been six waste-to-energy (WTE) incineration plants to treat municipal solid waste (MSW) which cover about 2% of Singapore's total electricity needs. Singapore's sixth WTE plant (TuasOne) can generate 120 MW of electricity daily and is designed for higher heat recovery from waste incineration and higher electrical power generation efficiency[3].

The upcoming Tuas Nexus Integrated Waste Management Facility (IWMF) allows co-sharing of resources between a water reclamation plant and a waste management facility. With a total generation capacity of 270 MW[4], it is expected to be completed by 2027 and can produce 1,980,000 MWh of energy annually. Only 10% of electricity is retained to operate the two facilities and the rest can be exported to the grid (Boh, 2016). Renewable biogas produced from the process of anaerobic digestion is subsequently converted to electricity. This increase in energy self-sufficiency is expected to result in savings of more than 200,000 tCO_2e annually (Chong, 2021).

2.2 Solar

Singapore has excellent solar irradiance. The annual irradiation recorded in Singapore is between 1580 to 1620 kWh/m^2 which makes solar PV the most promising renewable energy option for Singapore. The Solar Energy Research Institute of Singapore (SERIS) estimated that Singapore has the technical potential to deploy up to 8.6 GWp by 2050, which can meet 10% of Singapore's projected energy demand. However, the potential is hindered by limited land availability for large-scale deployment of solar panels and competing uses. Due to solutions such as the deployment of rooftop and floating solar PV facilities over water bodies, installed capacity and the number of grid-connected installations have risen exponentially over the decade[5]. Future AI developments in grid operations to forecast short-term electricity supply and demand may also be useful in mitigating intermittency challenges (EMA, 2022a).

The Housing Development Board (HDB) announced a solar power generation of 540 MWp by 2030 across its public estates which could potentially generate 648 GWh of clean energy per year[6]. The largest home-grown solar power producer Sunseap analysed that its total solar energy generated has helped corporate and retail customers to offset emissions of over 58,000 tCO_2e (Wong, 2020). Singapore aims to increase solar energy deployment from 515.9 MW in 2022 Q1 to least 2 GWp and meet around 3% of projected total

[1] Best-in-class technologies available in the market expected to be about 10% more efficient than the ones in Singapore's system today.
[2] https://www.nccs.gov.sg/media/press-release/sg-phase-out-unabated-coal
[3] https://www.nea.gov.sg/media/news/news/index/tuasone---the-latest-and-most-land-efficient-waste-to-energy-plant-in-singapore#:~:text=National%20Environment%20Agency-,TuasOne%20%2D%20The%20Latest%20And%20Most%20Land%20Efficient%20Waste,To%2DEnergy%20Plant%20In%20Singapore&text=Singapore's%20sixth%20waste%2Dto%2Denergy,power%20about%20240%2C000%20HDB%20flats.
[4] https://www.power-technology.com/data-insights/power-plant-profile-singapore-new-integrated-waste-management-facility-singapore/
[5] Installed capacity of 670 MWp and 5455 grid-connected installations in the residential and non-residential sectors as of 2022 Q1.
[6] https://www.aseanbriefing.com/news/hdb-green-towns-supporting-singapores-sustainable-development-goals/#:~:text=HDB%20announced%20a%20solar%20power,%2C%20four%2Droom%20HDB%20apartments.

electricity demand in 2030. Research is also being done to produce low-cost solar cells that have an efficiency of at least 30%, up from 25% for typical cells (Tan, 2023a).

2.3 Low-carbon alternatives

Here we discuss the potentially more feasible low-carbon alternatives for Singapore in the near and far future based on recent developments.

a) Hydrogen

Singapore has identified hydrogen as a major decarbonisation pathway and aims to supply up to 50% of its power needs with hydrogen by 2050 (Lee, 2022). Hydrogen power generation technology can potentially achieve a low cost of installation by maximising the use of existing facilities and converting them for hydrogen power generation. This effectively replaces natural gas as the fuel for OCGT and CCGT generation units.

In Singapore, new and repowered OCGT and CCGT generation units are required by EMA to be hydrogen-compatible, meaning both gaseous hydrogen and low-carbon hydrogen derivatives that may be used directly as a fuel. OCGT and CCGT generation units that can accommodate hydrogen blend which consists of 30% volume hydrogen with natural gas are already commercially available in the market today. Over time, as the technology matures and is more cost-effective, EMA may raise the required capabilities for hydrogen-compatibility (EMA, 2023). Singapore is expected to get its first hydrogen-ready power plant, known as the Keppel Sakra Cogen Plant, by the first half of 2026, which is slated to produce up to 600 MW of electricity. This can lead to a reduction of 220,000 tCO_2e of emissions annually (Ang, 2022b).

Low-carbon ammonia, another hydrogen derivative, is close to commercial readiness for power generation. The Maritime & Port Authority of Singapore (MPA) is exploring collaboration opportunities with EMA for an ammonia power generation project with a generation capacity between 55 MW and 65 MW from imported low-carbon or zero-carbon ammonia via direct combustion in OCGTs and CCGTs (Lim, 2023). One issue with ammonia fuel is that, even though it does not emit CO_2 when combusted, it emits nitrogen oxide, which has significantly more greenhouse warming potential than CO_2.

Moving forward, Singapore would also need to monitor its hydrogen supply chain to ensure that green hydrogen produced by renewable electricity is prioritised rather than blue hydrogen produced via a steam methane/natural gas reforming process. It is a promising sign that Singapore's sole piped town gas producer and the nation's gas utility provider, City Energy is conducting a feasibility study with Gentari, Petronas' renewables unit, on a proposed pipeline to export hydrogen from Malaysia to the city state, with a view to it becoming operational by 2027, in time to supply the fuel mix for Singapore's new hydrogen-ready power plant (Daiss, 2023).

b) Geothermal

Singapore has no known shallow heat source but has three confirmed hot springs situated at or near the coasts and estimated anomalous heat flow. Oliver (2010) investigated the feasibility of constructing a 50 MW commercial geothermal power generation station. This would involve the drilling of "3 km deep directional wells in hot sedimentary aquifers or in hot, wet and fractured granite and the generation of electricity from +150°C hot water through binary cycle turbines with wastewater being recycled down injection wells".

Conventional hydrothermal systems may be unsuitable for Singapore due to the lack of sufficient hot water and steam resources at shallower depths. However, EMA is currently conducting a feasibility study of using advanced geothermal systems (AGS) to extract heat from hot and dry rock from deep underground using fracking or closed-loop system methods with minimal negative environmental and safety externalities.

Nanyang Technological University (NTU) has been collaborating with TUM Create and Surbana Jurong Group since October 2021 to study the rocks' elemental concentration and the temperature of the granites from deep boreholes in the northern and eastern regions like the Sembawang hot spring park and Pulau Tekong that have higher surface temperatures and are deemed to have geothermal potential[7]. Based on current heat extraction and utilisation technologies, it was assessed that drilling a 4km to 5km depth is considered somewhat viable, where the geothermal site could start having a temperature of 200 degrees Celsius or more (Ng, 2023b).

In assessing the feasibility of harnessing geothermal energy, EMA has several key considerations. The first is about technical feasibility i.e., is it technically feasible to map the underground within the territorial waters surrounding Singapore and if so, are there any specific regions of territorial space that the project should focus on? The second consideration is about trade-offs with respect to the extent of coverage i.e., should the project cover the whole of Singapore (including territorial waters and offshore islands) or only mainland Singapore, including the cost and time of conducting the appropriate geological surveys? The third consideration is about the need for invasive methods associated with the drilling of boreholes and lastly, besides geothermal potential, whether it is appropriate to also assess CO_2 storage potential and potential for deploying underground power plant infrastructure in the process (EMA, 2022c).

c) Nuclear

Given the geographical and geological limitations of scaling up renewables, nuclear power could be an attractive option to achieving net zero emissions in the power sector. A pre-feasibility study of the deployment of nuclear energy in Singapore conducted in 2012 concluded that nuclear energy technologies available then were not yet safe enough due to the small size and density of the city-state.

However, modern advances in nuclear technology such as small modular reactors (SMR), floating nuclear power plants (FNPP) and nuclear fusion development have since alleviated some of the safety, spatial and environmental concerns associated with conventional large reactor technologies. Despite their small size, SMRs can generate nearly 300 MW of electricity, about one-third of the generation capacity of conventional nuclear reactors (Igini, 2022). An FNPP can generate between 200 megawatts electrical (MWe) to 800Mwe which can easily power about 350,000 to 1.4 million HDB flats in Singapore for a year. The 2050 Energy Committee Report has assessed that nuclear energy could supply about 10% of Singapore's needs by 2050 (Ang, 2022a).

[7] https://www.ntu.edu.sg/erian/news-events/news/detail/singapore-digs-deep-to-unleash-geothermal-energy-potential

Although nuclear SMRs and FNPPs remain politically challenging to deploy in and around Singapore even with the additional safety mechanisms, almost 60% of 620 young people in Singapore surveyed in mid-2021 say Singapore should consider adopting nuclear energy as part of its energy mix and over 90% think insufficient attention has been given to nuclear energy by the government, schools and the media[8].

With other ASEAN countries such as Indonesia, the Philippines and Vietnam also announcing national nuclear energy ambitions or are carrying out feasibility studies, nuclear SMRs and FNPPs may also be instrumental to sustainable financing and transforming Singapore's competitive advantage from a fossil fuel importer/re-exporter to being a green-energy exporter and regional nuclear capacity building hub in the long-term.

A new multimillion-dollar research building at the National University of Singapore (NUS) will house about 100 researchers working on nuclear-related technology such as SMRs and dispersion of radioactive materials if there is an accident (Tan, 2024). In 2023, NTU announced a new research centre for nuclear fusion with France's Alternative Energies and Atomic Energy Commission, known as the Singapore Alliance with France for Fusion Energy[9].

d) Carbon Capture

Carbon capture utilisation and storage (CCUS) is currently still in its infancy phases for Singapore due to the lack of appropriate geological sites such as gas and oil fields for the permanent storage of CO_2 underground, which entails additional transport costs to suitable sites. In addition, a substantial amount of capital investment is needed for the extraction and conversion of carbon into fuel, as well as for plant maintenance (NCCS, 2020). Nevertheless, Singapore is aiming to realise at least 2 $MtCO_2e$ of carbon capture potential by 2030 as part of a broader effort to make its energy and chemicals sector more sustainable[10].

A national feasibility study on carbon capture at WTE plants is also currently being conducted (Hong, 2023b). The feasibility and development of a CO_2 liquefaction and storage facility is also explored, where existing cold energy from the production of liquefied natural gas (LNG) is utilised to liquefy CO_2, thereby directly capturing CO_2 which may otherwise be emitted into the atmosphere (Jaganathan, 2021).

2.4 Regional power grid

Singapore has a target of importing 4GW of low-carbon electricity by 2035, which will make up about 30% of Singapore's projected energy supply in the same year. According to AEC (2022), Singapore is projected to be the second-largest electricity importer in the region, sourcing around 11% on average of its electricity demand from neighbouring countries from 2025-2050.

Under the Lao PDR-Thailand-Malaysia-Singapore Power Integration Project (LTMS-PIP), Singapore is importing 100 MW of renewable hydropower from Laos through Thailand and Malaysia using existing interconnectors from June 2022 as a two-year pilot phase, with full-scale commercial operation to follow. EMA appointed YTL PowerSeraya as the importer for

[8] https://www.nuclearbusiness-platform.com/media/insights/insights/is-nuclear-power-singapores-best-bet-for-energy-independence
[9] https://www.ntu.edu.sg/erian/news-events/news/detail/ntu-deepens-research-and-academic-ties-with-france
[10] https://www.nccs.gov.sg/singapores-climate-action/mitigation-efforts/industry/#:~:text=By%202030%2C%20Singapore%20aims%20to,e%20of%20carbon%20capture%20potential.

a 100 MW trial from Peninsular Malaysia, whereby electricity will be supplied via the existing interconnector between Singapore and Peninsular Malaysia over a period of two years starting in 2024.

Singapore also intends to explore the development of offshore wind farms in Vietnam to export electricity to Singapore and has signed an agreement to import 1.2 GW of wind-powered electricity from Vietnam (Yong, 2023; Tan, 2023d). Singapore-based Vena Energy is aiming for a 2026 construction start for its 2 GW solar and battery project in Indonesia's Riau Islands. This project plans to export up to 2.5 TWh of electricity annually to Singapore when it is completed in phases by 2032 (Fogarty, 2023). 2 GW of solar PV-generated electricity is slated to be imported from five other firms in Indonesia by 2027 (Baharudin, 2023).

Singapore is also negotiating with Sarawak to import up to 1GW of hydropower-generated electricity via new submarine cable technology by 2032 (Saieed, 2023). Conditional approval has also been approved to import 1 GW of renewable energy annually from Cambodia after 2030 (Tan, 2023c). The Conditional Approvals that EMA has granted as of February 2024 are 1 GW from Cambodia, 2 GW from Indonesia and 1.2 GW from Vietnam[11].

In 2022, the Sun Cable Project was conceptualised to use a 4,200km-long power cable to export 1.75 GW of electricity from Australia to Singapore. Although it was expected to be ready by 2027, it is no longer deemed to be commercially viable at the time of writing (Ng, 2023a).

[11] https://www.ema.gov.sg/our-energy-story/energy-supply/regional-power-grids#:~:text=Large%2Dscale%20Electricity%20Imports,-In%20July%202022&text=The%20Conditional%20Approvals%20that%20EMA,low%2Dcarbon%20electricity%20by%202035.

3. SINGAPORE'S DOMESTIC ENERGY DEMAND TRENDS AND POLICY TARGETS

We now shift our attention to the demand aspect, with a particular focus on three important sectors: transport, industry, residential and commercial.

3.1 Transport

For transportation, one important aspect of the green transition lies in electric vehicles. Singapore currently has more than 6,500 registered electric cars, and close to 10,000 EVs including other vehicle classes. Hybrid and electric cars and taxis constituted about 12% of the total car and taxi population in 2022, which is a significant increase from their less than 1% share in 2012 (LTA, 2022). It is reported that with the deployment of 60 electric buses in 2020, the CO_2 tailpipe emissions from buses will decrease by approximately 7,840 tons annually.

The Land Transport Authority (LTA) has laid out several policies to promote mass electrification of private and public transport. LTA aims to install 12,000 EV charging points by 2025 and 60,000 by 2030. From 2025, there will be no new diesel car and taxi registrations and from 2030, all newly registered cars and taxis to be of cleaner energy models. Half of the bus fleet will be electrified by 2030 with the goal of achieving a 100% cleaner energy bus fleet by 2040[12]. As per the Vehicle Quota System (VQS), the car and motorcycle population growth rate will be maintained at 0% per annum while goods vehicles and buses will maintain a 0.25% population growth until 31 Jan 2025 (Ong, 2021). The ultimate goal would be to phase out all internal combustion engine (ICE) vehicles by 2040.

Tightened pollutant thresholds for the purchase of cleaner car models will be introduced from 2024 to 2025 under the enhanced Vehicular Emissions Scheme (VES). The Ministry of Transport also aims to achieve 75% mass public transport (i.e., rail and bus) modal share by 2030 and double the length of the railway network. Tightened emission limits of 4.5% carbon monoxide by volume and 7,800 ppm hydrocarbons (for 2-stroke engine) or 2,000 ppm HC (for 4-stroke engine) will also be introduced for local motorcycles registered before 1 July 2023[13].

By 2030, the Maritime Port Authority of Singapore (MPA) aims to reduce absolute emissions from the domestic harbour craft fleet by 15% from 2021 levels, through the adoption of lower-carbon energy solutions such as blended biofuel, LNG, diesel-electric hybrid propulsion, and full electric propulsion. By 2050, MPA aims for the harbour craft

[12] https://www.lta.gov.sg/content/ltagov/en/industry_innovations/technologies/electric_vehicles/our_ev_vision.html#:~:text=We%20have%20started%20by%20deploying,emissions%20of%201%2C700%20passenger%20cars.

[13] https://www.nea.gov.sg/media/news/news/index/in-use-emission-standards-for-older-motorcycles-and-noise-standards-for-all-vehicles-will-be-tightened-in-april-2023#:~:text=Tightened%20In%2Duse%20Emission%20Standards,-2%20On%206&text=Hence%20from%206%20April%202023,for%204%2Dstroke%20engine).

fleet to halve 2030-level emissions by transitioning to full-electric propulsion and net zero fuels.

3.2 Industry and services

Sectors in Singapore can be classified into 2 broad categories, mainly goods-producing industries (manufacturing, construction, utilities) and service- producing industries (food and beverage, real estate, wholesale trade, information and communication technologies, retail trade, professional services, administrative and support, transportation and storage, finance and insurance, accommodation). Within the manufacturing sector, key industry clusters include transport and precision engineering, electronics, biomedical and chemicals.

Carbon taxes are expected to influence the decisions of firms. The carbon tax, at S$5/t$CO_2$e, was introduced in 2019 through the Carbon Pricing Act (CPA), which is applied to all industrial facilities (manufacturing and manufacturing related services; supply of electricity, gas, steam, compressed air and chilled water for air-conditioning; and water supply and sewage and waste management) with an annual direct GHG emissions of 25,000 tCO_2e. It is slated to increase to S$25/t$CO_2$e in 2024 and 2025, S$45/tCO_2e in 2026 and 2027, with the goal of reaching S$50 to S$80/tCO_2e by 2030. New industrial facilities will have to meet minimum energy efficiency standards (MEES) of 0.67 kW/RT in their water-cooled chilled water systems from 2020 Q4 which will reduce their energy consumption by at least 245 GWh annually[14].

In Southeast Asia, Singapore has the largest data-centre market on a city basis, with around 917 MW of capacity in operation, and 209 MW either planned or under construction[15]. Singapore data centre market size is estimated at 0.88 GW in 2024 and possibly exceeding 1 GW, and is expected to reach 1.02 GW by 2029, growing at a CAGR of 2.89% from 2024-2029[16].

