WRI CHINA

Powering a Carbon-Free Hong Kong

PATHWAYS TOWARDS A NET-ZERO EMISSIONS POWER SYSTEM FOR HONG KONG

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FOREWORD

UN Secretary General António Guterres stated in 2019 that "cities are where the climate battle will largely be won or lost," as cities account for around three-quarters of global final energy consumption. There have been encouraging signs that governments worldwide are becoming more ambitious in decarbonising their energy sectors, which would be pivotal for cities to meet their carbon targets.

In November 2020, Hong Kong became the first city in China to make a time-specific carbon neutrality pledge when the chief executive of Hong Kong announced that Hong Kong would strive to achieve carbon neutrality before 2050, joining 796 municipal governments in 63 countries with net-zero emissions targets.

The energy sector is the most important sector for Hong Kong to win the race to zero emissions, as electricity generation is Hong Kong's dominant source of greenhouse gas emissions. In the future, continued economic growth and population growth, as well as widespread electrification, will greatly increase demand for electricity. For this reason, a robust zero-carbon power system needs to be established as soon as possible.

According to the latest International Energy Agency (IEA) report, *Net Zero by 2050: A Roadmap for the Global Energy Sector*, nearly 90 percent of the global power generation will come from renewable energy to achieve net-zero emissions. Wind and solar photovoltaic power generation will account for nearly 70 percent, while the rest will predominantly come from nuclear. However, geographical and resource constraints mean that the contribution of local renewable energy to Hong Kong's energy mix will be limited. Therefore, Hong Kong needs to identify and develop alternative zero-carbon technologies—specifically, nuclear, hydrogen, and carbon capture and storage (CCS)—on a large scale.

This report proposes five energy-mix scenarios to decarbonise Hong Kong by 2050 and evaluates their climate, economic, environmental, health, and energy security impacts. Hong Kong's efforts will contribute to net-zero emissions in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA). Collaboration will drive greater investment, innovation, and talent to the region, laying the foundation for the GBA to lead the global energy transition.

Acting now is our only option. Our recommendations provide some solutions for Hong Kong towards a next-generation power system that fosters a cleaner, greener, and safer environment. World Resources Institute and Civic Exchange are proud to join the design of the greatest change that lies ahead. We hope this report will give insights into Hong Kong's future actions and its continued leadership in the new carbon-neutral era.

Li Fang
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EXECUTIVE SUMMARY

HIGHLIGHTS

- The IPCC's Sixth Assessment Working Group 1 Report, published in 2021, warns that if the world has any chance of keeping a temperature rise within 1.5°C, we need to reduce our emissions immediately, rapidly, and on a large scale. Hong Kong is already experiencing some climate stress, such as heatwaves, storm surges, and other extreme weather events. To minimise the threat of climate change, such as sea level rises which could damage the city's critical infrastructure and disrupt its economy, Hong Kong needs to decarbonise as quickly as possible.
- In November 2020, Hong Kong pledged to achieve carbon neutrality before 2050, making it China's first city with a time-specific carbon neutrality goal. On 6th October 2021, the Hong Kong Climate Action Plan 2050 was published. It set an interim target of reducing Hong Kong's carbon emissions by 50 percent before 2035 compared to 2005 levels.
- The greatest potential for reducing emissions is within the power sector, which accounted for approximately 66 percent of Hong Kong's total greenhouse gas (GHG) emissions in 2019. In the newly released Climate Action Plan, Government committed to cease coal usage for daily electricity generation by 2035, as well as increase the share of renewable energy to 7.5–10 percent by 2035 and to 15 percent gradually thereafter.
- This report is one of a number of sectoral reports under the Hong Kong 2050 Is Now initiative examining possible pathways to decarbonisation. It evaluates potential decarbonised power technologies and develops five energy-mix scenarios involving different technological combinations. These scenarios consider the economic, social, and environmental impact of building a decarbonised power system. Our recommendations can inform government planning in its pursuit of the mid- and long-term targets laid out in the Climate Action Plan.
- We have found that a decarbonised power system with a high ratio of imported nuclear energy has economic advantages and can reduce power system emissions by 70 percent by 2035. In contrast, power systems with a high reliance on emerging technologies, such as CCS and hydrogen, face higher costs and deployment feasibility challenges. Ultimately, the future costs of these technologies will determine their long-term utility.
- Hong Kong should, in a first instance, be proactive in scaling up domestic wind and solar energy, as well as expanding waste-to-energy facilities. Given its limited land area, Hong Kong also needs to enhance regional collaboration and import more low-carbon energy, such as nuclear and green hydrogen, to build a decarbonised power system.

Introduction

In her November 2020 annual Policy Address, Hong Kong's Chief Executive, Carrie Lam, set out the government's strategies and proposals to achieve carbon neutrality and promote green transport and energy efficiency, and pledged that the city would achieve carbon neutrality before 2050. Currently, the power sector is the primary source (66 percent) of carbon emissions in Hong Kong. Therefore, decarbonising this sector is critical for the city to achieve its carbon neutrality goal.

This report analyses Hong Kong's options in this regard. Based on an in-depth analysis of different power technologies, we developed five energy-mix scenarios and provide recommendations for policymakers and power companies.

Zero Carbon Technology Options for Hong Kong

We examine the feasibility, opportunities, and challenges for the large-scale deployment of renewable energy, CCS, and green hydrogen. We also evaluate the possibility of developing joint-venture opportunities with renewable energy and nuclear generators in Mainland China. Our objective is to promote regional collaboration on clean energy development and a power system that is better integrated with Mainland China.

Domestic renewable energy (RE): Limited by geographical conditions and resources, domestic RE can only play a limited role in Hong Kong's energy mix. However, it must undoubtedly be an indispensable part of any future decarbonised power system in Hong Kong. Our analysis shows that domestic RE could supply up to 4 percent of Hong Kong's electricity demand by 2030 and 10 percent by 2050. Among all RE options to help achieve decarbonisation, offshore wind farms appear to have the greatest potential. In the future, if CCS technology becomes commercially available, it could help abate emissions from fossil-fuel power plants while maintaining their dispatchable power output, and assure reliability in a flexible manner. This is of great value to Hong Kong because, with limited renewable energy resources, fossil fuel-based power generation is likely to perform some role.

Hydrogen has great potential as an alternative energy carrier in supporting Hong Kong's carbon-neutrality goal. The utilisation of low- or zero-carbon hydrogen can reduce our carbon footprint, as well as strengthen Hong Kong's energy security, thus contributing to greater climate resilience. The power sector could greatly benefit from hydrogen's contribution to grid balancing and the management of peak load issues, therefore enhancing supply reliability, deployment, and transport. The delivered cost of hydrogen could significantly affect the power-generation cost of electricity in Hong Kong.

Importing clean energy from Mainland China. Hong Kong should work with Guangdong Province and aspire for the Greater Bay Area to lead efforts in China to achieve carbon neutrality by 2050. Nuclear energy is technically feasible, commercially viable, and an available decarbonised option. There is potential for Hong Kong to import more nuclear energy from Guangdong as part of its clean energy transition. Offshore wind is also a promising, increasingly economic and available option. The main power-sector challenges for government include negotiating with cities in Mainland China for clean energy resources and, consequently, ensuring adequate infrastructure for transport and distribution. Government and the city's two local power companies need to begin negotiations with Mainland China to help secure stable, adequate, and decarbonised energy.

Hydrogen: Hydrogen has great potential as an alternative energy source in supporting Hong Kong's carbon-neutrality goal. The utilisation of low- or zero-carbon hydrogen can reduce the city's carbon footprint, as well as strengthen its energy security, thus contributing to greater climate resilience. The power sector could benefit greatly from hydrogen's contribution to grid balancing and the management of peak load issues, thereby enhancing the reliability of the power-sector supply. However, as Hong Kong has limited green hydrogen facilities, it will likely have to import green hydrogen from Australia, the Middle East, or Mainland China. Currently, using green hydrogen to power the base load faces challenges due to limited supplies and high fuel costs. The success of utilising hydrogen in Hong Kong's power sector depends on global efforts in green hydrogen development, deployment, and transport. The delivered cost of hydrogen could significantly affect the power-generation cost of electricity in Hong Kong.

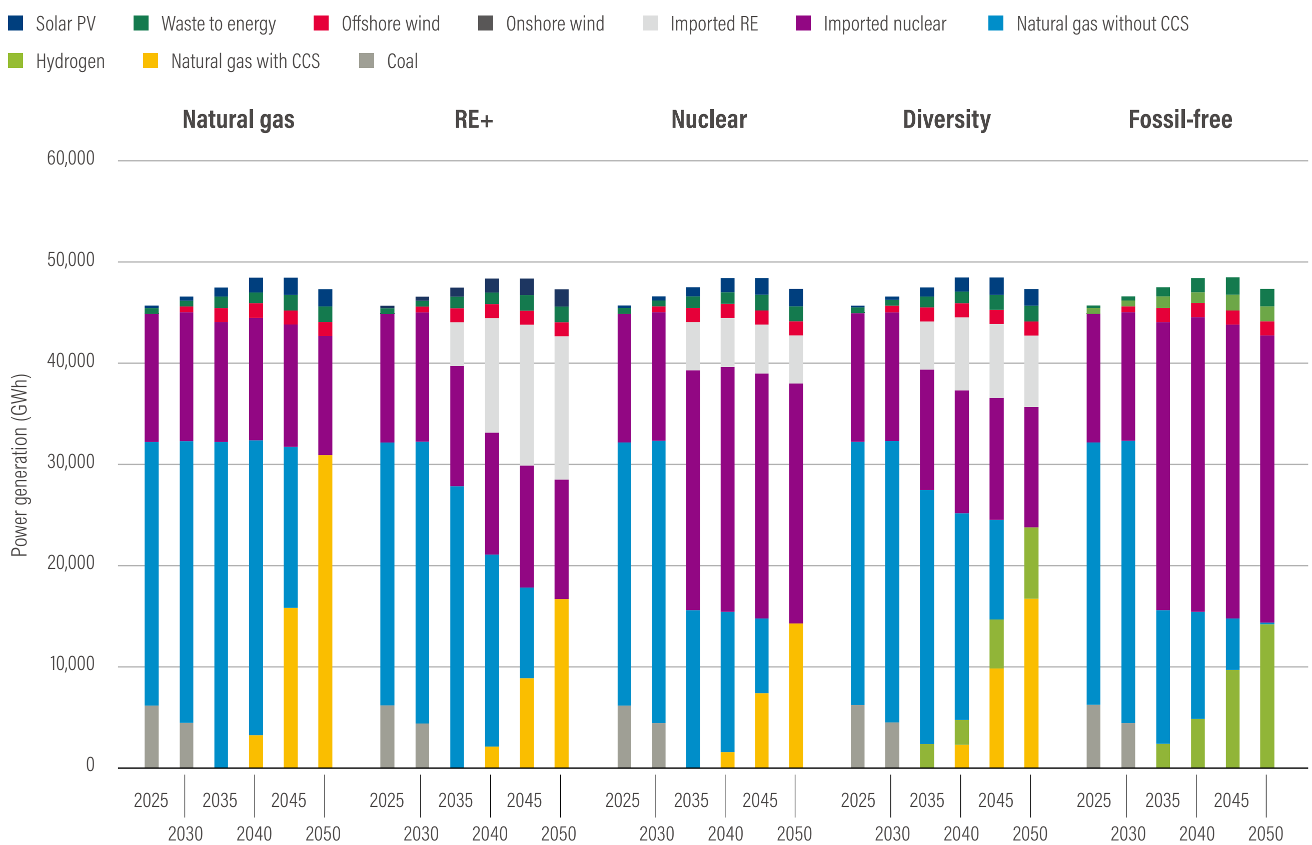
CCS. In 2020, natural gas contributed 48 percent of Hong Kong's electricity generation, while coal accounted for 23 percent. Despite Hong Kong's plans to phase out all coal in the future, electricity generation from natural gas would still produce worrying amounts of emissions. If CCS technology becomes commercially available, it could abate the emissions of fossil-fuel power plants while maintaining their dispatchable power output to underpin local reliability in a flexible manner. This is of great value to Hong Kong because, with limited renewable energy resources, fossil fuel-based power generation is likely to perform some kind of a role.

Pathways towards a Net-Zero Emissions Power System

Based on an analysis of the potential, feasibility, and readiness of the above technologies, as well as through consultations with stakeholders, we developed five scenarios to demonstrate the effects of different energy mixes. Figure ES-1 illustrates the energy mix of each scenario.

We examined the performance of the five scenarios in terms of cost, air pollution, and health risks. Table ES-1 shows that the five scenarios perform differently against these criteria, and no single scenario outperforms the others in all aspects. Government is advised to consider these five options in its efforts to achieve its 2050 carbon-neutrality goal.

Figure ES-1 | **Evolution of Power Generation Mix Assumed across Scenarios**



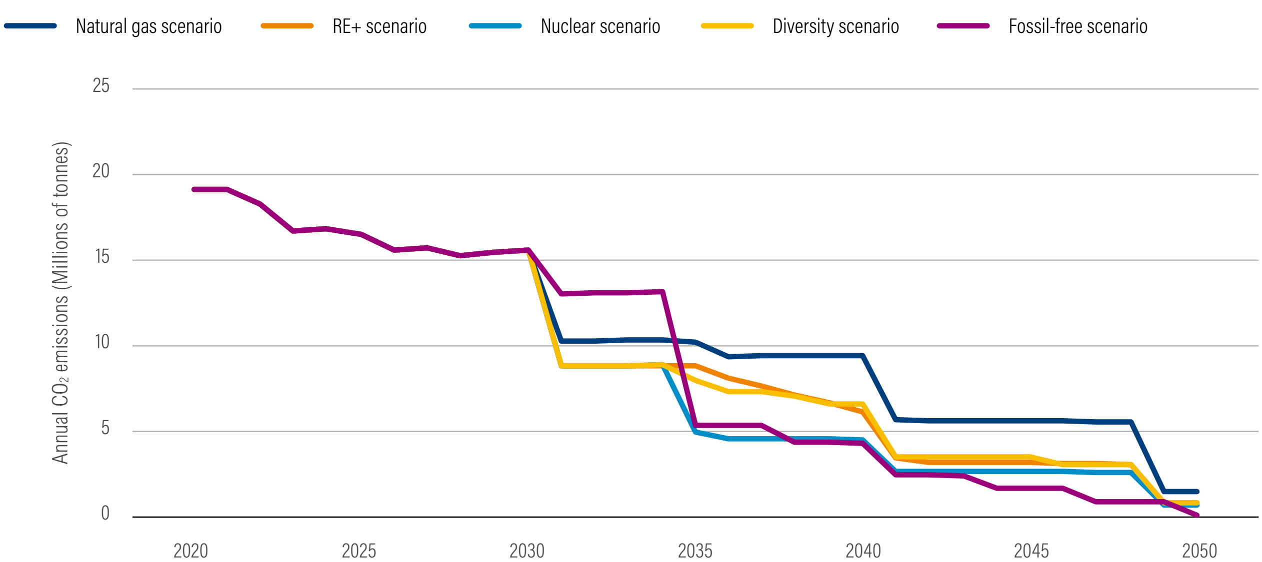
Source: Assumption of project team.