3.3 Residential and commercial

Finally, we turn to the residential and commercial sectors. To manage the use of household appliances, the National Environment Agency (NEA) tightened the Minimum Energy Performance Standards (MEPS) for air conditioners, refrigerators and clothes dryers based on coefficient of performance for air-conditioners and energy consumption for refrigerators and clothes dryers[17] in 2021.

For housing, a key aspect of the HDB Green Towns Programme[18] aims to reduce energy consumption in HDB towns by 15% (from 2020's levels) by 2030. This is done through the installation of more solar panels, smart LED lighting, Light Emitting Surfaces (LES) Block

[14] https://www.reach.gov.sg/Participate/Public-Consultation/National-Environment-Agency/Resource-Conservation-Department/Public-Consultation-on-the-Introduction-of-MEES-for-Water-cooled-Chilled-Water-Systems#:~:text=Minimum%20Energy%20Efficiency%20Standards%20(MEES),-9%20Unlike%20the&text=For%20chilled%20water%20temperature%20of,of%20the%20chilled%20water%20temperature.
[15] https://www.businesstimes.com.sg/startups-tech/startups/singapores-data-centre-market-surpass-1gw-milestone-challenges-ahead-cushman
[16] https://www.mordorintelligence.com/industry-reports/singapore-data-center-market
[17] https://www.nea.gov.sg/media/news/news/index/nea-to-enhance-minimum-energy-performance-standards-(meps)-for-refrigerators-clothes-dryers-and-air-conditioners
[18] https://www.hdb.gov.sg/about-us/our-role/smart-and-sustainable-living/Green-Towns-Progamme

Signages and retrofitting selected lifts with the Elevator Energy Regeneration System (EERS)[19].

The deployment of advanced electricity meters to facilitate real-time tracking and managing of energy usage in Singapore households is also gaining more traction. 650,000 smart electricity meters have been deployed islandwide and all 1.4 million residential households in Singapore are estimated to be equipped with smart meters over the next few years (NCCS, 2020). A smart meter trial in 2009 known as the Intelligent Energy System (IES) found an average reduction of overall electricity consumption of 2.4% and a 3.9% reduction in peak usage. This is a consequence of households being able to monitor household power consumption in real time with the implementation of time-of-use pricing[20].

Under the Building Construction Authority (BCA) Green Mark 2021, new and existing buildings will need to meet higher minimum energy efficiency levels and score sufficient points in the sustainability sections to be certified green. It targets greening 80% of Singapore's buildings by Gross Floor Area by 2030, 80% of new developments to be Super Low Energy buildings from 2030, and 80% improvement in energy efficiency to best-in-class green buildings by 2030[21]. Singapore has also made it easier for new buildings to get certified as green if new installations use electricity instead of gas connections for cooking (Hicks, 2023).

[19] The EERS converts energy generated from lift motions and braking operations into electrical energy to power other services within the lift such as lights and ventilation fans.
[20] https://www.siew.gov.sg/articles/detail/2010/08/01/singapore-smart-grid-city
[21] https://www1.bca.gov.sg/docs/default-source/docs-corp-news-and-publications/media-releases/bca-green-mark-2021-certification-scheme.pdf

4. REVIEW OF PAST CLIMATE MODELLING WORK FOR SINGAPORE

To benchmark our work, we now turn to past climate modelling work in the context of Singapore.

Based on 3 scenarios [Baseline (BAS), Business as Usual (BAU) and Alternative Policy Scenarios (APS)], Doshi and D'Souza (2013) found that Singapore can reduce its final energy consumption and energy intensity by around 12%–14% and CO_2 emissions by 19-22% in the BAU and APS scenarios from the BAS level by 2050. In the power sector by 2050, this assumes that existing OCGT generators are replaced by CCGT generators. Moreover, all new gas fired power plants commissioned from 2007 to 2030 are assumed to employ CCGT generators with higher overall efficiency of both gas-fired and oil-fired power plants. There is also higher solar PV share.

In the transport sector, the compound annual growth rates of diesel and gasoline fuel as well as electricity consumption of vehicles are modelled based on vehicle growth. In the residential and commercial sector, the electricity saving potential of using energy efficient appliances was estimated based on the Energy Labelling Scheme and reduction in electricity consumption of buildings under the BCA Green Mark Scheme. In the industrial sector, they estimated the energy savings potential of the Energy Efficiency National Partnership (EENP) programme, which is an industry-focused voluntary partnership programme for companies that wish to be more energy efficient.

Doshi and D'Souza (2013)'s assumptions in the power sector are similar to those of Loi (2019). Based on a BAU and 4 APS, Loi (2019) found that carbon abatement potential can reach 50 $MtCO_2e$ by 2020 under the most ambitious scenario. The demand of naphtha in the industrial sector is also accounted for, which is used as an intermediary fuel to produce petrochemicals for re-exporting purposes.

Based on 2 scenarios (BAU and Carbon-Neutral), APERC (2022) incorporated assumptions of gas-fired CCUS technologies, LTMS-PIP and Sun Cable project viability, greater increase of solar deployment, phasing out of coal, as well as SLNG import and LNG re-exports in the power sector. They also modelled energy and material efficiency measures, cleaner fuel substitution in the industrial and commercial sectors, as well as electrification and modal switching in the transport sector. They found that even the BAU scenario is more than sufficient for Singapore to achieve its previous NDC target of 65 $MtCO_2e$ by 2030 but will require additional offsets or sequestration to reduce its remaining emissions in 2050.

AEC (2022) modelled projections of energy demand and supply of the ASEAN region based on 3 scenarios (baseline, national and regional targets) from 2021 to 2050. In the case of Singapore, national targets pertaining to the improvement of industrial energy efficiency, reduction in energy intensity and consumption as well as achievement of 100% cleaner-energy public bus fleet and taxis by 2040 were modelled.

5. THE LEAP MODEL

Our model builds on the Low Emissions Analysis Platform (LEAP), a software system designed for assessing climate change mitigation and integrated energy planning. Developed by the Stockholm Environment Institute (SEI), the LEAP framework is a popular tool that is used by many countries in the assessment of GHG emissions.

In LEAP, we first inputted key assumptions pertaining to country demographics, extent of urbanisation, GDP, vehicle population, distance travelled by vehicle[22], value-added to GDP by sector etc. The base year is set at 1995, and the first scenario year[23] in 2023. For GDP in the baseline, we selected SSP2 which represents a "middle of the road" scenario where historical patterns of development are continued throughout the 21st century. Total final energy demand covers energy demands in four end-use sectors—industry, residential, transport and services.

Demand sectors typically rely on the top-down approach i.e., starting with aggregated energy consumption levels to model historical energy demand until the first scenario year, which is when the bottom-up approach takes over in calculating projected energy demand (and its corresponding emissions).

A direct growth constrain function can create a projected growth rate based on historical trends while filtering out very high growth rates in the data. For the goods producing industries and services sector, a top-down approach guided by an inverse growth constrain function was assumed to apply to the projection of energy intensities[24] and the projection of fuel shares from 2023-2022. The reasoning is that applying a direct growth constrain function to the growth of the manufacturing and services sectors would project a general decreasing trend in energy intensity based on historical trends. However, a general increasing trend may be more likely considering the government's vision to increase manufacturing value-add by 50% by 2030, for Singapore to become a global business, innovation, and talent hub for advanced manufacturing, as well as to grow the services sectors and anchor Singapore as a leading, vibrant hub for businesses, data centres, lifestyle and tourism.

Conversely, for the residential and transport sectors, a bottom-up approach i.e., starting with per capita energy consumption levels was used for the projection period. The projections based on the bottom-up approach are mainly driven by policy changes that affect either the composition of the disaggregated shares in the defined activity levels or the energy efficiencies of the defined technologies.

Calibration factors for fuels used in the transport and residential sectors were derived by setting the first scenario year (2023) to one year earlier. Subsequently, we divided the actual energy demand values by the projected values in that same year for each type of fuel in both sectors where necessary. The purpose of the calibration factors is to smoothen out the transition with regards to the energy consumption of each fuel by the corresponding demand sector from the historical period to the projection period since the methodologies and data used to calculate energy consumption in both periods may vary.

Within the residential sector, in the historical period, energy intensity was calculated based on the historical total energy consumption [natural gas, electricity and liquified petroleum gas (LPG)]

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[22] https://datamall.lta.gov.sg/content/datamall/en/search_datasets.html
[23] First year in which projections are made and when LEAP starts using process dispatch rules.
[24] The historical period taken into consideration with regards to the inverse growth constrain function for energy consumption in the goods producing industries and services sector starts from 2005-2022 for electricity, 2009-2021 for petroleum products and 2009-2022 for natural gas and coal and peat.

divided by the number of households. In the projection period, we disaggregate the residential sector into 4 main technologies, mainly: cooking, lighting, refrigeration and air-conditioning[25]. Each type of residential activity is then disaggregated by its corresponding fuel types. The projected energy demand can be calculated as the number of households multiplied by the shares of households using each type of technology for each activity and by SEI's estimated annual energy consumption per household for each type of activity for each fuel type.

Within the transport sector, we disaggregate it into the various modes of transport, mainly: road, rail and domestic shipping. For road transport, in the historical period, energy intensity was calculated based on the historical total energy consumption (diesel, natural gas and gasoline) divided by the total amount of passenger kilometres and freight tonne kilometres travelled annually. Passenger/freight kilometres of each type of transport are calculated based on the share of vehicle population multiplied by the annual vehicle mileage for that transport type and the passenger/freight vehicle loading factor[26] (vehicle capacity utilisation).

In the projection period, we further disaggregate road transport by vehicle type, mainly: cars and taxis, buses, motorcycles and goods and other vehicles (assumed to be light duty freight trucks), and these are further disaggregated into the various types of engine technology (petrol, diesel, CNG, petrol-CNG, electric hybrid[27], fully electric). Each mode of vehicle by fuel type is then further disaggregated into their respective VES bands from A1 to C2 where data is available. Vehicles belonging to A1 band are the "cleanest" on the road such as the more efficient fully electric vehicles while vehicles belonging to the C2 band are the most energy inefficient/emitting. There are only passenger rails in Singapore which are fully electrified. For electric hybrid cars and taxis, we disaggregate them into regular[28] and plug-in[29] hybrid instead.

Energy demand in the road and freight transport subsectors can be calculated as the shares of each vehicle type by type of fuel and by their corresponding VES bands, multiplied by their corresponding fuel economies (energy consumption per passenger/tonne-km travelled), the annual vehicle mileage and passenger/freight vehicle loading factor.

Within the industrial sector, we focus on goods-producing industries, mainly construction, manufacturing, utilities and other goods industries. Currently, we cannot further disaggregate the various types of energy consumption by each subsector within the manufacturing and services sector due to data unavailability. In both the historical and projection periods, energy intensity was calculated as the total energy consumption of each subsector by the value-added of industry/services to GDP.

For the transformation module, we focus on electric generation. We derived the yearly electricity peak load shape curve for Singapore using half-hourly system demand data[30] from EMA based on a total of 2016 time intervals (12 months/7 days of the week/24 hours). The load shape is specified by entering the percentage fraction of annual energy demand that occurs in each slice of the year. Hourly solar irradiation data from Renewables.ninja[31] was used to estimate the maximum fraction of hours that each electricity generation is available in each time slice and to derive the solar availability shape.

[25] There is a fifth category "Others" which we assume refer to household appliances such as water heater, washing machine and television.
[26] As derived from the International Council on Clean Transportation (ICCT).
[27] Can be petrol-electric or diesel-electric.
[28] Powered by both a petrol-fuelled internal combustion engine and a battery-powered electric motor that can work either independently or simultaneously.
[29] Powered chiefly by an electric motor and will only use its internal-combustion engine as a back-up should the electric motor's battery be depleted.
[30] https://www.ema.gov.sg/resources/statistics/half-hourly-system-demand-data
[31] https://www.renewables.ninja/

We inputted historical production, exogenous capacity and process efficiency values for natural gas OCGTs, CCGTs and diesel power plants which we assumed use steam turbines[32], as well as for coal and biomass cogeneration power plants, solar PV and WTE plants. Data was retrieved from the Singapore Energy Statistics (SES) by EMA as of 2023. Generally, the historical annual fuel mix proportions as reported in SES were multiplied by the total electricity production in the corresponding years[33] to estimate the historical production of the various processes. Annual fuel mix proportions for electricity generation from 1995-2004 pertaining to natural gas and petroleum products were estimated via backwards extrapolation based on their average annual growth rates between 2005-2022 and assumed to remain roughly constant between 1995-2005 for MSW[34].

To disaggregate the proportions of natural gas used to generate electricity into OCGT and CCGT, the ratios of the generation capacities of OCGT to CCGT were used in the corresponding years. The same method applies to WTE and solar PV generation capacities (starting from 2008) to disaggregate the proportions of MSW and solar used to generate electricity, which are classified under "Others" in the annual fuel mix. For generation capacity values from 1995-2004, because generation capacities of fossil fuel-based processes are unavailable, we had to approximate using the initial generation units' capacity information of each station from their industry license[35] prior to their commercial operation dates and assume that they remain constant over this period.

The generation capacity of Singapore's only coal-fired power plant known as the Tembusu Multi-Utilities Complex (TMUC) has a generation capacity of 133.5 MW and uses a mix of coal and biomass to produce electricity, generating an average of 588.9 GWh annually[36]. We assume a co-firing feedstock fuel ratio of 80% coal bituminous and 20% biomass in 2014 when the plant first opened, to 70% coal bituminous and 30% biomass in 2023[37].

EMA estimated that existing local generation has been observed to achieve 90% availability, which is defined as the amount of time that a generation process is able to provide electricity over a year, after accounting for planned and unplanned outages (EMA, 2022b). We assume that this applies to all generation processes, including electricity imports and the other cleaner and more renewable energy technologies without existing data on availability in each time slice.

We added two new fuels to the LEAP fuel database and their production plant modules. These fuels are hydrogen blend which is made from 70% natural gas and 30% hydrogen and low-carbon ammonia[38] which is made from 25% natural gas and 75% hydrogen as well as their associated chemical properties. Thereafter we added hydrogen and low-carbon ammonia power plants under the electricity generation module. We assume an initial co-firing feedstock fuel ratio of 30% hydrogen blend and 70% natural gas in 2026 when the Keppel Sakra Cogen Plant first opened. Process efficiencies of fuel combustion for hydrogen and low-carbon ammonia power generators are set at 65%[39] and 40% respectively (Sánchez et al., 2021).

Considering transmission losses for high voltage direct current (HVDC) cables of 12.9%, we estimate the "process efficiency" of electricity imports to be about 87% (DeSantis et al., 2021). WTE plants' historical emissions data were sourced from Singapore's Fifth National Communication and Fifth Biennial Update Report in various years and then divided by the estimated historical production in those years to obtain the environmental loading factor in terms of per unit of energy produced. According to the IPCC Guidelines, CO_2 emissions from waste

[32] The Tuas Steam Turbine Power Plant and Pulau Seraya Steam Turbine Power Plant are oil-fired plants, according to Power-technology.com.
[33] From CEIC Data: Electricity Generation: Annual: Singapore, series ID: 409116327.
[34] Proportions were adjusted to ensure that electricity generated by each fuel sums up to the total electricity production in each year.
[35] https://www.ema.gov.sg/regulations-licences/licences/industry-licences/licensees-directory
[36] https://www.mti.gov.sg/Newsroom/Parliamentary-Replies/2022/01/Written-reply-to-PQ-on-electricity-generation-of-coal
[37] https://sbr.com.sg/energy-offshore/exclusive/tuas-power-diversifies-business-singapores-energy-transition#:~:text=We%20have%20a%20plant%20which,in%20the%20years%20to%20come.
[38] While low-carbon ammonia is to be primarily imported to Singapore, we assume the possibility that it can be domestically synthesised by catalytic steam reforming of natural gas.
[39] https://www.twi-global.com/technical-knowledge/faqs/what-are-the-pros-and-cons-of-hydrogen-fuel-cells

incineration are estimated from the portion of waste that is fossil fuel based, thus biogenic CO_2 emissions are not considered along with methane and nitrous oxide emissions as they are dependent on waste volume (NEA, 2022). Because it is not possible to model imported renewable electricity directly for comparison purposes with the other power generation technologies, it is also included as a process module under electric generation.

Auxiliary fuel[40] electricity values for power generation technologies are based on the International Energy Agency (IEA) World Energy Balances 2020 values for Singapore and assumed to be allocated equally to all processes. The planning reserve margin[41] is set at 27% as per the required reserve margin set by Singapore's Ministry for Trade and Industry. IPCC Tier 1 default emission factors were used to approximate the average environmental loading factors in grams per unit of energy consumed based on the emissions generated from the combustion of feedstock and auxiliary fuels.

For goods producing industries and services, we inputted historical industrial-related energy consumption values for natural gas, petroleum products, coal and peat, and electricity from the SES. Due to a lack of information in the SES on the type of petroleum products consumed, we inferred the proportions of fuel oil, refinery gas, diesel, LPG and petroleum coke in goods producing industries based on energy consumption data on chemical and petrochemical industries[42] and other industries from IEA World Energy Balances (2020) for the same years and multiplied them by the aggregated data from SES. Likewise, we infer that the services sector use primarily LPG based on IEA World Energy Balances (2020).

For the residential sector, we updated historical energy consumption household values for natural gas, oil and electricity using data from SES. We inferred that oil consumption in the residential sector is referring to LPG consumption according to the United Nations databank[43]. Data from earlier years were sourced from IEA World Energy Balances where applicable. The percentages of households who use various technologies for cooking, lighting, refrigeration and air conditioning were also updated based on the Singapore Department of Statistics[44]. For cooking, based on the Singapore Department of Statistics regarding the town gas network, we assume that 62% of households use LPG-powered cookers[45] with the remaining using electric-powered cookers. The other activities are fully electrified.