Table ES-1 | **Comparison of Different Scenarios**

		NATURAL GAS	RE+	NUCLEAR	DIVERSITY	FOSSIL-FREE
Scenarios Energy Mix in 2050	**Natural gas with CCS**	65%	35%	30%	35%	-
	Local RE	10%	10%	10%	10%	10%
	Imported RE	-	30%	10%	15%	-
	Nuclear	25%	25%	50%	25%	60%
	Hydrogen	-	-	-	15%	30%
Evaluation Criteria	**Feasibility-technological maturity**	No for CCS	No for CCS	No for CCS	No for CCS and hydrogen	No for hydrogen
	Economic competitiveness (avg. LCOE in 2050)	$$$$$	$$$	$$	$$$$	$
	Carbon and air pollutant emissions	High	Medium	Low	Medium	Low
	Associated health concerns	High	Medium	Low	Medium	Low
	Diversity	Low	Medium	Medium	High	Low

Note: $ represents the lowest cost compared with the other scenarios; $$$$$ represents the highest cost compared with the other scenarios.
Source: Scenarios for the energy mix in 2050 are the authors' assumption; evaluation criteria are calculation results of the project team.

Figure ES-2 | **Annual CO_2 Emissions under Different Scenarios**



Source: Calculation of the project team.

In terms of climate mitigation, the Nuclear scenario has the lowest cumulative carbon emissions because it involves a one-time switch to a large-scale decarbonised energy source. The Fossil-Free scenario presents a pathway with the second-least cumulative carbon dioxide emissions and will lead to net-zero carbon emissions by 2050. The RE+, Nuclear, and Diversity scenarios will all bring carbon dioxide emissions in 2050 to less than 5 percent, compared with today's levels.

From a **technical readiness** perspective, all the scenarios rely to a certain degree on early-stage technologies—natural gas-fired power plants equipped with CCS and green hydrogen—that are not yet commercially viable. The Natural Gas and Diversity scenarios rely on these technologies for 50–65 percent of the total generation mix. The RE+, Nuclear, and Fossil-Free scenarios rely less on these technologies, taking up 30–35 percent of the total generation mix. The scenarios with a higher reliance on early-stage technologies bear greater uncertainties during energy transitions. In this respect, the Nuclear and Fossil-Free scenarios perform best as they leverage these technologies least. Global efforts in the development and deployment of CCS and green hydrogen will be crucial for CCS-equipped power plants to be commercially viable and for green hydrogen production to the economy scale.

In terms of cost-effectiveness, increasing imports of nuclear energy will help Hong Kong achieve its carbon neutrality goal, while avoiding the higher costs associated with technologies in early-stage development. Estimates on the future costs of various decarbonised power generation technologies mainly centre on the future price of green hydrogen and CCS technologies. The economic performance of the Nuclear and Fossil-Free scenarios outperforms the rest.

Recommendations

It is critical for Hong Kong to take ambitious and decisive action now to transform to a net-zero carbon power system. As government considers how to decarbonise the city's power system, potentially adopting one of the five scenarios or different combinations of them, it also needs to understand the importance, regardless of what it chooses, of keeping up with technological and market developments. Delay in action will lead to a carbon lock-in, which will eventually lead to larger cumulative emissions. It will also challenge Hong Kong's position as an important international financial centre.

These are what we call 'no-regret' actions. Regardless of which pathway government chooses, these recommendations should be for immediate implementation. Any delay will likely jeopardise Hong Kong's carbon-neutrality vision.

Scale up domestic wind and solar energy. Many studies indicate that Hong Kong's renewable energy potential could constitute up to 10 percent of total energy consumption, which is much higher than the current government target of 3–4 percent. Regardless of which pathway is chosen, government should utilise domestic renewable energy resources as much as possible. To do so, government should authorise a new study to examine the availability of Hong Kong's renewable-energy resources. In addition to the current Feed-in Tariff scheme, government should introduce other financial incentives, such as fiscal and taxation mechanisms, to encourage both utility and non-utility companies to develop renewable-energy technologies.

Further scale up waste-to-energy facilities. Waste-to-energy (WtE) technology is an invaluable domestic renewable resource that addresses both waste management and GHG emissions challenges. Regardless of which pathway is chosen, alongside policies that reduce waste, Hong Kong should optimise WtE utilisation. Government may include a WtE target in the Scheme of Control Agreements (SCAs) and ask both power companies to develop WtE facilities at their plant sites. For instance, Castle Peak and Lamma Island are potential sites for up to three incinerators. However, government needs to address residents' environmental concerns, such as air pollution and odours. These could easily be addressed, however, with greater transparency and, for example, real-time air quality monitoring during construction.

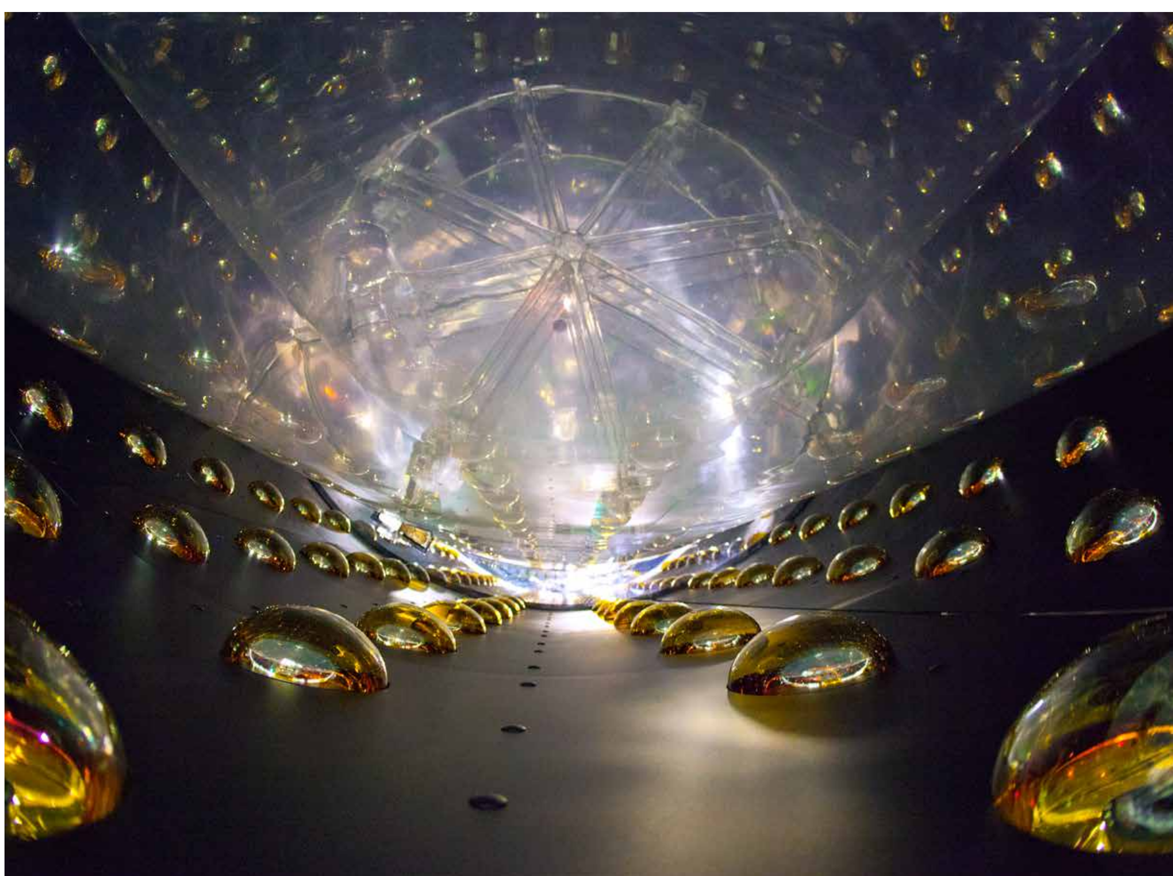
Explore ways to enhance regional collaboration towards increasing imports of renewable and nuclear energy from Mainland China. Building new nuclear power plants and offshore wind projects are at the top of Guangdong's energy-development agenda, and that could provide opportunities for Hong Kong to increase its proportion of imported clean energy through collaborative models, such as negotiating joint ventures with individual generators. Government may consider exploring the feasibility of importing renewable and nuclear energy from Guangdong. Government should also explore the viability of additional interconnections between Hong Kong and the China Southern Grid to ensure that reliability standards can be maintained.