For the transport sector, we inputted historical transport-related energy consumption values for natural gas, oil and electricity using data from SES. Similar to goods producing industries, due to a lack of information in the SES on the type of oil consumed, we inferred the proportions of gasoline and diesel for road transport from IEA World Energy Balances (2020) for the same years and multiplied them by the aggregated data from SES. Assuming that the SES aggregated coverage of fuel consumption for the transport sector includes domestic shipping for freight transport, we then subtracted diesel consumption in the domestic shipping sector as retrieved from IEA World Energy Balances (2020) for the same years, from this estimated aggregated diesel consumption to get a more accurate depiction of the diesel consumption for road transport.

We also obtained annual vehicle population statistics of cars, taxis, motorcycles, buses and light duty trucks by each fuel type between 2006-2022 from the Annual Vehicle Statistics by LTA[46] (LTA,

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[40] Energy use per unit of energy consumed or produced.
[41] Reserve margin refers to the percentage of generation capacity that needs to be kept on top of what the peak demand is. Also see: https://www.mti.gov.sg/Newsroom/Parliamentary-Replies/2022/11/Written-reply-to-PQ-on-Power-Generation-Capacity#:~:text=Over%20the%20last%205%20years,demand%20of%20around%207.8%20GW
[42] Because industrial-related sectors do not consume crude oil according to SES, we assume that the oil refining sector (which consumes crude oil) is not included here and is instead modelled under the transformation sector, using historical production, exogenous capacity and process efficiency values from IEA World Energy Balances (2020).
[43] http://data.un.org/Data.aspx?d=EDATA&f=cmID%3ALP%3BtrID%3A1231
[44] https://www.singstat.gov.sg/publications/households/household-expenditure-survey
[45] Note that this may not be entirely accurate as town gas also consists of other types of gases besides LPG such as natural gas. However, because the composition of town gas is currently unknown, we assume that it is primarily LPG that is used for cooking as LPG is a superior cooking fuel.
[46] https://datamall.lta.gov.sg/content/datamall/en/static-data.html

2022). Fuel economy data (in l/100km or m^3/km or Wh/km) for car, bus and light duty truck models are available from the LTA OneMotoring Fuel Cost Calculator[47] website. Generally, the average fuel economy was derived for each mode of vehicle by fuel type and its corresponding VES band using this dataset. If fuel economy data is unavailable for a particular fuel type for any mode of vehicle, we rely on general SEI estimates instead.

For electric hybrid cars and taxis, instead of categorising them by their VES bands, we categorised them according to whether they are regular electric hybrid or plug-in hybrid. Because only the fuel economy of the petrol/diesel component is available for regular electric hybrids, we assigned gasoline as their primary fuel. However, because both the fuel economy of the petrol/diesel component and electrical energy for plug-in electric hybrids are available, we assigned electricity as their primary fuel.

CNG cars and taxis are assumed to be 30% more efficient than their gasoline counterpart[48]. Fuel economy of petrol-CNG cars was derived from halving the average fuel consumption of SEAT Ibiza TGI and SEAT Leon TGI 5D & ST (two petrol-CNG models)[49]. Petrol-CNG buses and light duty trucks are also assumed to have half the sum of the energy intensity of gasoline buses/trucks and that of CNG buses/trucks. We conjecture that diesel-electric buses and light duty trucks have 25% lower energy intensity compared to diesel ICE ones (using diesel as the primary fuel) as electricity consumption data was unavailable (Byun and Choi, 2021).

In the historical period and in the projection period where data is unavailable, IPCC Tier 1 default emission factors were used to approximate the average environmental loading factors from fuel consumption in the goods producing industries, transport, services and residential sectors. To calculate the average environmental loading factor for each mode of vehicle by fuel type in the projection period of the transport sector, total annual loading was used, whereby the adopted emission factors (g/km) were multiplied by the corresponding passenger/freight tonne km which is independent of energy consumption.

For the transport sector (projections), CO_2 emission factors (g/km) were derived from the Fuel Cost Calculator dataset that are available for individual vehicle models and the LTA Vehicle Emission Schemes[50] website for hydrocarbon, carbon monoxide, nitrogen oxides and Particulate Matter (PM) 10 emission factors. The average CO_2 emission factors for each mode of vehicle by fuel type and their corresponding VES bands were then derived in the same way as we did for the fuel economy using the Fuel Cost Calculator dataset, and the average or minimum/maximum of the emission threshold for each VES band for the other types of pollutants were applied to cars and taxis irrespective of their fuel types. Interestingly, the dataset shows that electric cars even in the A1 band have assigned CO_2-equivalent emission factors even though EVs do not generate tailpipe emissions, which indicates that the upstream CO_2 emissions produced by electricity generation from fossil fuels could have been accounted for[51].

For vehicles which do not have direct estimates of emission factors for a particular pollutant, before relying on IPCC Tier 1 default emission factors, we attempted to refer to other countries' literature estimates such as from the WRI GHG Emission Factors Compilation or scientific articles (Clairotte et al., 2020; Lowell, 2012; Pratti et al., 2012; Seo et al., 2020; Xu et al., 2017)[52]. These estimates were adjusted based on annual mileage differences between Singapore and the country of reference where data is available. We assumed that Petrol-CNG buses and light duty trucks have

[47] https://vrl.lta.gov.sg/lta/vrl/action/pubfunc?ID=FuelCostCalculator
[48] https://apea.org.uk/fcev-vs-cng-vs-lng-vs-ev-which-is-the-right-future-fuel-for-you/
[49] https://www.seat.sg/company/easy-mobility-cars/future-today/move-and-green/tgi
[50] https://onemotoring.lta.gov.sg/content/onemotoring/home/buying/upfront-vehicle-costs/emissions-charges.html
[51] https://www.nea.gov.sg/media/news/news/index/enhanced-vehicular-emissions-scheme-to-be-extended-with-tightened-pollutant-thresholds#:~:text=%5B1%5D%20To%20account%20for%20the,hybrid%20electric%20vehicles%20(PHEVs).
[52] Gasoline hybrid emission factors were used for diesel-electric LDVs due to unavailable diesel hybrid emission factors. We assume that CNG trucks emit 15% less CO_2 than diesel trucks and that this is the case even for LDVs. Average concentration of CO_2, NOx, PM 2.5 emissions of hybrid buses is lower by 8%, 44% and 51% respectively compared to diesel buses. Tail-pipe CO_2 emissions from CNG buses are assumed to be 22% lower than CO_2 emissions from diesel buses.

half the emission factors of petrol and CNG buses/trucks combined. Emission factors of gasoline and electric motorcycles were derived from Sudmant et al. (2020).

For the domestic shipping sector, we assume that all vessels use diesel historically (Ju and Hargreaves, 2021). In Singapore, there are around 2,300 harbour craft (1,600 with engines) operating within Singapore waters, consisting of 11% tankers, 29% supply vessels, 7% passenger boats, 16% tugboat, and 37% others. A SP vessel travels 66.2 nautical miles (NM) in a 5-day period. Due to lack of data on vessel travel schedules, we assume that this is the distance travelled by all vessel types in a month, and that fuel consumption per NM travelled (energy intensity) is the same for all fuel types (Xiao, 2022). Because fuel consumption per distance varies according to vessel speed category, we obtained average values of the speed of each domestic vessel type[53] and matched them to the appropriate fuel consumption per distance values.

For future shipping fuels, we consider electric-hybrid, CNG, fully electric, biodiesel, methanol, very low sulphur fuel oil (VLSFO), green ammonia liquid and blended biofuel. Emission factors for domestic shipping are directly transferred from other foreign literature where data is available and only tank-to-propeller emissions are considered, assumed to be the same for all vessel types. Based on Liu, M. (2020), hybrid-fuelled ships have a lower GHG impact of about 18.6% compared to marine gasoline oil (equivalent to diesel).

Due to the lack of emission factor data for biofuels, we had to approximate by taking an average of SOx and PM reductions by 65% and an average net NOx increase by 119% (Zhou et al., 2020). For VLSFO, SOx and SO2 values for heavy fuel oil (HFO) are adjusted based on the fact that VLSFO has 7 times less sulphur content that HFO[54]. For blended biofuel, we refer to B24 daily assessment, which is made up of 24% used cooking oil methyl ester (UCOME), assumed to be biodiesel and 76% very-low sulphur fuel oil (VLSFO)[55].

[53] www.marinetraffic.com
[54] https://www.alfalaval.sg/industries/marine-and-transportation/marine/oil-treatment/fuel-line/marine-fuels-in-the-low-sulphur-era/#:~:text=Very%2Dlow%20sulphur%20fuel%20oil,Heavy%20fuel%20oil%2C%20max%203.50%25
[55] https://www.argusmedia.com/en/press-releases/2023/20230131-argus-launches-worlds-first-biofuel-blended-ship-bunker-price

6. LEAP SCENARIOS MODELLED

In our model, we have incorporated 4 scenarios. To begin with, we have the Baseline (BAS) scenario, which represents the case without any policies in place[56], except for the MEPS in the residential demand sector, vehicle growth policy in the transport demand sector and electricity imports via the LTMS-PIP in the power sector. Next, we have the Business-As-Usual (BAU) scenario which consists of selected existing policies and targets pertaining to the power generation, transport, industry and residential sectors. Finally, we have two Highly Ambitious (HA) scenarios which serve as an extension of the BAU scenario pertaining to the power sector in developing a more renewable energy portfolio in the future.

Exogenous capacities refer to capacity additions/subtractions of fuel transformation technologies which are specified externally and automatically added to the model without being determined by internal calculations or optimisation. By contrast, the endogenous capacities as specified to the model are situationally added to meet module requirements and maintain the planning reserve margin according to the built order of generation processes[57].

When each endogenously added process reaches its specified lifetime[58], it will be automatically retired (and additional processes added if necessary). All current policy targets pertaining to power generation under the BAU scenario are represented as exogenous capacity (Table 1). We also include mitigation impacts on emissions[59] and improvements in resource properties of fuel combustion where data is available.

The first HA scenario (HA1) assumes that the existing capacities of natural gas CCGTs remains the same until 2050. It then assumes that hydrogen-ready power generation capacity can grow linearly from 2026 and fully accommodate the planned capacities of the two new natural gas OCGTs to be built by 2025 and the existing capacities of CCGTs when they retire following a negative linear growth function by 2050. Oil-fired generators are also assumed to be retired in the same way by 2050. WTE plants are also expected to be gradually phased out after the construction of the IWMF in 2027, leaving only a generation capacity equivalent to the IWMF of 270 MW by 2050.

The share of coal burned in coal and biomass cogenerators is expected to be zero by 2050, which is equivalent to the Tembusu Multi-Utilities Complex being converted from a coal to fully biomass power plant. The generation capacity addition of the proposed low-carbon ammonia power plant in 2027 is also exogenously determined by taking the average of the estimated generation capacity of 55 MW and 65 MW (60 MW). The installed solar PV capacity target of 2 GW that is assumed to be attained by 2030 in the BAU is in turn assumed to grow linearly to its maximum technical potential of 8.6 GW in 2050.

Electricity imports of 335 MW from 2032 which is equivalent to the annual import amount from Indonesia's Riau Islands[60] plus 1/20 of the import target from Sarawak by 2032, 50 MW of

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[56] The state of development regarding certain features of the energy demand and supply sectors are expected to remain constant in all projected years in cases where growth rates/additions/subtractions etc. are not specified.
[57] See Table 1 for which policies are modelled under exogenous capacity and Table 2 for which policies are modelled under endogenous capacity.
[58] OCGTs and CCGTs have a 25-year lifespan and solar PV systems have a 40-year lifespan (https://www.ema.gov.sg/resources/faqs/solar/solar-installation-guide/how-long-will-a-solar-pv-system-last#:~:text=Solar%20PV%20systems%20are%20designed,of%205%20to%2012%20years). Nuclear and geothermal power plants are assumed to have a 60-year and 30-year lifespan respectively.
[59] With reference to 2020 CO_2 emissions data from fuel combustion by sector, sourced from the Greenhouse Gas Emissions from Energy by the International Energy Agency.
[60] Ideally assuming that transmission lines operate around-the-clock and that a year has 8760 hours (1 terawatt = 1,000,000 megawatts): 2.5 TWh/8760 * 1,000,000 ≈ 285 MW

geothermal generation capacity from 2032 which is equivalent to the generation capacity analysed by Oliver (2010), and 300 MW of nuclear plant capacity from 2032 which is equivalent to the maximum generation capacity of a SMR, are all modelled under endogenous capacity.

Regarding the second HA scenario (HA2), while fossil fuels are similarly intended to be phased out in the energy mix with lesser waste incineration in the future, one difference from HA1 is that HA2 does not automatically assume that existing and new natural gas OCGTs and CCGTs are displaced by hydrogen power generators by 2050. Instead, under endogenous capacity, we include 200 MW of hydrogen generation capacity addition from 2027 which is equivalent to 1/3 of the upcoming hydrogen-ready plant's generation capacity to be built by 2026 in the BAU. The 60 MW generation capacity addition of the proposed low-carbon ammonia power plant in 2027 is also endogenously determined.

330 MW of solar PV generation capacity addition is also modelled under endogenous capacity from 2031 which is equivalent to the average annual increase in annual generation capacity derived by dividing the difference between 8.6 GW and 2 GW by 20 years (2030-2050)[61]. These endogenous capacities (solar PV, hydrogen and low-carbon ammonia power generators) are added on top of the other endogenous capacities (geothermal and nuclear power generators as well as electricity imports) that are specified in HA1.

Suppose that, in HA2, all the available endogenous capacities of each technology have been added up in a given year e.g., 2035 but are still insufficient to meet the planning reserve margin at the minimum. As such, a further 330 MW of solar PV generation capacity will be added again, followed by 200 MW of hydrogen power generation capacity, 60 GW of low-carbon ammonia, 335 MW of imported electricity, 50 MW of geothermal, 300 MW of nuclear, and so on.

In the case of an earlier year e.g., 2030, because only endogenous capacity additions of hydrogen and low-carbon ammonia power generators are specified by that year, only the endogenous capacity additions of these 2 technologies will be added repeatedly until the reserve margin is at least equal to the planning reserve margin. The same also applies to HA1 less the endogenous capacity additions of solar PV, hydrogen and low-carbon ammonia power generators in any given year.

We specified that the electricity generation module can only produce 0.3% of electricity from diesel power plants annually starting in the first scenario year in BAS/BAU, which is consistent with the energy mix proportion for petroleum products reported in SES as of the first half of 2023. In HA1/HA2, we specified that this share of petroleum products in the fuel mix will be gradually reduced to zero by 2050. We assumed that all other power generation processes are of equal dispatch priority in all scenarios and thus are dispatched together in proportion to their available capacity starting in the first scenario year.

[61] Also see Table 3 for a summary of the comparison between HA1 and HA2 with regards to generation capacity changes.

Table 1

Sector	Processes	Exogenous policies modelled	Scenario
Power generation	WTE incineration plants	The Integrated Waste Management Facility (IWMF), built by 2027, has a generation capacity of 270 MW and is expected to result in savings of more than 200,000 tonnes of CO_2 annually.	BAU
		Existing WTE plants except the IWMF to be retired by 2050, retaining only the IWMF's generation capacity (270 MW).	
	Solar PV power plants	Increase solar energy deployment by five-fold to at least 2 GWp by 2030 with production of low-cost solar cells that have an efficiency of at least 30% from 2026.	BAU
		Deploy up to 8.6 GWp in Singapore by 2050.	HA1
	Natural gas OCGT and CCGT power plants	When the two OCGT generation units are operational in 2025, they can each produce 340 MW of electricity, with natural gas being the primary fuel. • Assuming that existing natural gas OCGT units are retired by 2025 due to exceeding their operational lifetime. New and repowered natural gas plants to be 10% more efficient in 2023 with the introduction of emission standards.	BAU
		Natural gas as a generation fuel to be phased out by 2050.	HA1; HA2
	Diesel power plants	Oil as a generation fuel to be phased out by 2050.	HA1; HA2
	Coal and biomass cogenerators	Feedstock fuel share[62] of 70% coal and 30% biomass from 2023 to 30% coal and 70% biomass by 2050.	BAU
		100% of feedstock fuel share being biomass by 2050.	HA1; HA2
	Electricity imports	100 MW of renewable hydropower to be imported from Laos from 2022.	BAS

[62] See Table 4.

	100 MW imported from Peninsular Malaysia over a period of two years starting in 2024. **From 2028, 2 GW of solar-generated renewable electricity imported from Indonesia.** **From 2033, 1.2 GW of wind-generated renewable energy imported from Vietnam.** **1 GW of renewable energy (mix of hydropower, solar and potentially wind power) imported from Cambodia, assumed to be from 2035.**	BAU
Hydrogen power plants	**The Keppel Sakra Cogen Plant, a CCGT hydrogen-compatible plant, will be ready by 2026 which can produce up to 600 MW of electricity. More energy-efficient technology at the Keppel Sakra Cogen power plant will lead to a reduction of 220,000 tonnes of CO_2 annually.** • Feedstock fuel share[63] will initially include 30% hydrogen blend and 70% natural gas. There will 50% hydrogen blend, 26.3% green hydrogen and 23.8% of natural gas by 2035. In 2050, the share of hydrogen blend will be reduced to 20%, with the addition of 70% green hydrogen into the mix and 10% being natural gas. • Amount of CO_2 emissions by power generation = 20.5 $MtCO_2e$ - Amount that hydrogen plant can abate from reduced usage of natural gas = 220,000/20,500,000 * 100	BAU
	• 50% hydrogen blend, 37.5% green hydrogen and 12.5% natural gas by 2035. 100% of feedstock fuel share being green hydrogen by 2050.	HA1; HA2
	• The two OCGT generation units built in 2025, including existing and upcoming natural gas OCGTs and CCGTs, will be retrofitted to be 100% hydrogen-compatible by 2050.	HA1
Low-carbon ammonia power plants	**60 MW power station built by 2027.**	HA1
CCUS	**2 $MtCO_2e$ of carbon capture potential by 2030 for power generation and WTE plants.** • Based on IEA (2022), the proportion of CO_2 emissions by power generation sector = 20.5/43.7 • Amount that CCUS can abate = 20.5/43.7 * 2 $MtCO_2e$ • Based on the share of electricity produced by type of generator in 2020: - % of emissions abated in natural gas OCGT: 1.496967394 * (20.5/43.7 * 2)/20.5)	BAU

[63] See Table 4.