Explore the potential of large-scale green hydrogen utilisation. Hydrogen-based technologies are becoming an important solution for a net-zero carbon society and have the potential to satisfy Hong Kong's peak load, grid balancing, and energy-security issues. Government may consider establishing a cross-agency task force to develop a green hydrogen strategy for Hong Kong. It would also be worthwhile to explore the potential of 'pink' hydrogen produced by nuclear power, or 'blue' hydrogen produced from fossil fuels plus CCS. Hong Kong power plants built after 2020 should also be hydrogen-ready. Government should consider providing subsidies for green hydrogen research and development, as well as fostering carbon pricing to allow green hydrogen to become a cost-competitive alternative.

Enhance grid balancing and energy storage to accommodate a broader energy mix. Grid balancing becomes more challenging as a higher percentage of the energy supply moves from coal and gas to multiple sources. Hong Kong needs to look at all options, such as improving interconnections within the city, constructing an interconnection with the China Southern Grid that maintains Hong Kong's current reliability, and increasing storage capacity. Government may consider conducting a study to identify measures to enhance grid balancing. It could seek investment in new sources of system reliability and flexibility in response to the shift from a dispatchable generation-dominated power system to one relying more on renewable power.

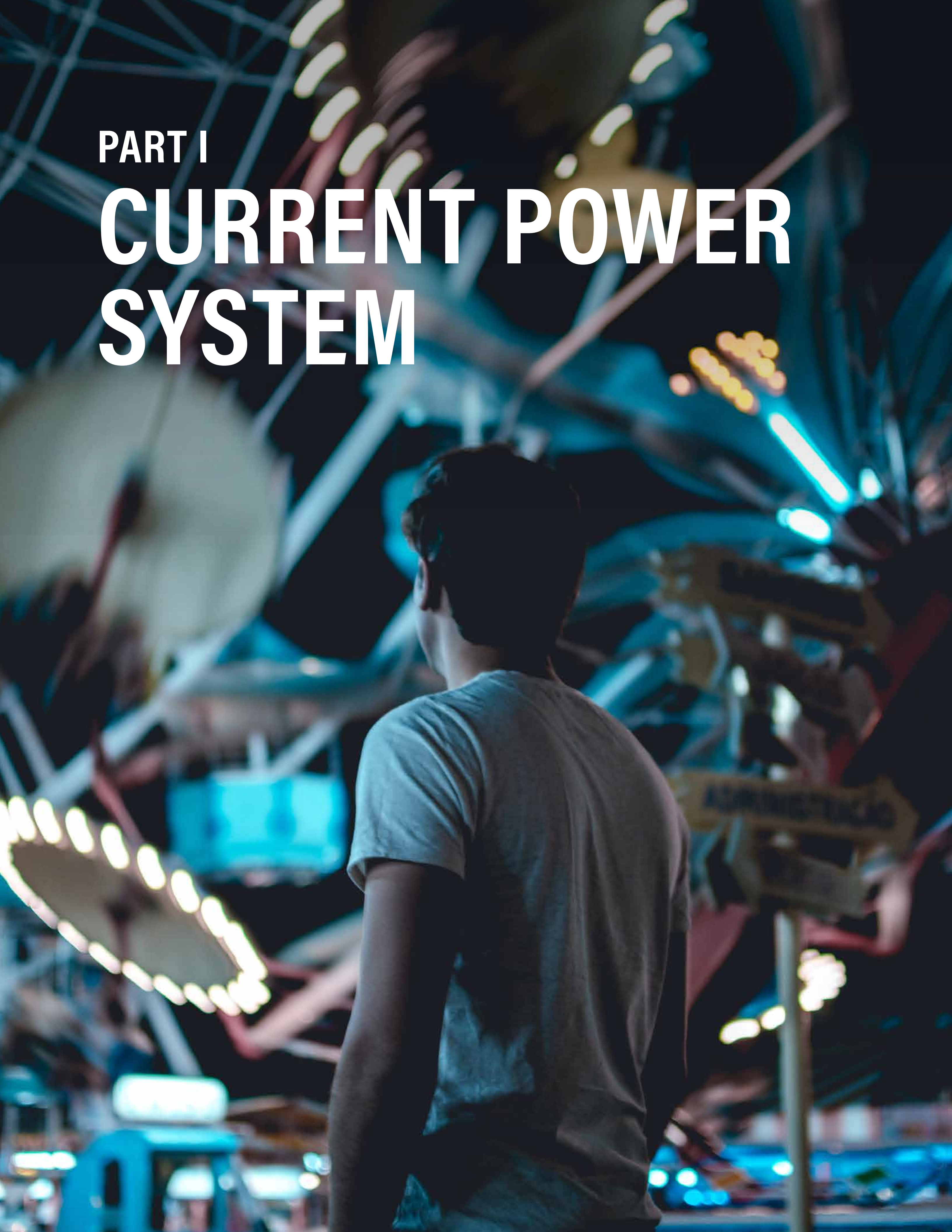
Explore the possibility of CCS technology deployment. There is growing recognition of the part CSS can play in the decarbonisation process. It is important to ensure that all fossil fuel-based power plants built after 2020 are CCS-ready. Retrofitting existing facilities with CCS technologies is costly and sometimes infeasible. While the future development of CCS is still uncertain, government and the utility companies should start actively engaging in regional CCS development projects, including in Guangdong. This will help ensure better planning for future CCS deployment.

Continue to increase the electrification of Hong Kong society. Although this report focuses on reducing emissions from the power sector, no single industry's efforts can ensure that Hong Kong achieves carbon neutrality before 2050. Detailed recommendations for the transport and building sectors can be found in other reports in the Hong Kong 2050 Is Now series.



PART I

CURRENT POWER SYSTEM



CHAPTER 1

POWER SYSTEM IN TRANSITION

In November 2020, Hong Kong's chief executive pledged that the city would achieve carbon neutrality before 2050, making it the first city in China to set a time-specific carbon-neutrality goal. Published in June 2020, the first Hong Kong 2050 Is Now[1] report, *Towards a Better Hong Kong: Pathways to Net-Zero Carbon Emissions By 2050*[2], demonstrates that Hong Kong could achieve net-zero GHG emissions by 2050 through a broad range of initiatives, including decarbonising its power system, building energy-efficiency enhancements, and improving transport systems.

In October 2021, government published the Hong Kong Climate Action Plan 2050, which set an interim target of reducing Hong Kong's carbon emissions by 50 percent before 2035 as compared to 2005 levels. The plan committed to cease coal usage for daily electricity generation by 2035, as well as increase the share of renewable energy to 7.5–10 percent by 2030 and to 15 percent gradually thereafter (Hong Kong Government 2021). These measures represent a significant increase of ambition from the previous targets outlined in the 2017 Climate Action Plan 2030+, which aimed for 3–4 percent renewable energy by 2030. However, the updated plan does not contain a concrete direction towards the achievement of the new targets. This report offers road maps that aim to guide Hong Kong towards a decarbonised power system and will hopefully inform government's plans.

The Need for a Clean Power System

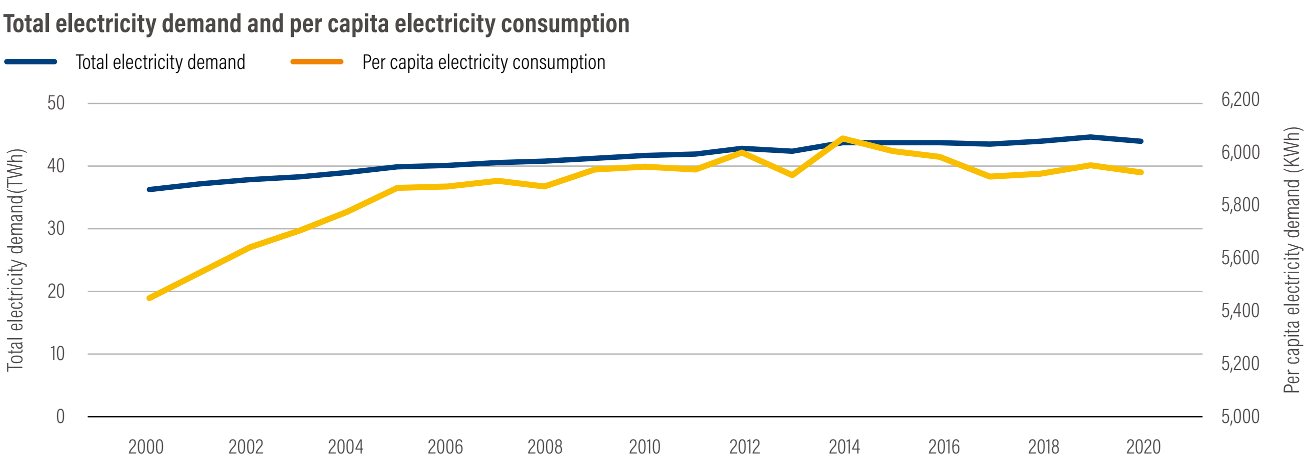
Power generation and other energy industries are the single largest source of GHG emissions in Hong Kong. According to Hong Kong's 2019 GHG inventory, approximately 66 percent, or 26.3 $MtCO_2e$ of its emissions came from electricity generation and town gas[3] production that year (EPD 2021). Our analysis shows that decarbonising the power sector is key to achieving net-zero carbon emissions and shows the potential for emissions reductions of 27 $MtCO_2$ by 2050. That represents 60 percent of Hong Kong's total emissions reduction potential (Jiang et al. 2020).

This report is divided into three parts: Chapter 1 elaborates on the current power system in Hong Kong and the need to decarbonise this system. Based on an analysis of various zero-emissions power technologies—including developing domestic renewable energy resources, equipping coal and gas power generation with CCS technologies, replacing coal or gas with green hydrogen, and importing clean energy from Mainland China. Chapters 2 to 5 offer an evaluation and recommendations for Hong Kong when considering different net-zero carbon-technology options, including renewable energy, fossil fuels with CCS, and green hydrogen, as well as regional collaboration on low-carbon energy development. Chapter 6 defines concrete pathways and implementation road maps for decarbonising the power system. Finally, Chapter 7 delves into recommendations for action over the next 5 to 10 years.

Increasing Power Demand

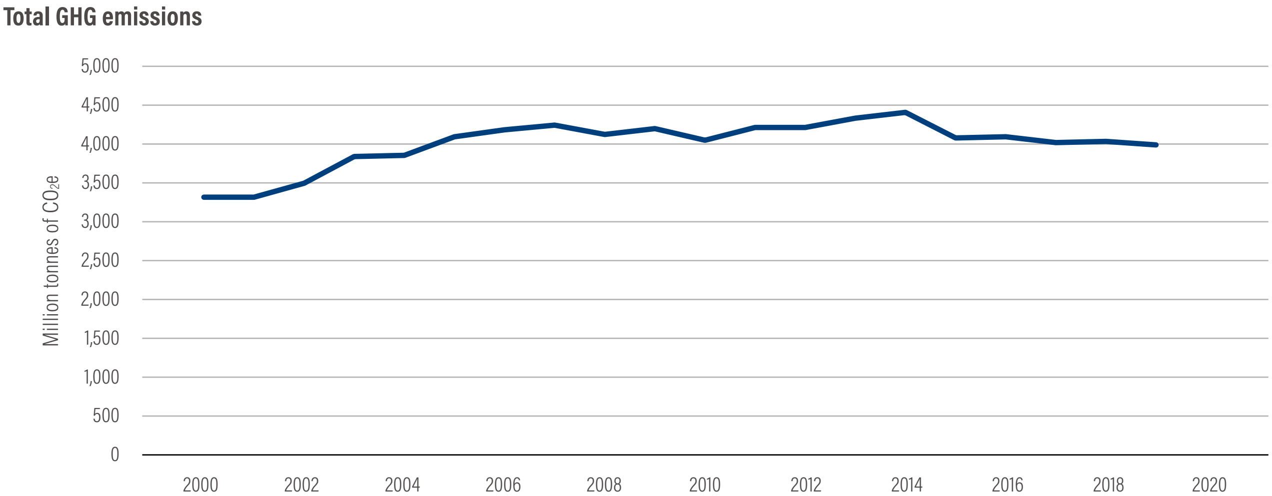
Hong Kong's electricity consumption was 44.1TWh in 2020 (CSD 2021), a slight decrease from 2019 levels due to the COVID-19 pandemic. In the past 20 years, growth in electricity demand has slowed. Per capita electricity consumption peaked in 2014, the same year that total emissions peaked.

Figure 1 | **Hong Kong's Electricity Consumption and GHG Emissions (I)**



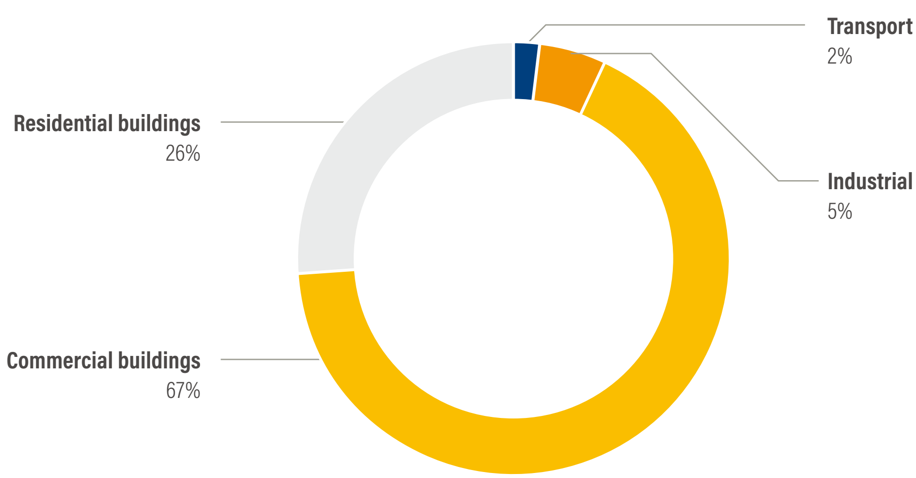
Source: CSD 2021; EPD 2021.

Figure 1 | **Hong Kong's Electricity Consumption and GHG Emissions (II)**



Source: CSD 2021; EPD 2021.

Figure 2 | **Electricity Consumption by Sector in 2018**

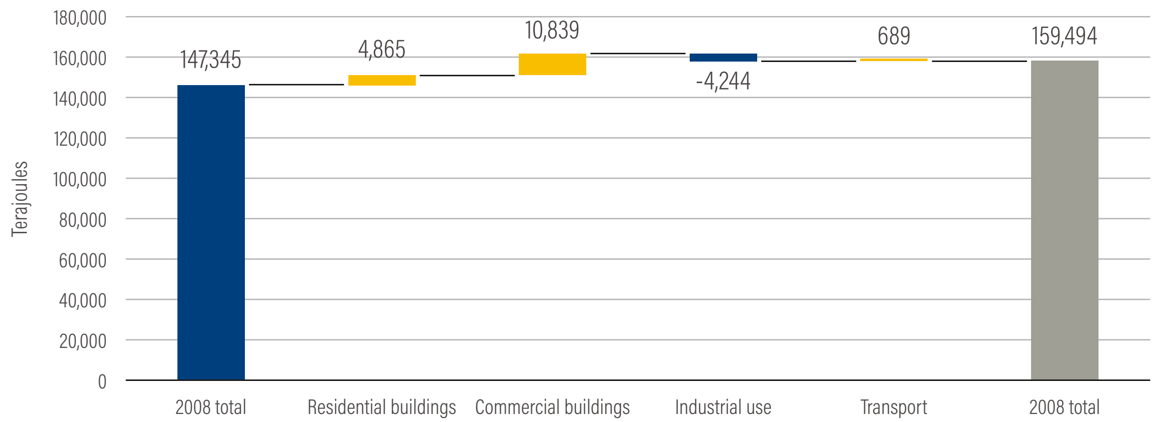


Source: EMSD 2020.