	- % of emissions abated in natural gas CCGT: 86.13725029 * (20.5/43.7 * 2)/20.5) - % of emissions abated in oil power generators: 6.350468343 * (20.5/43.7 * 2)/20.5) - % of emissions abated in WTE plants: 2.135673481 * (20.5/43.7 * 2)/20.5) - % of emissions abated in coal and biomass cogeneration plant: 0.55720453 * (20.5/43.7 * 2)/20.5)	
Transport	**The car and motorcycle population growth rate will be maintained at 0% per annum, while goods vehicles and buses will maintain a 0.25% population growth, until Jan 31 in 2025.** • Between 2012-2025, total cars and taxis population could increase at an average of 0.2% annually and projected to 2050 based on this historical trend. • Between 2012-2025, total bus population could increase at an average of 0.5% annually and projected to 2050 based on this historical trend. • Between 2012-2025, total motorcycle population could increase at an average of 0.1% annually and projected to 2050 based on this historical trend[64]. • Between 2012-2025, total freight truck population could increase at an average of 0.05% annually and projected to 2050 based on this historical trend.	BAS
	LTA will electrify half of the bus fleet by 2030 and achieve a 100% cleaner energy bus fleet by 2040. • The projected electric bus population in 2030 is derived by halving the adjusted total bus projected population for that year (based on the annual 0.25% growth rate policy from 2022-2025). - The average electric bus population growth rate from 2023-2030 can then be derived via an exponential function and the electric bus populations for each year until 2030 estimated. - For the bus populations of other fuel types which constitute the other half of the adjusted total bus projected population in 2030, the projected petrol bus population in 2030 is assumed to be of the same proportion as the petrol bus population in 2022; the projected diesel-electric bus population in 2030 follows the calculation in the second part of the policy as detailed below; and the projected diesel bus population is the remainder.	BAU

[64] Because there is an overall net decrease in motorcycle population from 2012-2025, we adjusted the starting year to one with a motorcycle population that is lower than the projected motorcycle population in 2025 based on this vehicle growth rate policy.

- Assumed the composition of cleaner energy bus fleet by 2040 (e.g., 70% fully electric, 30% hybrid). The projected electric and diesel-electric bus population in 2040 is then derived using the adjusted total bus projected population for that year (based on the annual 0.25% growth rate policy from 2022-2025).
  - The average diesel-electric bus population growth rate from 2023-2040 can then be derived via an exponential function and the diesel-electric bus populations for each year until 2040 estimated.
  - The average electric bus population growth rate from 2030-2040 can then be derived via an exponential function and the electric bus population populations for each year until 2040 estimated.
- Petrol bus population will reach zero by 2040.
  - The average petrol bus population growth rate from 2030-2040 can then be derived via an exponential function and the petrol bus populations for each year until 2040 estimated.
- Diesel bus population will reach zero by 2040.
  - The average diesel bus population growth rate from 2030-2040 can then be derived via an exponential function and the diesel bus populations for each year until 2040 estimated.
- The percentage of each bus by fuel type is then computed via dividing their respective projected populations (as influenced by their historical growth rate and the electrification policy) by their total unadjusted population in each projected year (adjusted population = unadjusted population in 2030 and 2040).

Assumed the composition of bus fleet by 2050 will consist of only fully electric buses (diesel-electric bus population will reach zero by 2050).

- The projected fully electric bus population in 2050 is assumed to be equal to the adjusted total bus projected population for that year (taking into account the annual 0.25% growth rate policy from 2022-2025).
  - The average fully electric and diesel-electric bus population growth rates from 2040-2050 can then be derived via an exponential function and the fully electric and diesel-electric bus populations for each year until 2050 estimated.

HA1/HA2

• Similar computation of the percentage of each bus by fuel type in each projected year as in BAU.	
From 2025, no new diesel car and taxi registrations. From 2030, all newly registered cars and taxis to be of cleaner energy models (electric and hybrid). From 2040, all vehicles to be of cleaner energy models with the phasing out of ICE vehicles. • Between 2015 and 2022, gasoline car and taxi population decreased by an average of 0.6% annually and new annual registrations decreased by 9.1% annually. - Assumed that they continue to decrease at these rates from 2023-2030. - In 2030, under this policy, newly registered gasoline ICE cars and taxis become 0 and the new population is derived by subtracting the number of newly registered gasoline cars and taxis from the original projected population had the policy not been implemented. - Assumed an exponential function to derive the population growth from 2030-2040, where population becomes zero in 2040. • Between 2015 and 2022, diesel car and taxi population decreased by an average of 3.3% annually and new annual registrations decreased by 10.6% annually. - Assumed that they continue to decrease at these rates from 2023-2030. - In 2025, under this policy, newly registered diesel cars and taxis become 0 and the new population annually until 2030 is derived by subtracting the number of newly registered diesel cars and taxis from the original projected population had the policy not been implemented. - Assumed an exponential function to derive the population growth from 2030-2040, where population becomes zero in 2040. • Between 2015 and 2022, petrol-CNG car and taxi population decreased by an average of 11.9% annually. New annual registrations of petrol-CNG cars and taxis become 0 in 2022. - Assumed that petrol-CNG car and taxi population continues to decrease at this rate from 2023-2030.	BAU

- Assumed that newly registered petrol-CNG cars and taxis continue to be 0 from 2023-2030. Therefore, there is no need to subtract newly registered petrol-CNG cars and taxis from the original projected population.

- Assumed an exponential function to derive the population growth from 2030-2040, where population becomes zero in 2040.

- Assumed that the composition of car and taxi population consists of 50% electric hybrid and 50% fully electric by 2050[65].

    - The projected fully electric and electric hybrid car and taxi population in 2050 is derived by halving the adjusted total car and taxi projected population for that year (taking into account the annual 0% growth rate policy from 2022-2025).

    - The average electric hybrid and fully electric car and taxi population growth rate from 2023-2050 can then be derived via an exponential function and the electric hybrid and fully electric car and taxi populations for each year until 2050 estimated.

- The percentage of each car and taxi by fuel type is then computed via dividing their respective projected populations (as influenced by their historical growth rate and the registration policy) by the total unadjusted population in each projected year (adjusted population = unadjusted population in 2050).

- Assumed that the projected motorcycle population in 2040 consists of all electric motorcycles and zero petrol motorcycles.

    - Assumed an exponential function to derive the population growth of electric and petrol motorcycles from 2023-2040.

- Assumed a 70% electric share of light duty trucks and 30% hybrid by 2040 and using the projected population of trucks in 2040 to derive the populations of hybrid and electric trucks.

    - Assumed an exponential function to derive the population growth of hybrid, electric and ICE trucks from 2023-2040.

- The percentage of each motorcycle and freight truck by fuel type is then computed via dividing their respective projected populations (as influenced by their historical

[65] https://www.climateaction.org/news/50_of_singapores_cars_to_be_electric_by_2050

growth rate and the cleaner energy policy) by the total unadjusted population in each projected year (adjusted population = unadjusted population in 2040).	

Assumed that the composition of car and taxi population consists of 50% electric hybrid and 50% fully electric by 2040 and it will be 100% fully electric by 2050 (electric hybrid cars and taxis will reach zero by 2050).
 	
• The projected (unadjusted) fully electric and electric hybrid car and taxi population in 2040 is derived by halving the adjusted total car and taxi projected population for that year and is equal to the adjusted total car and taxi projected population in 2050 (taking into account the annual 0% growth rate policy from 2022-2025).
  - The average fully electric and electric hybrid car and taxi population growth rates from 2023-2040 and 2040-2050 can then be derived via exponential functions and the fully electric and electric hybrid car and taxi populations for each year until 2050 estimated.
• Similar computation of the percentage of each car and taxi by fuel type in each projected year as in BAU.
 	
Assumed the composition of light duty truck population by 2050 will consist of only fully electric light duty trucks (electric hybrid light duty truck population will reach zero by 2050).
 	
• The projected (unadjusted) fully electric light duty truck population in 2050 is assumed to be equal to the adjusted total light duty truck projected population for that year (taking into account the annual 0.25% growth rate policy from 2022-2025).
  - The average fully electric and electric hybrid light duty truck population growth rates from 2040-2050 can then be derived via an exponential function and the fully electric and electric hybrid light duty truck populations for each year until 2050 estimated.
• Similar computation of the percentage of each light duty truck by fuel type in each projected year as in BAU.
	HA1/HA2

Assumed that the CO_2 emission factor of all fully electric vehicles (upstream emissions) will be reduced to zero by 2050, coinciding with the phasing out of all fossil fuels for electricity generation.	HA1/HA2

	Cleaner fuels to be used by all types of domestic shipping vessels, from primarily diesel to only 25% diesel, 25% blended biofuel, 20% electric-hybrid and 5% fully electric, CNG, biodiesel, methanol, VLSDO and green ammonia liquid by 2030.	BAU
	Shares of cleaner fuels used by the domestic shipping fleet improved to 25% fully electric, biodiesel, methanol and green ammonia liquid, with the phasing out of diesel, electric-hybrid, CNG, VLSFO and blended biofuel by 2050.	HA1; HA2
Residential	**NEA enhanced Minimum Energy Performance Standards (MEPS) for refrigerators, clothes dryers and air-conditioners.** • Refrigerator with freezer is assumed to be > 300L to 900L as this is closer to the recommended volume for 4-room households in Singapore, which most residents live in: - Current MEPS: *AEC < [(465 + 1.378 x Vadj tot) x 0.506]*; Enhanced MEPS: *AEC < [(465 + 1.378x Vadj tot) x 0.427]* - Difference between current and enhanced MEPS taken as: 0.427/0.506 = 0.84 (this percentage is applied to the energy intensity of current refrigerators to derive the reduced energy intensity of efficient refrigerators), in effect from 2022 • Assuming casement/window air-conditioners: - Current MEPS: *COP100% ≥ 2.9*; Enhanced MEPS: *COP100% ≥ 3.78* - Difference between current and enhanced MEPS taken as: 2.9/3.78 = 0.77 (this percentage is applied to the energy intensity of current refrigerators to derive the reduced energy intensity of efficient refrigerators), in effect from 2022	BAS
	1.4 million residential households in Singapore estimated to be equipped with smart meters over the next few years to facilitate real-time tracking and managing of energy usage which may achieve an average reduction of overall electricity consumption of 2.4%. • In 2030, assuming a linear function, multiply the final energy intensities of efficient cooking, lighting, refrigeration and air-conditioning by 0.976 (assumed to apply to all households).	BAU

	Phasing out of LPG-powered gas cookers after 2030. All cookers to be electric-powered by 2050.	HA1/HA2

Goods producing industries/oil refining	**2 $MtCO_2e$ carbon capture potential by 2030 as part of a broader effort to improve sustainability of semiconductor plants and petrochemical processes.**
	
	• Based on IEA (2022), the proportion of CO_2 emissions by manufacturing industries and construction sector from fuel combustion in 2020 = 12.1/43.7
	• Amount that CCUS can abate in manufacturing industries = 12.1/43.7 * 2 $MtCO_2e$
	• Emissions from refinery gas consumption, which is the largest contributor to emissions out of all fuels in manufacturing industry in 2020 (calculated in LEAP): 11.3 $MtCO_2e$
	  - % of emissions that may be abated = (12.1/43.7 * 2)/11.3 * 100
	
	• Based on IEA (2022), the proportion of CO_2 emissions by petroleum refineries from fuel combustion in 2020 = 4.3/43.7
	• Amount that CCUS can abate in oil refining = 4.3/43.7 * 2
	• Emissions from refinery gas consumption, which is the largest contributor to emissions out of all fuels in oil refining in 2020 (calculated in LEAP): 3.6 $MtCO_2e$
	  - % of emissions that may be abated = (4.3/43.7 * 2)/3.6 * 100
		BAU

Table 2

Generation processes	Endogenous policies modelled	Scenario
Geothermal power plants	50 MW from 2032 [capacity addition as estimated by Oliver (2010)]	HA1; HA2
Nuclear power plants	300 MW from 2032 (equivalent to the maximum generation capacity of a SMR)	HA1; HA2
Hydrogen power plants	200 MW from 2027 (equivalent to 1/3 of the upcoming hydrogen-ready plant's generation capacity to be built by 2026)	HA2
Low-carbon ammonia power plants	60 MW from 2027 (equivalent to the average generation capacity of the proposed low-carbon ammonia plant to be built by 2027)	HA2
Electricity imports	335 MW from 2032 (equivalent to the annual import amount from Indonesia's Riau Islands plus 1/20 of the import target from Sarawak by 2032)	HA1; HA2
Solar PV power plants	330 MW from 2031 [equivalent to the average annual generation capacity derived by dividing the difference between 8.6 GW and 2 GW by 20 years (2030-2050)]	HA2

Table 3

Generation processes	HA1	HA2
Natural gas OCGT and CCGT power plants	To be phased out by 2050 (exogenous)	To be phased out by 2050 (exogenous)
Diesel power plants	To be phased out by 2050 (exogenous)	To be phased out by 2050 (exogenous)
WTE incineration plants	270 MW remaining by 2050 (exogenous)	270 MW remaining by 2050 (exogenous)
Nuclear power plants	300 MW from 2032 (endogenous)	300 MW from 2032 (endogenous)
Geothermal power plants	50 MW from 2032 (endogenous)	50 MW from 2032 (endogenous)
Electricity imports	335 MW from 2032 (endogenous)	335 MW from 2032 (endogenous)
Solar PV power plants	8.6 GW by 2050 (exogenous)	330 MW from 2031 (endogenous)
Hydrogen power plants	Increases from 600 MW in 2026 to accommodate the total combined capacities of new and existing natural gas OCGT and CCGT by 2050 (exogenous)	200 MW from 2027 (endogenous)
Low-carbon ammonia power plants	60 MW from 2027 (exogenous)	60 MW from 2027 (endogenous)

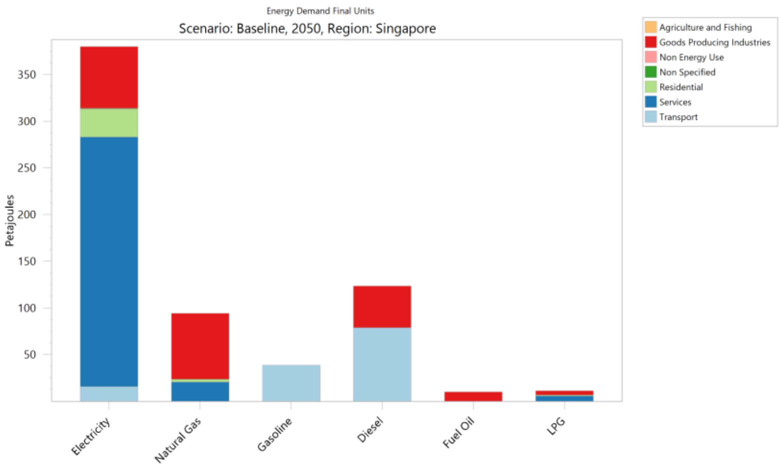
Table 4

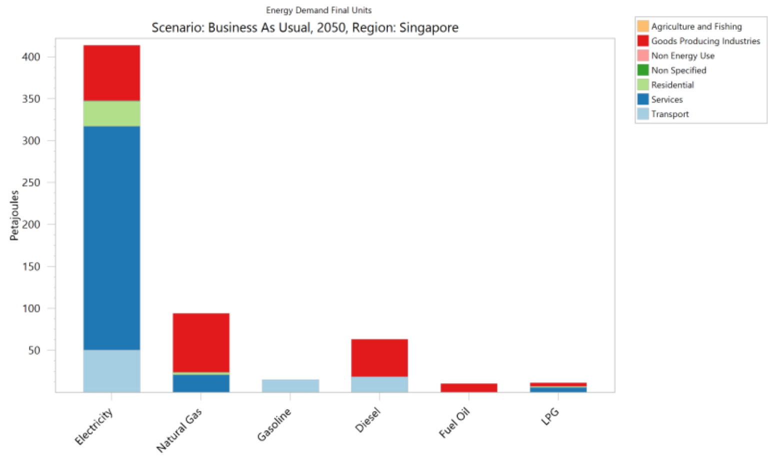
Generation process	Year	Fuel consumed in hydrogen PP for electricity generation	Feedstock fuel share for electricity generation (BAU)	Feedstock fuel share for electricity generation (HA1 and HA2)
Hydrogen power plants	2026	Natural gas	70%	70%
		Hydrogen blend (30% hydrogen + 70% natural gas)	30%	30%
		Hydrogen	0%	0%
	2035	Natural gas	23.8%	12.5%
		Hydrogen blend (30% hydrogen + 70% natural gas)	50%	50%
		Hydrogen	26.3%	37.5%
	2050	Natural gas	10%	0%
		Hydrogen blend (30% hydrogen + 70% natural gas)	20%	0%
		Hydrogen	70%	100%
Coal and biomass cogenerators	2014	Coal	80%	80%
		Biomass	20%	20%
	2023	Coal	70%	70%
		Biomass	30%	30%
	2050	Coal	30%	0%
		Biomass	70%	100%

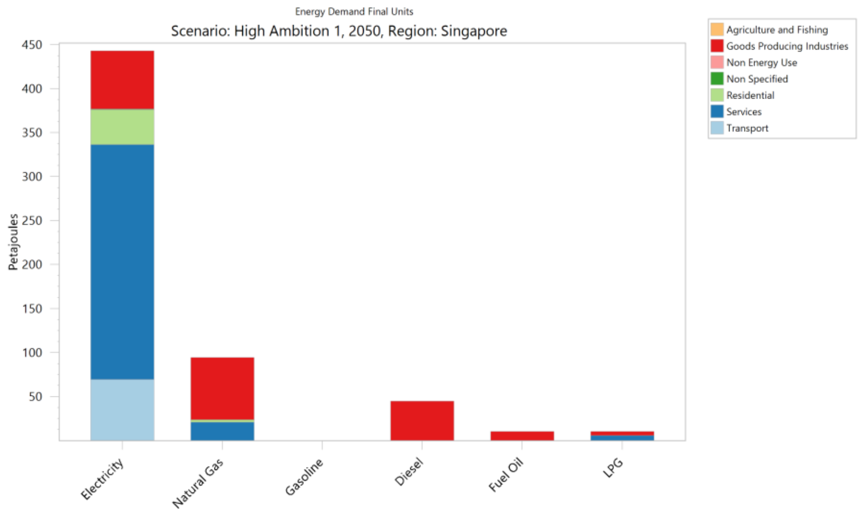
7. RESULTS AND ANALYSIS

In this section, we present and compare our simulation results of the BAS, BAU and the two HA scenarios.