Electricity is playing an increasingly important role in Hong Kong's energy system. Electricity accounted for 55 percent of the final energy demand in 2018, with most coming from commercial buildings, residential buildings, industries, and transport (EMSD 2020). The building sector dominates Hong Kong's electricity consumption, accounting for more than 93 percent of total electricity use (EMSD 2020), as shown in Figure 2. Electrification will continue in the future and is vital for local sustainable development.

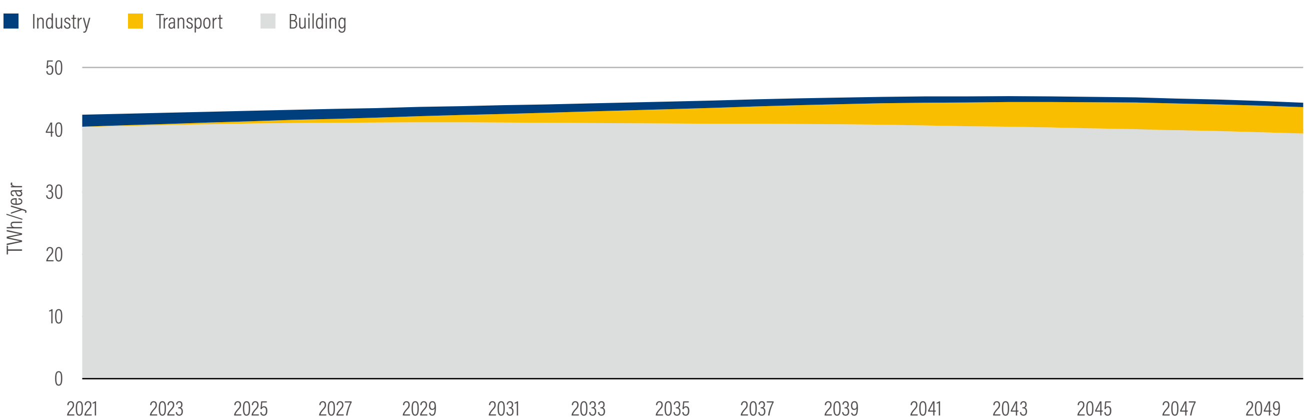
Driven by economic and population expansion, both commercial and residential buildings have experienced moderate growth over the past decade. The number of residential units increased by 14 percent between 2008 and 2018, while the floor area of commercial and industrial buildings rose by 4 percent (CSD 2019). This trend increased electricity demand in the building sector, especially from commercial buildings. Though the transport sector accounted for a relatively small percentage of total electricity consumption in Hong Kong during this time, it actually grew

Figure 3 | **Hong Kong's Electricity Consumption Change by Sector, 2008–2018**



Source: EMSD 2020.

Figure 4 | **Hong Kong's Future Electricity Demand by Sector, 2021-2050**



Source: Hong Kong Energy Policy Simulator (https://hongkong.energypolicy.solutions/).

faster than the others, at 27 percent. This is mainly due to increased demand from the MTR and Tram—large transport systems powered by electricity (EMSD 2020). During the same period, electricity consumption in Hong Kong's industrial sector declined 34.5 percent due to a decrease in industries located in the city (Figure 3).

Based on the results from the Hong Kong Energy Policy Simulator (Hong Kong EPS)[4], which were also presented in *Towards a Better Hong Kong: Pathways to Net-Zero Carbon Emissions by 2050*, Hong Kong's future power demand will gradually increase at an average annual growth rate of 0.4 percent. Total power demand is expected to reach around 46.7 TWh in 2043. After that, it will start to decline to around 45.6 TWh in 2050 (Jiang et al. 2020).

The building sector is forecast to dominate demand for electricity in Hong Kong over the next three decades. Total demand will remain at the current level as a result of increased building areas and electrification, but with improved energy efficiency, according to the Hong Kong EPS. In March 2021, government released the *Hong Kong Roadmap on Popularisation of Electric Vehicles*, which stipulates that Hong Kong intends to prohibit new registrations of private fossil fuel-powered cars, including hybrids, by 2035. This should accelerate a move towards electrification in Hong Kong and increase demand for electricity in the transport sector. It is expected that transport will account for 10.9 percent of total electricity demand in 2050, compared with only 1 percent in 2020 (Figure 4).

Transitioning from Coal to Clean Energy

In 2020, local power plants, dominated by fossil fuel-fired power plants, provided 73.4 percent of Hong Kong's total electricity demand, while imported nuclear energy from the Daya Bay Nuclear Power Station in Guangdong Province contributed the remainder. (CSD 2020a).

Historically, coal has dominated local power generation, but it is gradually being replaced by gas-fired power generation. In 1997, government decided to stop building new coal-fired power plants. In 2017, it published *Hong Kong's Climate Action Plan 2030+*, which laid out a plan to continue phasing out coal for electricity generation to 25 percent of the energy mix, to increase the share of natural gas to 50 percent by 2020, and to increase non-fossil fuel sources. (Hong Kong Steering Committee on Climate Change 2017). In 2020, natural gas (48 percent) surpassed coal as the primary source of electricity generation, followed by imported nuclear energy (28 percent) and coal (23 percent) as shown in Figure 5.

Hong Kong also seeks to develop and introduce clean energy solutions, such as solar and wind power generation, as well as hydrogen, to reduce carbon emissions and achieve its carbon neutrality target. However, considering resource and geographical constraints, Hong Kong needs to develop refined policies for both renewable energy substitution and decarbonisation of its fossil-fuel dominated power system.

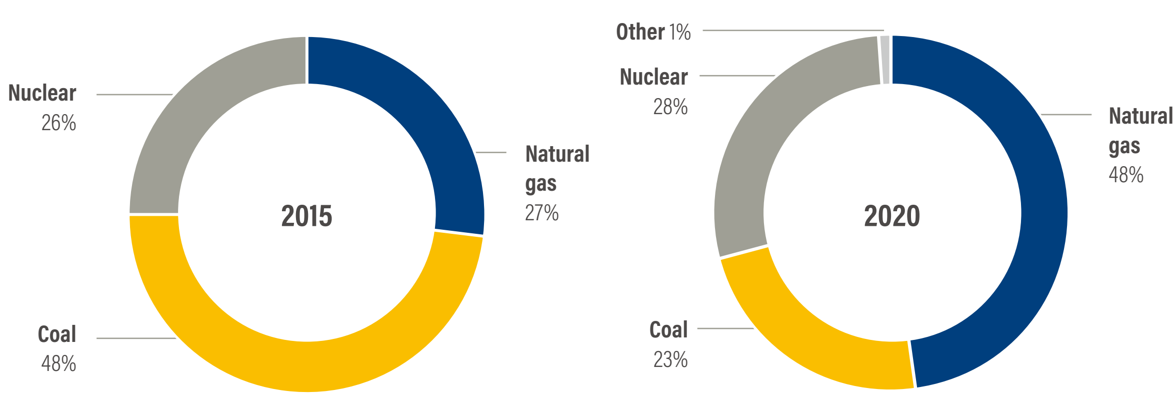
Institutional and Regulatory Framework for the Transition

Hong Kong's electricity is supplied by two investor-owned and vertically integrated utility companies, CLP Power Hong Kong (CLP) and the Hong Kong Electric Company Limited (HKE). These two companies own and operate Hong Kong's local power-generation plants and transmission and distribution network, whilst serving different areas of the city.

CLP supplies electricity to Kowloon and the New Territories, including Lantau, Cheung Chau, and most of the outlying islands. CLP owned a total installed capacity of 9,573 MW in 2020 (CLP 2021b) and has 25 percent equity in the Daya Bay nuclear power plant (CLP n.d.b). HKE supplies electricity to Hong Kong Island, Ap Lei Chau, and Lamma Island, and owned a total installed capacity of 3,617 MW in 2020 (HK Electric Investment 2021). The two companies are the implementing parties for the power sector's decarbonisation goal.

Government is responsible for regulating the electricity market. Every 15 years, it enters SCAs

Figure 5 | **Electricity Generation Mix in Hong Kong, 2015 and 2020**



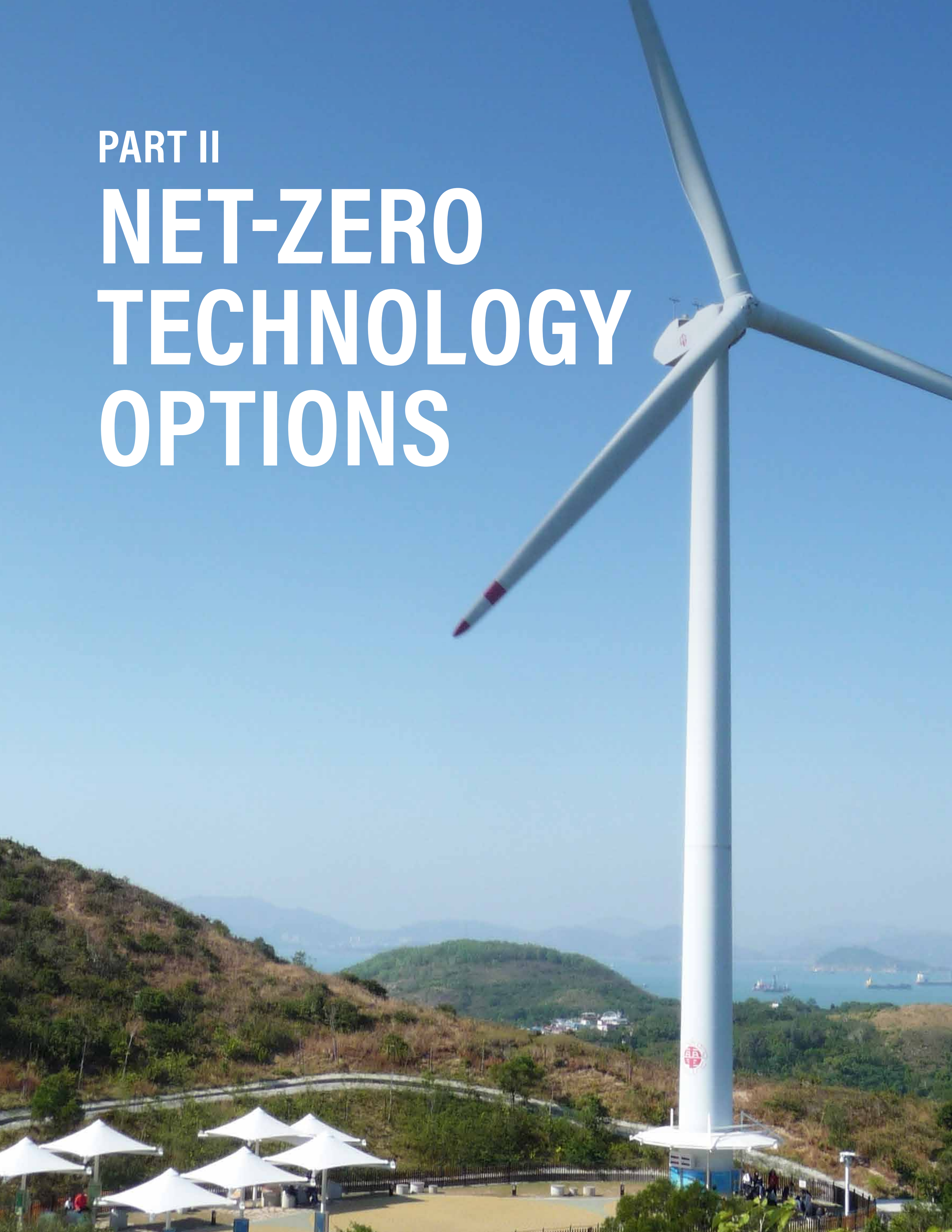
Source: Hong Kong Steering Committee on Climate Change 2017; CLP 2021a; 2021b; HKE 2021.

with each utility company, imposing specific requirements on the two monopolies regarding shareholder dividend limits, electricity prices, and corporate responsibilities and obligations, as well as other finance-related matters. Any additional generation, transmission, and distribution facilities must be approved by government. As SCAs regulate the rights and obligations of the companies, they are considered the most important documents in the local electricity market. They are a vital tool in ensuring energy security and minimising the environmental impact of electricity generation, while promoting energy efficiency and conservation (ENB 2021a).

The first SCA was signed in 1964. The current SCAs were signed in 2017 and became effective in 2018 for CLP and 2019 for HKE. The two agreements will expire in 2033. They reflect Hong Kong's commitment to combatting climate change, promoting efficiency and conservation, developing renewable energy sources, and meeting public expectations for the future development of the electricity market. Ever since the first SCA, the agreements have focused on government's role in monitoring electricity-related financial affairs, such as the rate of return, which is currently at 8 percent for shareholders under the current SCA. Increasingly, government has focused on providing financial incentive schemes for the promotion of sustainability, such as an additional rate of return for the improvement of energy-efficient performance through energy audits and supporting the Feed-in Tariff Scheme. SCAs are important regulatory tools for the electricity market. Our recommendations in this report highlight their potential.

PART II

NET-ZERO TECHNOLOGY OPTIONS



CHAPTER 2

RENEWABLE ENERGY AND WASTE TO ENERGY

Less than 1 percent of Hong Kong's electricity consumption is supplied by renewable energy sources (Figure 6). Hong Kong's Climate Action Plan 2030+ indicates a renewable energy target of 3–4 percent by 2030, but other research suggests the city should aim much higher in this field. (Hong Kong Steering Committee on Climate Change 2017). This Chapter examines the potential of WtE, solar power, and wind power in Hong Kong.

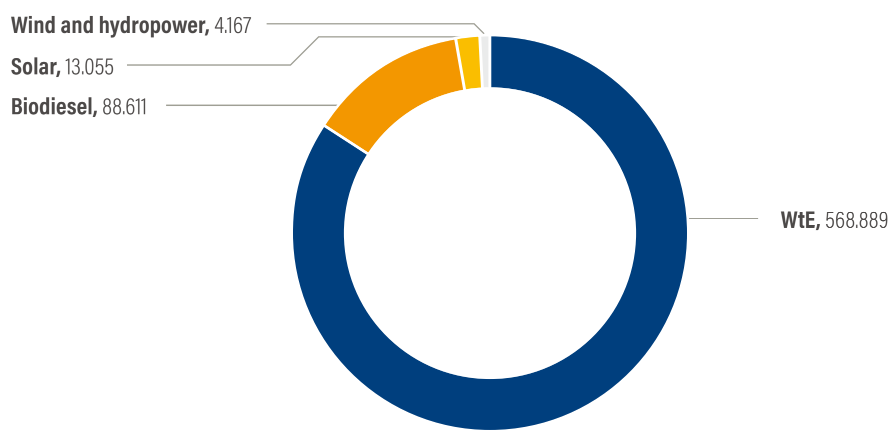
Waste to Energy

Current Capacity

As a city with one of the world's highest levels of waste per capita per day (1.47 kg), Hong Kong sent 4.04 million tonnes of municipal solid waste (MSW) to landfills in 2019 (ENB 2021b). GHG emissions from the waste sector doubled from about 1,550 kilotonnes CO_2e in 1990 to 2,940 kilotonnes CO_2e in 2019 (EPD 2021). It is the only sector in Hong Kong that has increased its emissions since 2014. WtE contributed 84% of electricity generation from local renewable energy (Figure 6).