7.1 Final energy demand







First, we focus on energy demand in the domestic sectors. In the BAS scenario, Singapore's total final energy demand in the domestic sectors is projected to grow from 1034.7 PJ in 2024, reaching 1497.3 PJ in 2050. In 2050, within the energy use sectors, goods producing industries (manufacturing) continue to demand the most energy overall (466.1 PJ), followed by services (293.4 PJ), transport (133.2 PJ) and residential (34.4 PJ). Services may be expected to overtake transport in terms of energy demand starting from 2028.

In the BAU scenario, energy demand is projected to reach 1447.6 PJ in 2050. This is higher than APERC (2022)'s estimate of about 1000 PJ in their BAU-equivalent scenario. Total electricity demand of all demand sectors grows at an average annual rate of 2.7%, reaching 413.7 PJ (114.9 TWh) in 2050. Services may be expected to overtake transport in terms of energy demand starting from 2027.

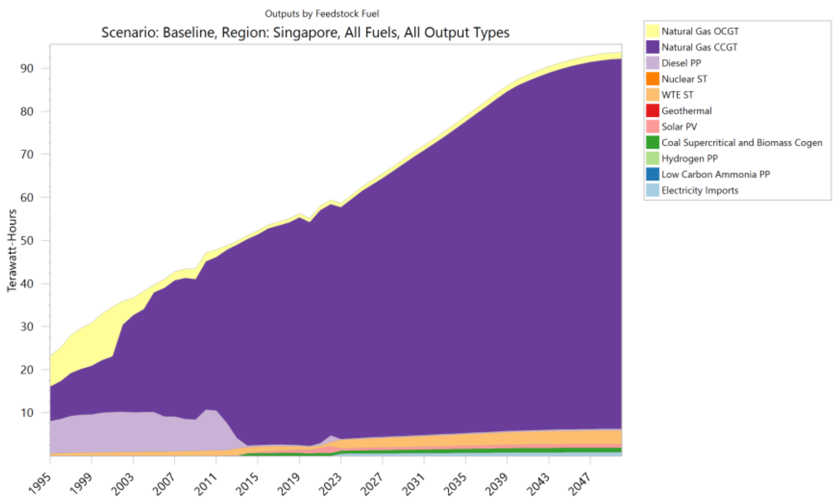
For the projected years, net energy demand reduction of the transport sector in BAU relative to BAS cumulatively amount to 1005.8 PJ, which translates to an average annual 28.8% improvement in energy efficiency. In 2050, road transport (cars and taxis, motorcycles, buses and light duty trucks) in BAU has an overall net lower energy demand of 47.9 PJ compared to BAS, where electricity demand is higher by 34.4 PJ but demand for gasoline, diesel and CNG are lower by 23.8 PJ, 58.4 PJ and 0.1 PJ respectively.

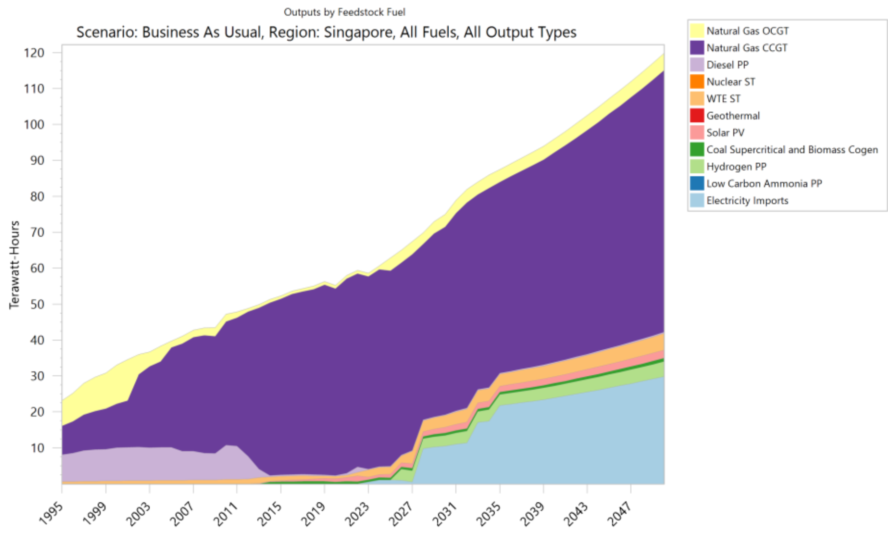
For the projected years, net energy demand reduction of the transport sector in HA1/HA2 relative to BAU cumulatively amount to 161.9 PJ, which translates to an average annual 7.1% improvement in energy efficiency. In 2050, road transport in HA1/HA2 has an overall net lower energy demand of 13 PJ compared to BAU, where electricity demand is higher by 18.9 PJ but demand for gasoline and diesel are lower by 14.9 PJ and 17 PJ respectively.

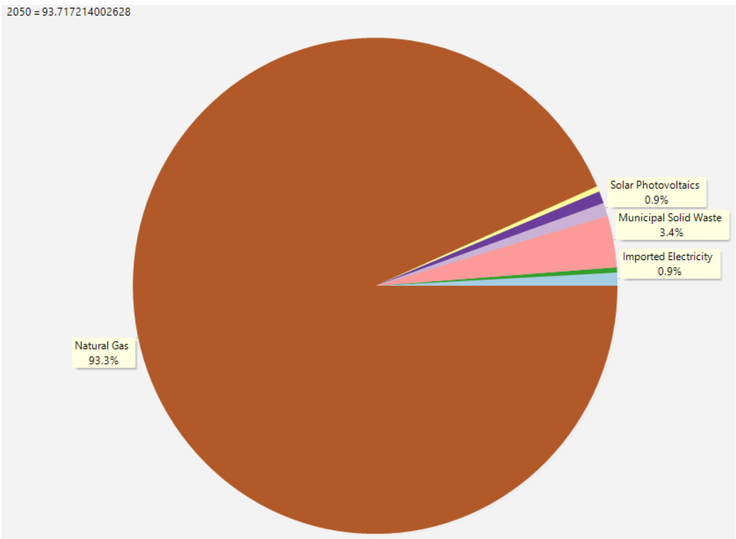
In the domestic shipping sector, when HA1/HA2 is compared to BAU in 2050, there is a reduction of 1.5 PJ in the demand for diesel, a reduction of 0.06 PJ each for VLSFO and CNG, and a 0.3 PJ decrease in the demand for blended biofuel. However, there is an increase of 0.1 PJ each in the demand for methanol and green ammonia liquid, and an increase of 0.2-0.3 PJ each in the demand for biodiesel and electricity.

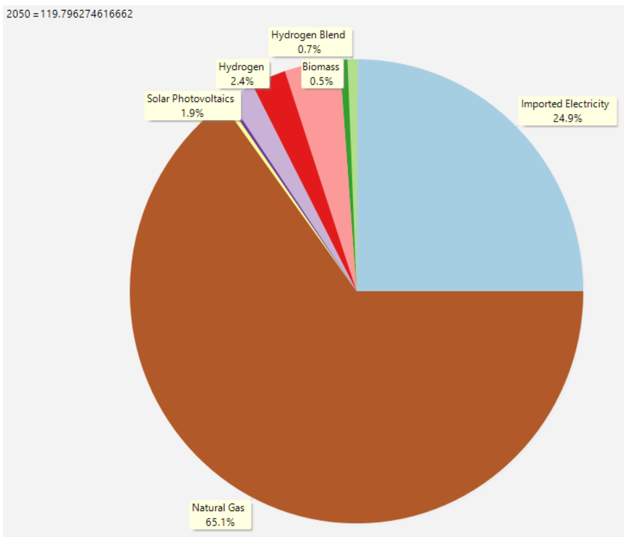
For the projected years, net energy demand reduction of the residential sector in BAU relative to BAS cumulatively amount to 15.8 PJ, which translates to an average annual 1.7% improvement in energy efficiency. However, there is an increase in net energy demand of 13.8% annually between 2031-2050 in HA1/HA2 relative to BAU. When HA1/HA2 is compared to BAU in 2050, there is a reduction of 1.1 PJ in the demand for LPG but an increase of 10 PJ in the demand for electricity.

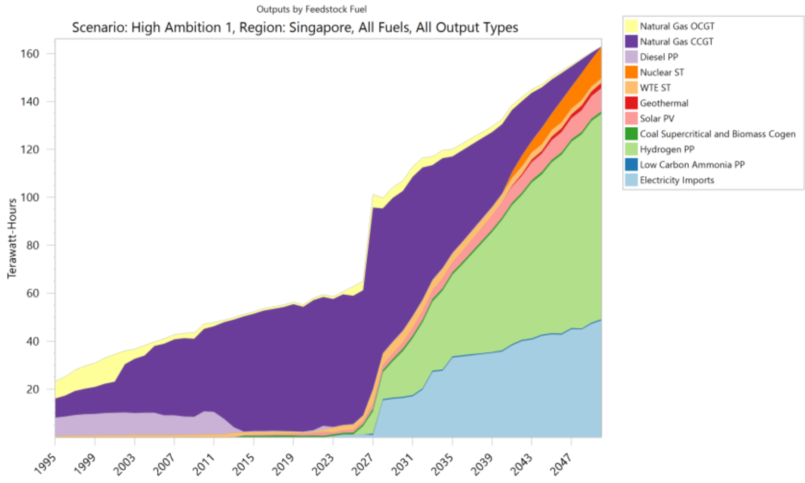
7.2 Share of electricity generation by technology

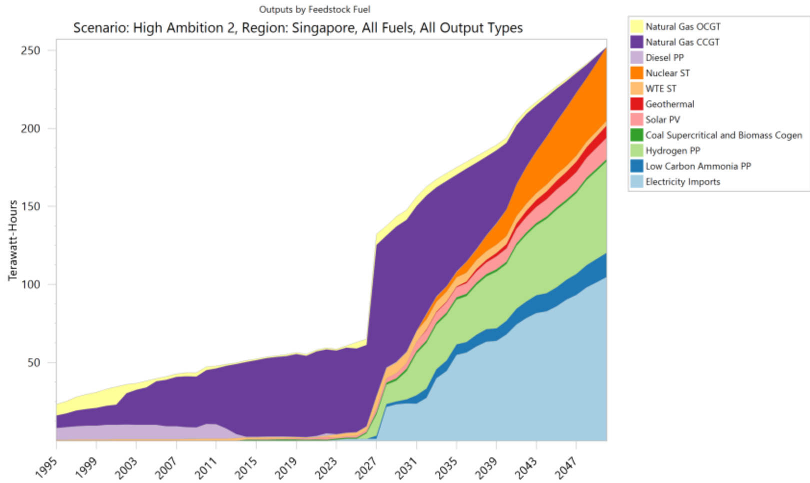


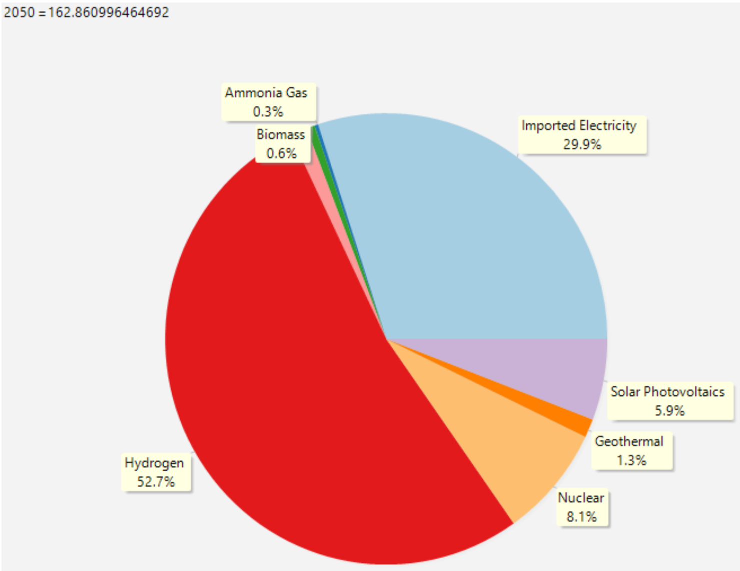


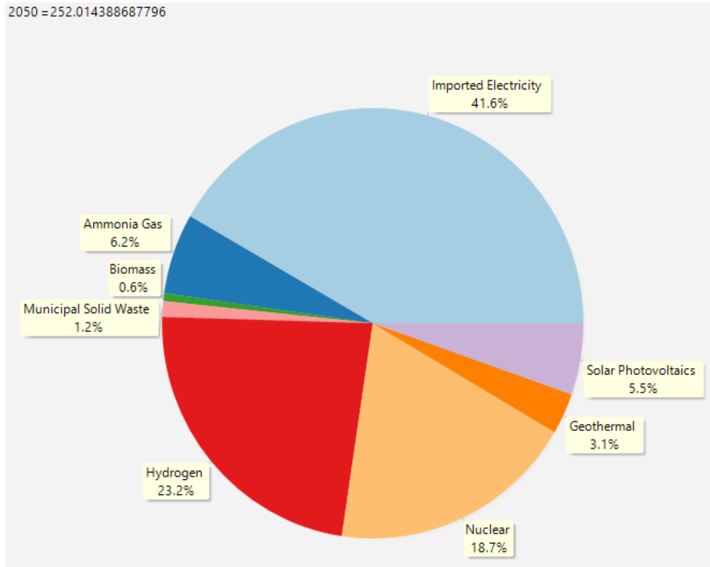





Outputs by Feedstock Fuel
Scenario: High Ambition 1, Region: Singapore, All Fuels, All Output Types
Terawatt-Hours
Natural Gas OCGT
Natural Gas CCGT
Diesel PP
Nuclear ST
WTE ST
Geothermal
Solar PV
Coal Supercritical and Biomass Cogen
Hydrogen PP
Low Carbon Ammonia PP
Electricity Imports


Outputs by Feedstock Fuel
Scenario: High Ambition 2, Region: Singapore, All Fuels, All Output Types
Terawatt-Hours
Natural Gas OCGT
Natural Gas CCGT
Diesel PP
Nuclear ST
WTE ST
Geothermal
Solar PV
Coal Supercritical and Biomass Cogen
Hydrogen PP
Low Carbon Ammonia PP
Electricity Imports


2050 = 162.860996464692
Ammonia Gas 0.3%
Biomass 0.6%
Imported Electricity 29.9%
Solar Photovoltaics 5.9%
Geothermal 1.3%
Nuclear 8.1%
Hydrogen 52.7%


2050 = 252.014388687796
Imported Electricity 41.6%
Ammonia Gas 6.2%
Biomass 0.6%
Municipal Solid Waste 1.2%
Solar Photovoltaics 5.5%
Geothermal 3.1%
Hydrogen 23.2%
Nuclear 18.7%

Next, we move on to the share of electricity generation by technology. In the BAS scenario, power generation is projected to increase to 93.7 TWh in 2050. In the BAU scenario, power generation is projected to increase to 119.8 TWh by 2050. In the HA1 and HA2 scenarios, power generation is projected to increase to 162.9 TWh and 252 TWh respectively in 2050. These estimates are higher than that of APERC (2022), with their estimate of 80 TWh in 2050 in both their BAU and Carbon-Neutral scenarios, and also higher than that of Loi (2019)'s estimates of about 90 TWh in two of their alternative policy scenarios.

In the BAU scenario, natural gas OCGTs and CCGTs also constitute the dominant share of electricity generation in 2050 but only at 64.7% compared to 93.3% in the BAS scenario. In 2050, imported renewable electricity constitutes 24.9%, oil power generators at 0.3%, WTE plants at 3.8%, coal and biomass cogeneration at 0.8%, hydrogen power generators at 3.5% and solar PV at 1.9%.

Under BAU, we would expect to see a future where Singapore's energy portfolio is still dominated by natural gas in 2050. The reserve margin is above the planning reserve margin of 27% between 2023-2041. However, it is below the planning reserve margin between 2042-2050 and falls to 5% in 2050, indicating that energy security is compromised in the later projected years. The reserve margin is 40.4% in 2025, which is slightly higher than EMA's upper bound projection of 32% in the same year. From 2022-2032, due to the growth of data centres, population changes, temperature and GDP growth rates etc., EMA projects the annual system demand[66] and system peak demand to grow at a CAGR between 2.8-3.2% from 2022-2032 (EMA, 2021). In the BAU scenario, electricity generation grows at an average annual rate of 3.3% over the same period, which is similar to EMA's projection.

In the HA1 scenario, the combined electricity generated by hydrogen-compatible and low-carbon ammonia power plants increases at an average annual rate of 16.3%, constituting the dominant share of electricity generation at 86.2 TWh (52.9%) in 2050. Imported renewable electricity increases at an average annual rate of 69.2%, constituting 27.7% of Singapore's projected energy supply in 2035 and reaching 48.7 TWh in 2050, constituting 29.9% share. Solar PV-generated electricity increases at an average annual rate of 10.9%, meeting around 3.5% of total electricity demand in 2030 and reaching 9.6 TWh in 2050, constituting 5.9% share.

After the two new replacement OCGT units are built in 2025, natural gas-generated electricity decreases at an average annual rate of 20.3% and is phased out in 2050. Oil-generated electricity decreases at an average annual rate of 7.1% and is phased out in 2050. WTE-generated electricity increases at an average annual rate of 2.3%, reaching 2 TWh in 2050, constituting 1.2% share. Coal- and biomass-generated electricity[67] increases at an average annual rate of 1.7%, reaching 1 TWh in 2050, constituting 0.6% share. Nuclear-generated electricity increases at an average annual rate of 24.4%, reaching 13.2 TWh in 2050, constituting 8.1% share. Geothermal-generated electricity increases at an average annual rate of 24.7%, reaching 2.2 TWh in 2050, constituting 1.3% share.

Under HA1, we would expect to see a future where Singapore's energy portfolio is dominated by low-carbon hydrogen in 2050. Except for 2026 and 2027, the reserve margin is expected to remain nearly equal to or above the planning reserve margin of 27% throughout the other projection years.

In the HA2 scenario, the combined electricity generated by hydrogen-compatible and low-carbon ammonia power plants increases at an average annual rate of 29%, constituting 73.9 TWh (29.3%) in 2050. Imported electricity increases at an average annual rate of 77.9%, constituting 31.4% of Singapore's projected energy supply in 2035 and reaching 104.8 TWh (41.6%) in 2050. Solar PV-generated electricity increases at an average annual rate of 13.4%, meeting 5.1% of projected total electricity demand in 2030 and reaching 13.8 TWh (5.5%) in 2050.

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[66] System demand refers to gross electricity generation required to meet electricity consumed by all consumers.
[67] Note that by 2050 in both HA1 and HA2, the coal and biomass cogeneration plants will only be using biomass as feedstock fuel.

After the two new replacement OCGT units are built in 2025, natural gas-generated electricity decreases at an average annual rate of 15.8% and is phased out in 2050. Oil-generated electricity decreases at an average annual rate of 4.8% and is phased out in 2050. WTE--generated electricity increases at an average annual rate of 5.5%, reaching 3 TWh (1.2%) in 2050. Coal- and biomass-generated electricity increases at an average annual rate of 3.9%, reaching 1.5 TWh in 2050, constituting 0.6% share. Nuclear-generated electricity increases at an average annual rate of 17.8%, reaching 47.2 TWh (18.7%) in 2050. Geothermal-generated electricity increases at an average annual rate of 17.8%, reaching 7.9 TWh (3.1%) in 2050.

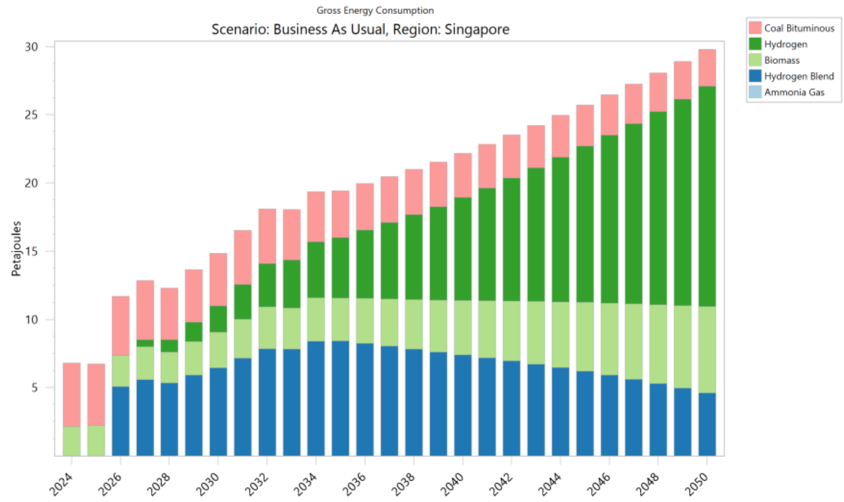
Under HA2, we would expect to see a future where Singapore's energy portfolio is diversified in cleaner energy sources in 2050. Except for 2026, the reserve margin is expected to remain nearly equal to or above the planning reserve margin of 27% throughout the other projection years.

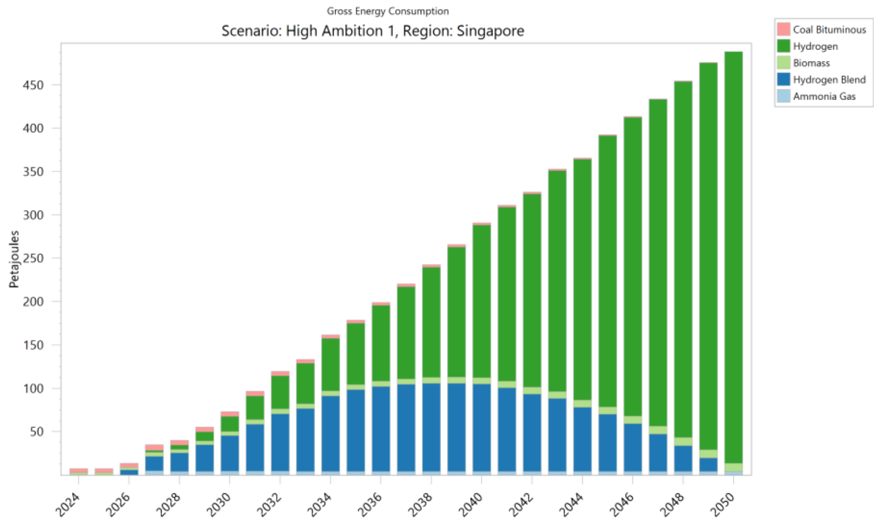
In HA1 scenario, hydrogen-compatible with low-carbon ammonia power generators, imported electricity and solar PV can supply about 70.1%, 39.6% and 7.8% of Singapore's energy needs respectively by 2050. Moreover, nuclear and geothermal power generators can supply about 10.7% and 1.8% of Singapore's energy needs respectively by 2050.

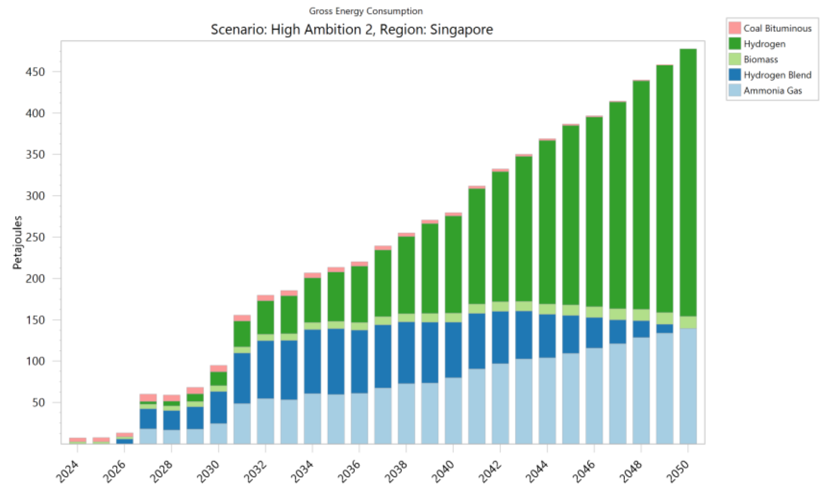
In the HA2 scenario, hydrogen-compatible with low-carbon ammonia power generators, imported electricity and solar PV can supply about 60.1%, 85.2% and 11.2% of Singapore's energy needs respectively by 2050. Moreover, nuclear and geothermal power generators can supply about 38.4% and 6.4% of Singapore's energy needs respectively by 2050.

The amount of electricity that needs to be generated in BAU in 2032 (81.9 TWh) is similar to EMA's projected value in that same year (79.5 TWh). However, the amount of electricity that needs to be generated in HA1 and HA2 in 2032 (116.5 TWh and 162.6 TWh) exceeds this projection (EMA, 2021).

7.3 Fuel consumption in the power sector







We then analyse the consumption of hydrogen and its derivatives, as well as coal and biomass over time in the power sector. In the BAU scenario, the amount of hydrogen blend consumed initially starts out at 5.1 PJ in 2026, increases to a peak of 8.4 PJ in 2035 (average annual increase of 5.9%) and decreases to 4.6 PJ in 2050 (average annual decrease of 3.9%). The amount of hydrogen consumed starts out at 0.5 PJ in 2027 and increases to 16.2 PJ in 2050 (average annual increase of 17.4%).

There is a net decrease in the amount of coal consumed from 4.7 PJ in 2024 to 2.7 PJ in 2050 (average annual decrease of 1.9%). There is a net increase in the amount of biomass consumed from 2.1 PJ in 2024 to 6.3 PJ in 2050 (average annual increase of 4.4%).

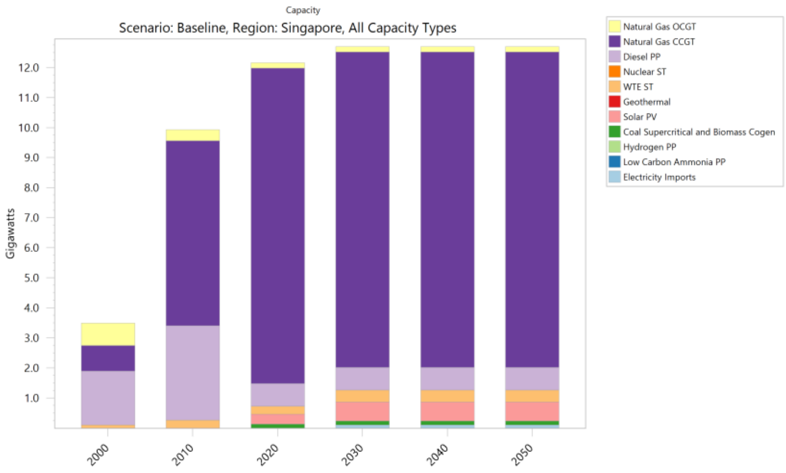
In the HA1 scenario, the amount of hydrogen blend consumed initially increases from 5.8 PJ in 2026 to a peak of 101.7 PJ in 2038 (average annual increase of 32.8%) and then decreases over time to being phased out in 2050 (average annual decrease of 14.4%). The amount of hydrogen consumed starts out at 2.2 PJ in 2027 and increases to 474.9 PJ in 2050 (average annual increase of 29.5%). The amount of low-carbon ammonia consumed starts at 4.7 PJ in 2027, exhibits a fluctuating trend and reaches 4 PJ in 2050 (net average annual decrease of 0.7%).

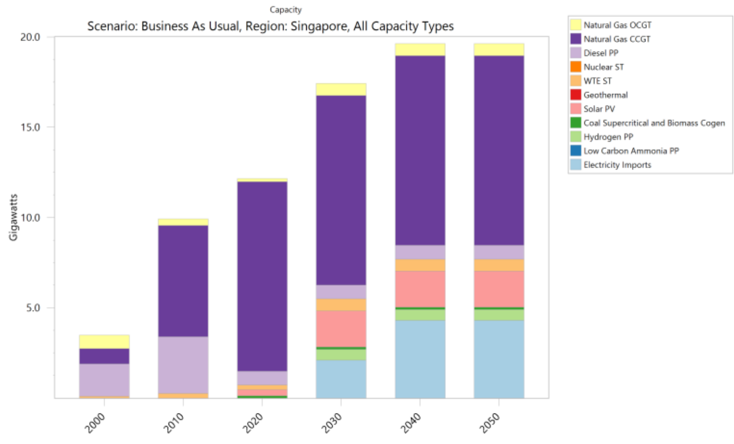
There is a net decrease in the amount of coal consumed from 4.9 PJ in 2024 to being phased out in 2050 (average annual decrease of 9.4%). There is a net increase in the amount of biomass consumed from 2.4 PJ in 2024 to 9.5 PJ in 2050 (average annual increase of 6.4%).

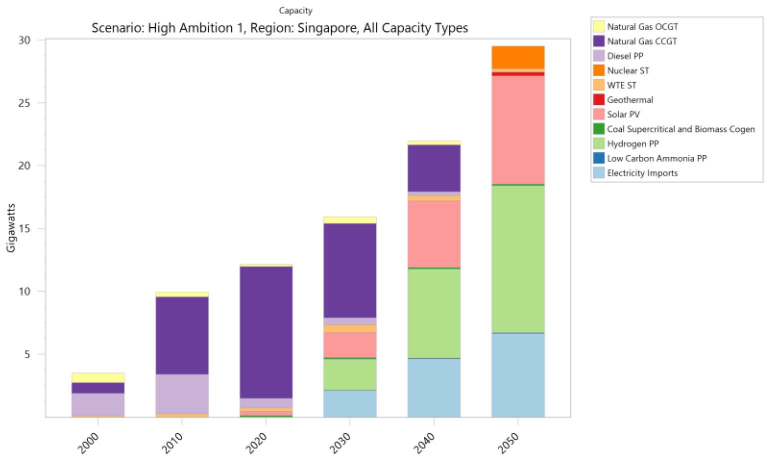
In the HA2 scenario, the amount of hydrogen blend consumed initially increases to a peak of 79.6 PJ in 2035 (average annual increase of 50.9%), before decreasing over time to be phased out in 2050 (average annual decrease of 12.3%). The amount of hydrogen consumed starts out at 3.1 PJ in 2027 and increases to 323.5 PJ in 2050 (average annual increase of 24.5%). The amount of low-carbon ammonia consumed starts out at 18.2 PJ in 2027, exhibits a general increasing trend and reaches 139.5 PJ in 2050 (net average annual increase of 10.6%).

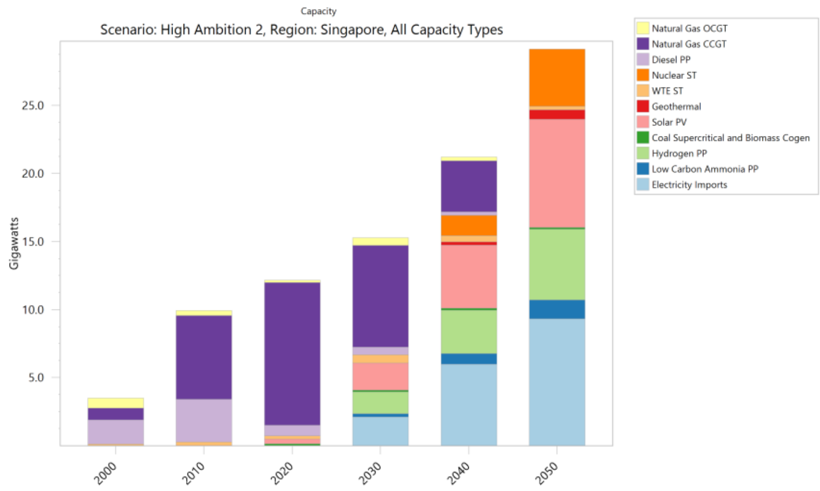
There is a net decrease in the amount of coal consumed from 4.9 PJ in 2024 to being phased out in 2050 (average annual decrease of 7.3%). There is a net increase in the amount of biomass consumed from 2.4 PJ in 2024 to 14.6 PJ in 2050 (average annual increase of 8.7%).

7.4 Share of installed generation capacity by technology (overall)









We then analyse the share of overall installed generation capacity by technology. In the BAS scenario, total generation capacity increases from 3.5 GW in 1995 to 12.7 GW in 2050. Generation capacities of natural gas OCGT and CCGT amount to 10.7 GW, diesel power plants at 0.8 GW, WTE plants at 0.4 GW, coal and biomass cogeneration power plants at 0.13 GW, solar PV at 0.6 GW and imported electricity at 0.10 GW in 2050.

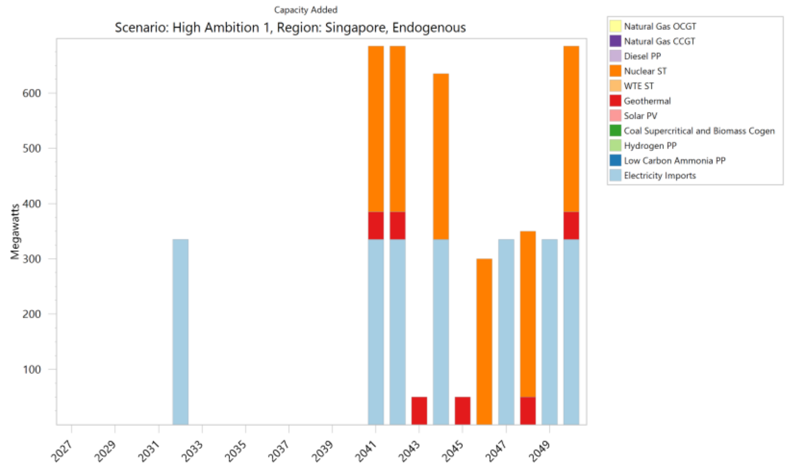
In the BAU scenario, total generation capacity increases to 19.6 GW in 2050. This is slightly higher than APERC (2022)'s estimate of 17 GW for their BAU scenario in 2050. Generation capacities of natural gas OCGT and CCGT amount to 11.2 GW, diesel power plants at 0.8 GW, WTE power plants at 0.7 GW, coal and biomass cogeneration power plants at 0.13 GW, solar PV at 2 GW, hydrogen power plants at 0.6 GW and imported electricity at 4.3 GW in 2050.

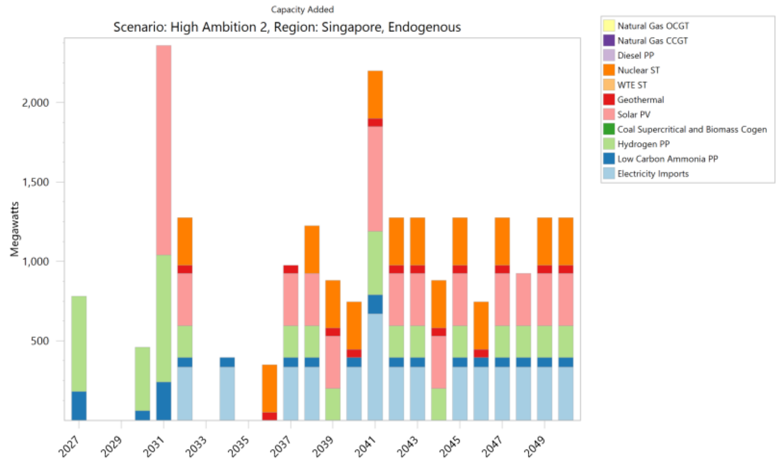
In the HA1 scenario, total generation capacity increases to 29.5 GW in 2050. This is higher than APERC (2022)'s estimate of 21 GW total generation capacity in 2050. The top 3 generation capacities are hydrogen power plants at 11.7 GW, solar PV at 8.6 GW and imported electricity at 6.6 GW.

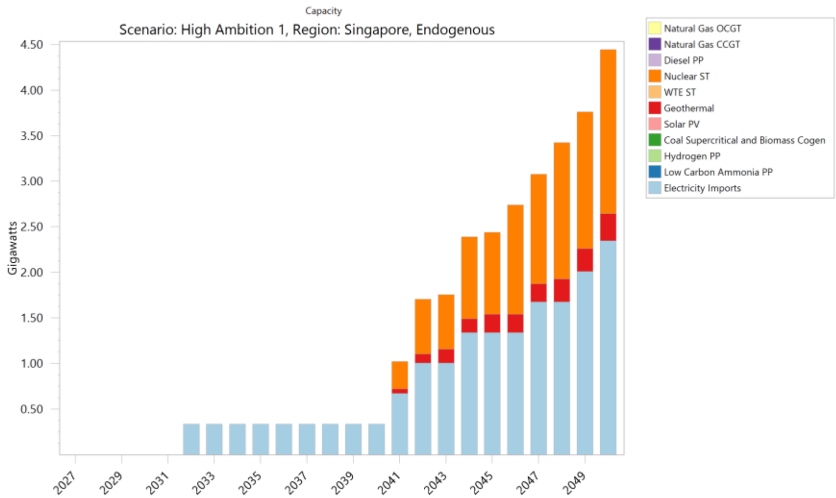
In the HA2 scenario, total generation capacity increases to 29.1 GW in 2050. The top 3 generation capacities are imported electricity at 9.3 GW, solar PV at 7.9 GW and hydrogen power plants at 5.2 GW.

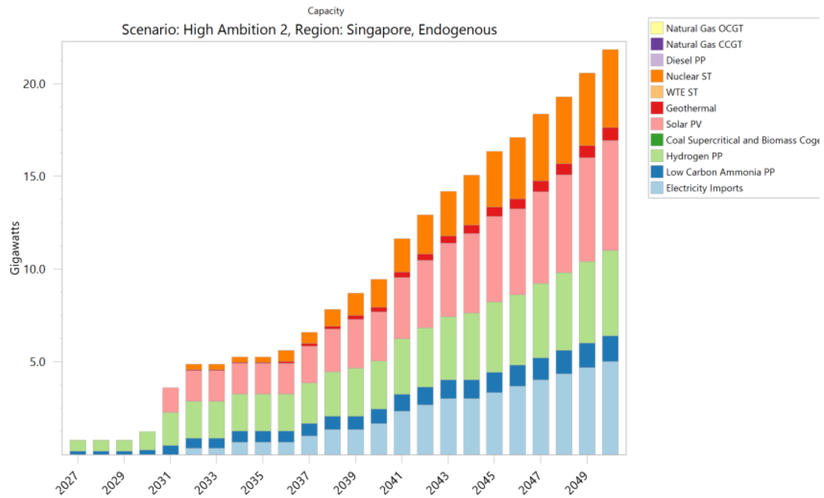
Total generation capacity in 2025 is 13.8 GW and 12.6 GW in BAU and HA1/HA2 respectively, which are higher than the projected generation capacity by EMA in 2025 (11.6 GW) (EMA, 2021).

7.5 Share of installed generation capacity by technology (endogenous)









Next, we analyse the amount of endogenous capacity additions by technology. In HA1, 300 MW of nuclear generation capacity needs to be endogenously added in 2041-2042, 2044, 2046, 2048 and 2050.

50 MW of geothermal generation capacity needs to be endogenously added in 2041-2043, 2045, 2048 and 2050.

335 MW of electricity imports needs to be endogenously added in 2032, 2041-2042, 2044, 2047 and 2049-2050.

In terms of the cumulative amount added in HA1: 1.8 GW of nuclear and 300 MW of geothermal generation capacity as well as 2.3 GW of electricity imports would have been endogenously added by 2050 respectively.

In HA2, 300 MW of nuclear generation capacity needs to be endogenously added in 2032, 2036, 2038-2047 and 2049-2050.

50 MW of geothermal generation capacity needs to be endogenously added in 2032, 2036, 2038-2047 and 2049-2050.

1320 MW of solar PV capacity needs to be endogenously added in 2031, followed by 330 MW in 2032 and 2037-2039, 660 MW in 2041, then 330 MW in 2042-2045 and 2047-2050.

600 MW of hydrogen generation capacity needs to be endogenously added in 2027, followed by 400 MW in 2030, 800 MW in 2031, 200 MW in 2032 and 2037-2039, 400 MW in 2041, then 200 MW in 2042-2045 and 2047-2050.

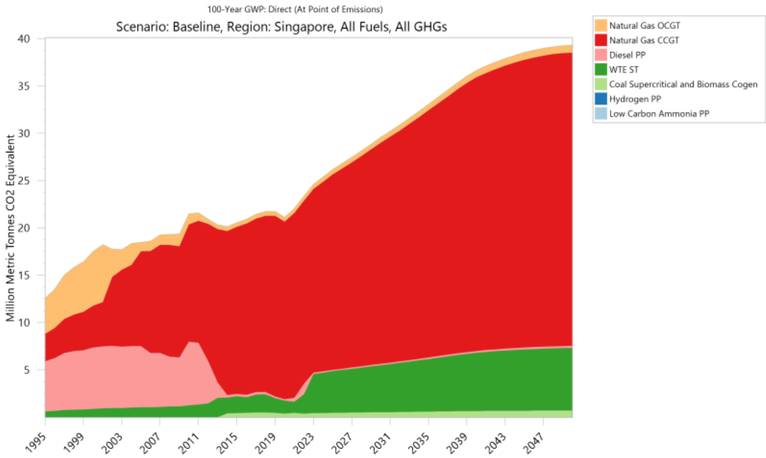
180 MW of low-carbon ammonia generation capacity needs to be endogenously added in 2027, followed by 60 MW in 2030, 240 MW in 2031, 60 MW in 2032, 2034, 2037-2038 and 2040, 120 MW in 2041, then 60 MW in 2042-2043 and 2045-2050.

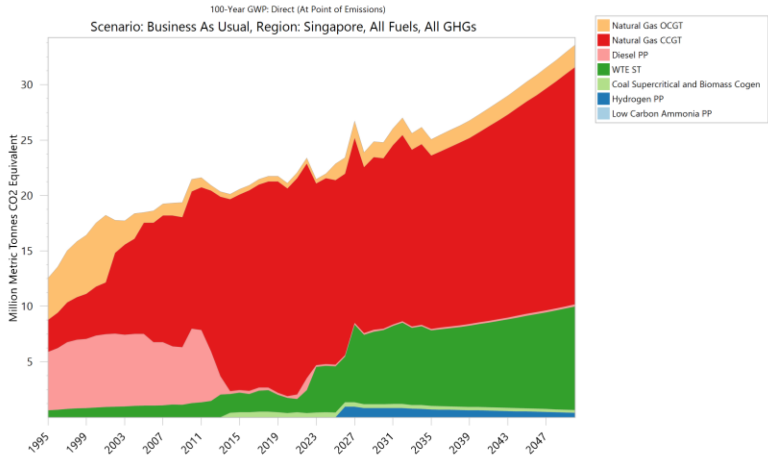
335 MW of electricity imports needs to be endogenously added in 2032, 2034, 2037-2038 and 2040, followed by 670 MW in 2041, then 335 MW in 2042-2043 and 2045-2050.

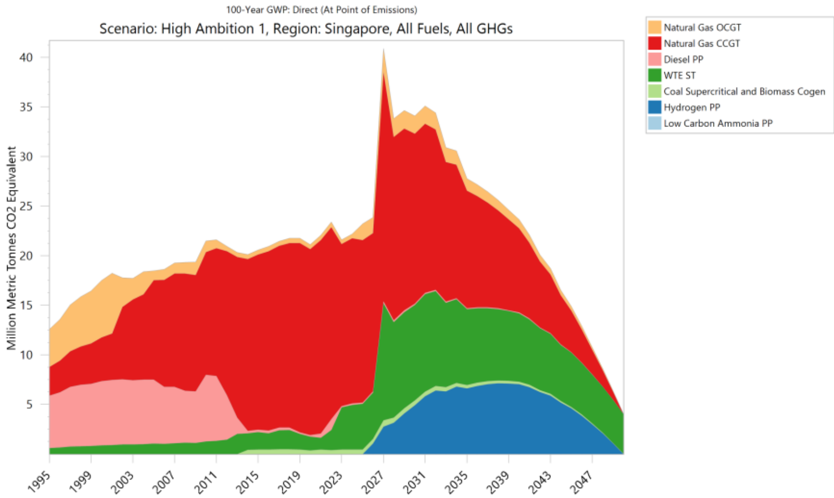
In terms of the cumulative amount added: 4.2 GW of nuclear, 700 MW of geothermal, 5.9 GW of solar PV[68], 4.6 GW of hydrogen and 1.4 GW of low-carbon ammonia power generation capacity as well as 5 GW of electricity imports would have been endogenously added by 2050.

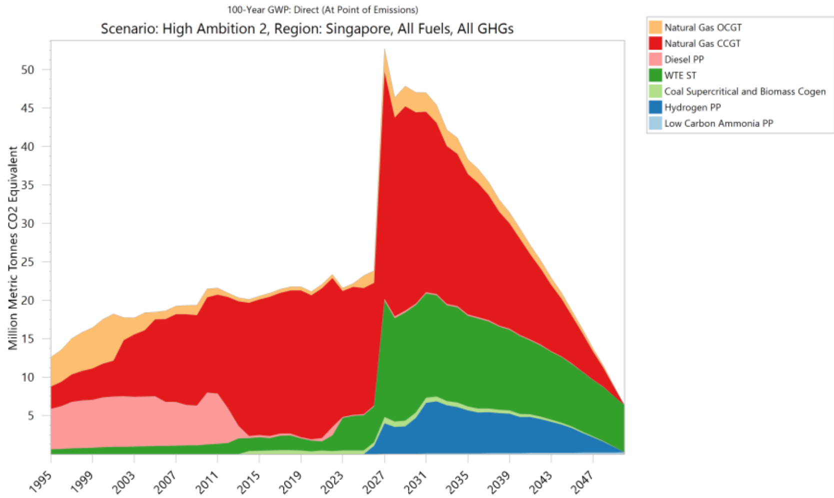
[68] As noted in section 7.4, the sum of the cumulative amount of exogenous solar PV generation capacity added by 2030 (BAU) and endogenous capacity added from 2031-2050 (HA2) is at 7.9 GW, which is still lower than Singapore's maximum technical potential for solar PV deployment of 8.6 GW.

7.6 Absolute emissions in power sector by technology









Assessing the absolute emissions in terms of GHG warming potential over a 100-year period in the power sector is a critical highlight of this exercise. In the BAU scenario, GHG emissions from the power sector are projected to generally increase from 21.5 $MtCO_2e$ in 2023 to 24.8 $MtCO_2e$ in 2030, reaching 33.6 $MtCO_2e$ in 2050. This is 4.8 $MtCO_2e$ and 5.7 $MtCO_2e$ more carbon abatement potential than the BAS scenario in 2030 and 2050 respectively. Natural gas OCGTs and CCGTs contribute predominantly to emissions in 2030 (67.8%) and in 2050 (69.7%).

In the HA1 and HA2 scenarios, GHG emissions from the power sector are projected to peak at 40.9 $MtCO_2e$ and 52.7 $MtCO_2e$ in 2027 respectively, and generally decreasing to 4.04 $MtCO_2e$ and 6.4 $MtCO_2e$ respectively in 2050. Emissions start decreasing consistently after 2031 in HA1 and after 2029 in HA2.

The higher absolute emissions relative to the BAU scenario in 2030 (by 9.3 $MtCO_2e$ and 22.3 $MtCO_2e$ in HA1 and HA2 respectively) are attributed to the higher amount of electricity mainly generated by fossil fuel-fired power plants, WTE plants, as well as hydrogen[69] and low-carbon ammonia power plants (by 25.2 TWh and 57.5 TWh) in HA1 and HA2 respectively.

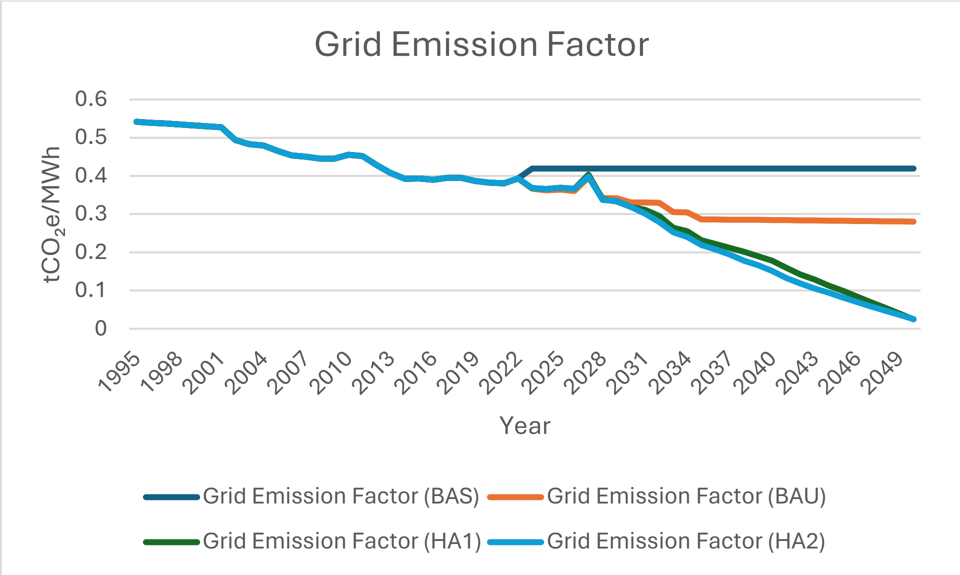
However, as hydrogen-compatible technologies become more mature with the phasing out of all fossil fuels in the energy mix, there would be a significantly lower amount of emissions generated relative to the BAU scenario. Specifically, total emissions of the power sector in the HA1 and HA2 scenarios are initially higher than the BAU scenario, but progressively lower from 2038 and 2041 respectively onwards.

On average, HA1 has lower annual emissions of 7.6 $MtCO_2e$ than HA2 between 2027-2050. From 2027-2050, the rate of average annual decrease in emissions in HA1 is 9.1% compared to 8.5% in HA2.

In 2050, the remaining emissions in the HA1 and HA2 scenarios come from the combustion of MSW, low-carbon ammonia and biomass, with WTE plants generating the majority (4.01-6.2 $MtCO_2e$) of emissions[70]. Between 2027-2050, the HA1 scenario can abate a net total of 181.3 $MtCO_2e$ more emissions compared to the HA2 scenario. However, despite HA2 having a significantly lower overall emissions abatement potential relative to HA1, hydrogen power plants in HA1 generate 21.3 $MtCO_2e$ more emissions during that period compared to hydrogen power plants in HA2.

[69] Note that the upcoming hydrogen power plant will still be relying mostly on natural gas and hydrogen blend as fuels in 2030.
[70] Tangri (2023) found that in the U.S., contrary to the defense of WTE plants as a source of cleaner energy relative to fossil fuels, the amount of GHG emissions per unit of electricity produced from MSW incineration is 1707 gCO_2e/kWh. When Tangri (2023)'s environmental loading factor for MSW incineration was used in our model instead, we found that it results in a generation of 3.3-5.1 $MtCO_2e$ of emissions in 2050, which does not differ significantly from our result.

7.7 Grid emission factor

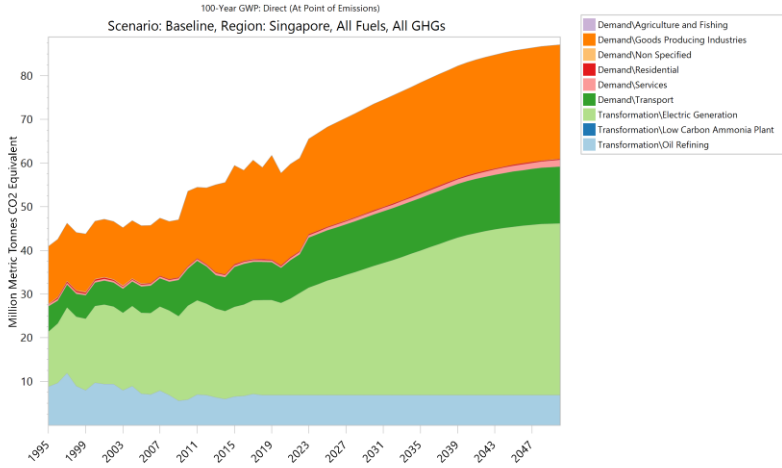


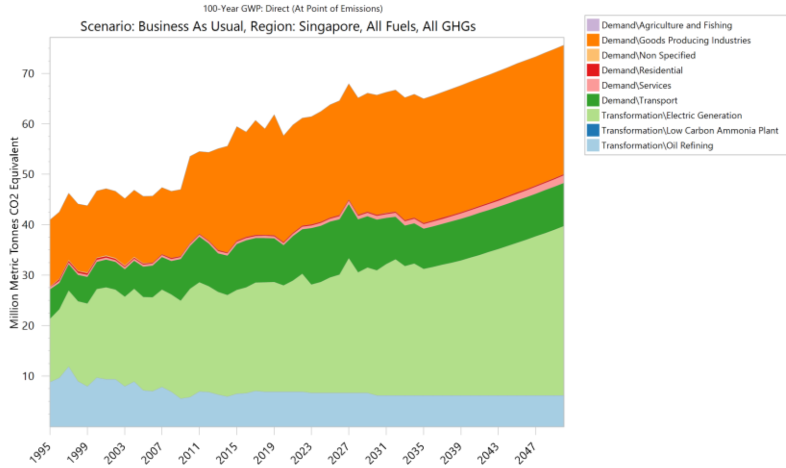
Grid emission factor measures the amount of carbon emissions per unit of electricity generated. Historical data inputs on electricity generation and its corresponding emissions result in a grid emission factor of 0.394 tCO_2e/MWh in 2022, which is slightly lower than EMA's estimate of 0.417 tCO_2e/MWh in the same year. In the BAS scenario, grid emission factor is projected to increase very slightly to 0.420 tCO_2e/MWh in 2050. From 1995-2050, grid emission factor would have been reduced by 22.6%.

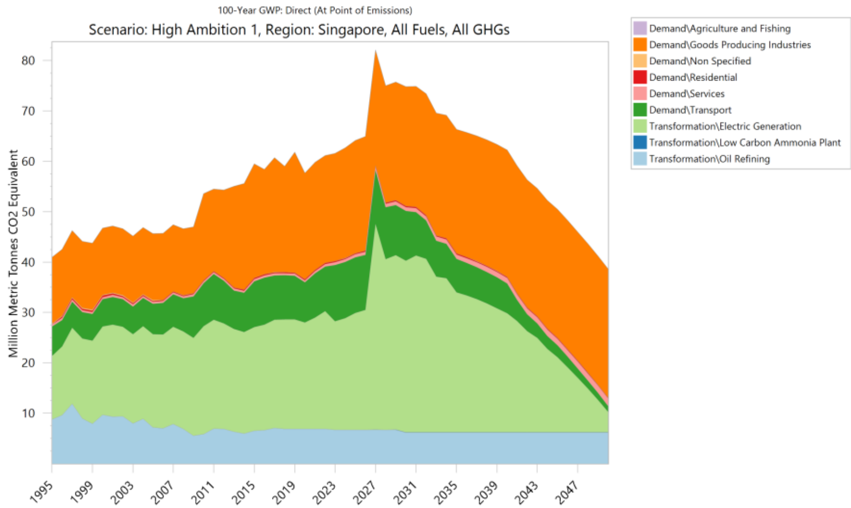
In the BAU scenario, however, grid emission factor is projected to reduce to 0.367 tCO_2e/MWh in 2023, to 0.331 tCO_2e/MWh in 2030 and to 0.280 tCO_2e/MWh in 2050. The new emission standard of 0.355 tCO_2e/MWh for generation units overall is reached in 2028 at 0.342 tCO_2e/MWh. From 1995-2050, grid emission factor would have been reduced by 48.3%.

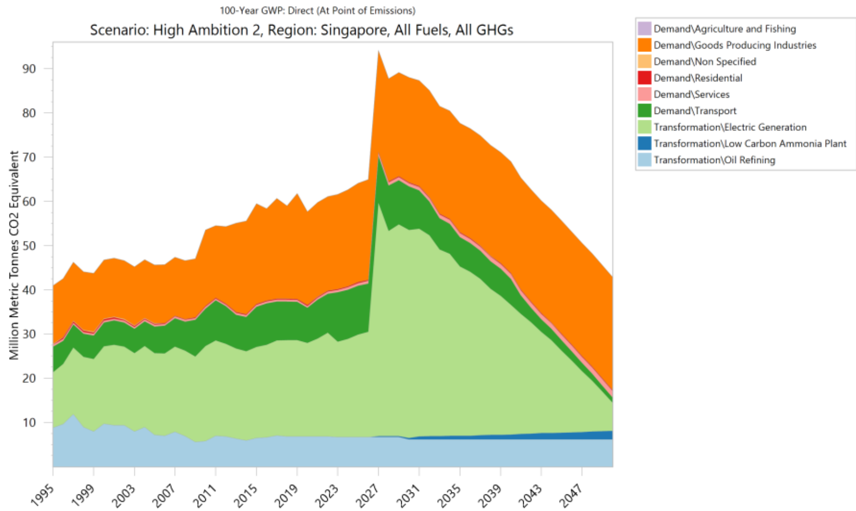
In the HA1 and HA2 scenarios, grid emission factor is projected to reduce to 0.3188 tCO_2e/MWh and 0.3186 tCO_2e/MWh in 2030 respectively and to 0.0248 tCO_2e/MWh and 0.0254 tCO_2e/MWh in 2050 respectively. Grid emission factor is generally lower in HA2 compared to HA1 during the projection period except during 2029 and 2050.

7.8 Absolute emissions from all domestic sectors









Next, we turn to absolute emissions from all domestic sectors. Based on the national GHG inventory[71], Singapore's GHG emissions are at 53.7 $MtCO_2e$ in 2021. Our BAS estimates accounting for historical GHG emissions from all domestic sectors are higher at 59.8 $MtCO_2e$ in 2021.

In the BAU scenario, there is a net average annual increase in GHG emissions from all domestic sectors from 61.5 $MtCO_2e$ to 75.6 $MtCO_2e$ between 2023-2050, with the power generation sector constituting the majority (44.4%) of overall emissions. This is higher than APERC (2022)'s estimate of 50 $MtCO_2e$ and lower than Doshi and D'Souza (2013)'s estimate of 95.6 $MtCO_2e$ by 2050 in their BAU-equivalent scenarios. This is 7.9 $MtCO_2e$ and 11.5 $MtCO_2e$ less emissions than the BAS scenario in 2030 and 2050 respectively.

At 65.7 $MtCO_2e$ of emissions in 2030 and continuing to show a general increase (0.7%) for the remainder of the projection period, this suggests that the BAU scenario does not meet the first part of the revised 2022 NDC target of 60 $MtCO_2e$ by 2030 and falls short of peaking emissions before 2030.

In the HA1 scenario, GHG emissions from all domestic sectors are projected to increase to a peak of 82.1 $MtCO_2e$ in 2027, reaching 74.8 $MtCO_2e$ in 2030 and continue to generally decrease to 38.6 $MtCO_2e$ in 2050, with goods producing industries constituting the majority (66.1%) of overall emissions. This suggests that the HA1 scenario is further from BAU in failing to meet the first part of the revised 2022 NDC target of 60 $MtCO_2e$ by 2030. However, emissions can be peaked before 2030.

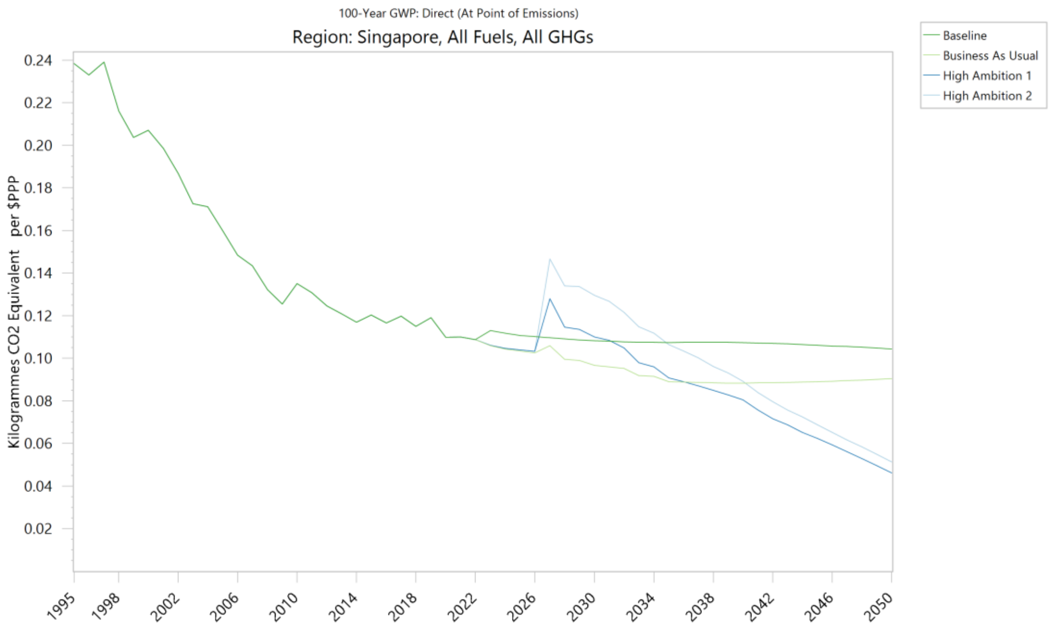
The HA2 scenario peaks emissions in 2027 at 94.2 $MtCO_2e$, reaching 88.1 $MtCO_2e$ in 2030 and continue to generally decrease to 42.9 $MtCO_2e$ in 2050. This means that HA2 also falls short of meeting the first part of the revised 2022 NDC target of 60 $MtCO_2e$ by 2030 but peaks earlier in the same year as HA1, albeit at a higher level of emissions than HA1.

BAU is closer to meeting the first part of the previous enhanced 2020 NDC target of 65 $MtCO_2e$ by 2030 compared to HA1 and HA2. However, HA1 is closer to meeting the second part of the previous enhanced 2020 NDC target (33 $MtCO_2e$ by 2050) compared to HA2 and BAU.

Our 2050 estimates in all scenarios are higher than that of APERC (2022) and Loi (2019) (16 $MtCO_2e$ and less than 14 $MtCO_2e$ in 2050 respectively) with overall fewer highly ambitious demand sector energy efficiency/carbon abatement measures in our model.

[71] https://www.nea.gov.sg/our-services/climate-change-energy-efficiency/climate-change/greenhouse-gas-inventory

7.9 Emission intensity



Emission intensity is the volume of emissions per unit of GDP. In the BAS scenario, under SSP2, emission intensity of all domestic sectors is expected to reduce from 0.113 kgCO_2e/$PPP (at 2007 prices) in 2023 to 0.108 kgCO_2e/$PPP in 2030 and to 0.104 kgCO_2e/$PPP in 2050. In the BAU scenario, emission intensity is expected to generally decrease from 0.106 kgCO_2e/$PPP in 2023 to 0.0966 kg$CO_2$e/$PPP in 2030 and to 0.0905 kgCO_2e/$PPP in 2050.

In the HA1 scenario, emission intensity is expected to peak at 0.128 kgCO_2e/$PPP in 2027 and reduce to 0.110 kgCO_2e/$PPP in 2030 and to 0.0463 kgCO_2e/$PPP in 2050. In the HA2 scenario, emission intensity is expected to peak at 0.147 kgCO_2e/$PPP in 2027 and reduce to 0.130 kgCO_2e/$PPP in 2030 and to 0.0514 kgCO_2e/$PPP in 2050.

This implies that only the BAU scenario can achieve the government's initial 2015 emissions intensity target of 0.113 kgCO_2e/S$GDP at 2010 prices (converted to 0.0976 kgCO_2e/$PPP at 2007 prices[72]) by 2030. HA1 and HA2 can only achieve this level of emission intensity from 2034 and 2038 onwards respectively.

Emission intensities in the HA1 and HA2 scenarios are higher than that of the BAU scenario until the turning point occurs at 0.0870 kgCO_2e/$PPP in 2037 and 0.0838 kgCO_2e/$PPP in 2041 respectively, and that emission intensities in HA1 are generally lower than in HA2 between 2027-2050.

It is also interesting to note that there is a year-on-year increase in absolute emissions but a year-on-year decrease in emission intensity between 2023-2026, 2028-2029, 2030-2032, 2033-2034 and 2035-2040 in BAU; between 2023-2026, 2028-2029 and 2030-2031 in HA1 and between 2023-2026 and 2028-2029 in HA2. An increase in absolute emissions (the numerator) with a larger increase in GDP (the denominator) relative to emissions would still result in a decrease in emission intensity, but not absolute emissions. However, the trade-off is that while setting an emissions target independent of GDP is more effective at reducing absolute emissions, it could have an adverse effect on economic competitiveness.

[72] https://data.oecd.org/conversion/purchasing-power-parities-ppp.htm

8. IMPLICATIONS AND FUTURE WORK

In sum, our results show:

- The technical constituents of a renewable energy portfolio that is largely dependent on hydrogen as a potential replacement for natural gas and a renewable energy portfolio that is diversified.

- In terms of absolute emissions, our modelling results show that by following the Business-As-Usual (BAU) scenario, Singapore can mitigate emissions in the power sector to 24.8 $MtCO_2e$ by 2030. Based on our two Highly Ambitious (HA1 and HA2) scenarios, despite a higher level of emissions in 2030 compared to BAU (by 9.3 $MtCO_2e$ and 22.3 $MtCO_2e$ respectively), emissions can be further reduced to 4.04 $MtCO_2e$ or 6.4 $MtCO_2e$ by 2050, implying that near net-zero emissions by 2050 in the power sector may be potentially achievable given further refinements of the outlined policies and assumptions.

- More electricity is generated in HA1 and HA2 relative to BAU for all projected years. By 2050, the amount of endogenous capacity that needs to be added and in turn, electricity that is generated in HA2 are significantly higher than the amounts needed in HA1, given less exogenous capacity additions (hydrogen, low-carbon ammonia and solar PV) to compensate for the retirement of fossil fuel power plants.

- EMA assessed that hydrogen could meet up to 50% of Singapore's projected electricity demand by 2050, while solar PV and nuclear could meet up to 10%. HA1 demonstrates how EMA's hydrogen and nuclear targets can be achieved, while HA2 demonstrates how EMA's hydrogen, solar PV and nuclear targets can be achieved. The trade-off is that higher electricity generation may result in higher emissions initially compared to the BAU scenario until 2038 for HA1 and 2041 for HA2, where the trend reverses.

- Regarding Singapore's 2022 revised NDC emissions (overall) target by 2030: BAU comes closest out of the three scenarios to achieving 60 $MtCO_2e$ by 2030 (exceeding by 5.7 $MtCO_2e$) but is unable to peak emissions in the projected years; HA1 and HA2 are able to peak emissions before 2030 but are far from being able to achieve 60 $MtCO_2e$ by 2030.

- Out of all the scenarios modelled, HA1 has the lowest overall emissions in 2050 (followed by HA2 and then BAU), although it still exceeds the 2020 enhanced NDC target of 33 $MtCO_2e$ in 2050 (by 5.6 $MtCO_2e$).

Technology plays a pivotal role in shaping the future. Future work could attempt to model more ambitious policies not just for the power sector but also for the other transformation sectors and demand sectors. This is important given that in the projection years, fuel oil continues to contribute to the bulk of emissions in the demand sectors (about 17-18 $MtCO_2e$) which is largely concentrated in the manufacturing industries and oil refining contributes to about 6.2 $MtCO_2e$ of emissions after a mild implementation of carbon capture solutions.

Using bottom-up approaches which have greater flexibility in modelling changes in the energy intensities of the industrial and services sectors due to the implementation of industrial and service-oriented energy efficiency policies would allow for more pronounced differences in the projected energy demand and emissions across the various scenarios. For example, not only can hydrogen, hydrogen blend and ammonia be considered as a potential clean fuel in the power sector, but also in the transport and industrial sectors. In addition, due to Singapore's open economy and as a leading commodities' trading hub, it would be prudent to relate energy use and emissions from not only the domestic demand sectors but also from the transboundary sectors i.e., international aviation and shipping.

More importantly, however, would be to optimise the cost-effectiveness of supplying each type of fuel for power generation for a more practical approach to determine the feasibility of achieving the different types of renewable energy portfolios. For example, the Energy Research Institute of NTU estimated that electricity prices are likely to climb to two to three times their current rates if Singapore were to switch out natural gas for low-carbon hydrogen, assuming a low-carbon hydrogen cost of US$6.60 per kg and accounting for distribution costs provided domestic hydrogen-compatible infrastructure is already built up.

Within the context of the energy trilemma, where should Singapore focus be? How would this consideration affect how Singapore's net zero carbon pathways, and how it reaches there?

We are of the opinion that Singapore's focus should be on minimising this trilemma, keeping energy security as the priority. Singapore would need to explore feasible options to import cost competitive low-carbon hydrogen, similar to how Singapore is importing its current supply of natural gas. However, global gas supply chain disruptions in the future might see Singapore falling back on standby fossil fuels such as diesel to ensure energy security if the deployment of other clean alternative reserves such as nuclear energy or solar PV are inadequate in meeting energy demand.

Moreover, it is unclear as to how much green hydrogen fuel (created from renewable energy) is imported relative to blue hydrogen fuel (created from natural gas), and the efficacy of carbon capture solutions to sequester CO_2 released from burning blue hydrogen for power generation and industrial processes.

Cross-border renewable energy trade is another attractive solution to reduce reliance on fossil fuels for power generation, especially since governments of neighbouring countries with high potential in indigenous renewable energy production and/or being strategically positioned in the ASEAN region (i.e., Malaysia) have recognised the benefits to the growth of the clean energy industry by becoming a regional renewable energy generation hub. However, risks associated with engineering of undersea cables and high interconnection infrastructure costs may be a setback, as seen in the failed Sun Cable project to import 1.75 GW from Australia. Therefore, adjusting for such uncertainties in the transition would be necessary to flatten Singapore's trajectory in achieving its net zero emissions target.

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