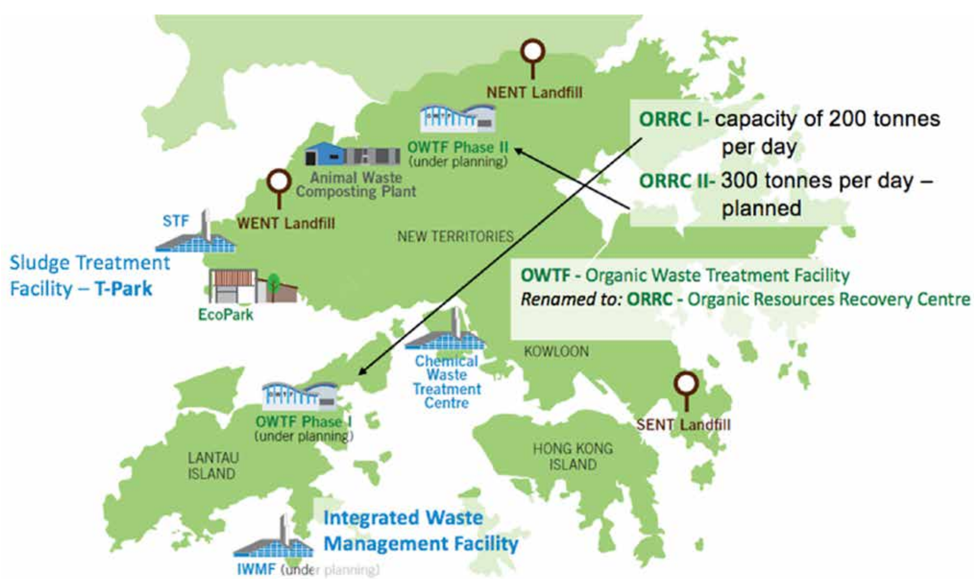
WtE technology offers a solution to three of the city's most pressing problems: an overburdened waste management system, the lack of low-carbon energy, and limited land available for landfill and waste disposal. Currently, WtE produces 560.83 GWh of energy and makes up 86 percent of all the renewable energy in Hong Kong (EMSD 2020). Major WtE technologies include landfill gas utilisation, anaerobic digestion, and thermal treatment with energy recovery.

Figure 6 | **Composition of Renewable Energy in Hong Kong (GWh)**



Source: EMSD 2020.

Figure 7 | **Location of Waste Management Facilities**



Source: ENB, 2013.

Potential Capacity

Hong Kong's waste management structure relies heavily on landfills and has virtually no incineration capacity, as government shut down all municipal waste incinerators during the 1990s.

In *Hong Kong's Climate Action Plan 2030+*, government estimates no more than 1.5 percent of Hong Kong's electricity will come from WtE through the Organic Resources Recovery Centre (ORRC) Phase 3 and Integrated Waste Management Facilities (IWMFs) that recover heat energy from the MSW incineration process.

In 2017, the Environmental Protection Department (EPD) commissioned an environmental impact assessment of the ORRC Phase 3, or O-Park3, with a proposed capacity of 300 tonnes per day (EPD 2017). A site in Shek Kong, Yuen Long, was identified for this facility, yet no further action has been taken.

In addition to the commissioned IWMF Phase 1 site in Shek Kwu Chau, which is predicted to produce approximately 480 million kWh of surplus energy for the power grid annually, the Tsang Tsui Ash Lagoon was also identified as a suitable site for IWMF Phase 2 (EPD 2008). Situated adjacent to the WENT Landfill and CLP's Black Point Power Station, this new location offers multiple advantages, including the ability to share existing infrastructure, such as berthing facilities and the easy disposal of ash residue generated by IWMF into the landfill. Its proximity to the power plant also means easy connection to the power grid.

Challenges and Opportunities

Liu et al. (2017) conducted an analysis of the environmental impact of five waste-management technologies. They found that the optimum strategy for GHG reduction was the anaerobic digestion (AD) of source-separated organic waste and the incineration of portions of waste high in plastics. Residue landfilling was the least optimal option. Iqbal et al. (2019) supports this conclusion. In their analysis of various integrated solid waste management scenarios based on net GHG emissions and energy use, they found that integrating incineration with combined AD and composting has the best potential for energy recovery and can save up to 87 percent of GHG emissions. Without energy recovery, though, the incineration method is unfavourable. The application of carbon sequestration is also a decisive factor that affects the overall impact of each scenario.

When estimating the potential GHG emissions in Hong Kong's waste development plan, Dong et al. (2017) found that after implementing IWMF, GHG emissions from landfills would decrease by 52 percent by 2030, compared to 2018 levels. However, total GHG emissions from the entire waste sector were predicted to increase by 332,206 tonnes of CO_2e in 2020, compared to 2010 levels. The additional emissions come from the combustion of petroleum products when plastics are thrown away. This can be negated by robust recycling and waste-sorting efforts to remove plastics from the incineration stream or by reducing overall solid waste disposal by 40 percent. Dong et al. (2017) demonstrate that incineration is not a silver bullet for the city's waste or clean energy issues; instead, there must be active waste-reduction efforts and improvements in recycling for IWMF to be considered a climate-friendly solution.

Despite the benefits of integrated waste management and the potential for incineration, the people of Hong Kong are resistant to the new Shek Kwu Chau incinerator. In 1989, government issued *Pollution in Hong Kong—A Time to Act*, a white paper which determined that incinerators were a major source of pollution in urban areas, accounting for approximately 18 percent of all respirable particulates emitted into the atmosphere, as well as a source of trace quantities of highly toxic substances. This led government to shut down municipal waste incinerators in the 1990s. Since then, incinerator technologies have improved. By adopting advanced process-control measures to optimise the combustion process and meeting stringent international emission standards, incineration has become more accepted and is widely used around the world today. Government reversed its decision against incinerators in their 2005 *Policy Framework for the Management of Municipal Solid Waste* *in Hong Kong*, which included building IWMFs with incineration as the core technology for final waste treatment. However, the 1989 white paper brought about negative public attitudes towards incineration that continue to be the majority view today. Some also consider incineration as a bandaid solution to larger waste issues and an ineffective use of public funds. These concerns are certainly warranted. Burning waste could cause adverse health conditions, and, furthermore, so long as volumes continue to rise, it is not sustainable over the long term. Government should educate the public about incineration to build support but not without communicating its disadvantages. If incineration is still judged a viable option upon evaluation, then government should seek technology and management methods to mitigate as much of the negative impact as possible. This may include using advanced incineration technologies that reduce pollutant emissions from incineration, comply with stringent emission standards, and do not cause adverse health impacts.

Solar Energy

Current Capacity

Over the past 10 years, solar power systems have experienced a 35 percent build-out rate due to heavy investments and policy support globally (Hydrogen Council 2021). In 2015, Hong Kong's photovoltaic (PV) capacity was less than 5 MW, involving an accumulation of distributed small-scale projects. Currently, Hong Kong has several planned and constructed large-scale PV systems. Examples include HKUST, which intends to install 8,000 monocrystalline solar panels generating 3 million KWh annually; Dairy Farm International, which is building a 1-million-KWh solar panel system at its Wellcome Fresh Food Centre in Tseung Kwan O; Hong Kong Disneyland, which is aiming to install more than 4,500 solar panels to produce 1.86 MWh annually; the Siu Ho Wan Sewage Treatment Works, with a capacity of 1 MW, producing 1 million KWh of electricity annually (built in 2016); and a 1 MW solar panel system at the Lamma Power Station (constructed in 2013 by HK Electric). There are other small-scale systems in government buildings, school campuses, and private buildings.

In 2017, government began a Feed-in Tariff (FiT) Scheme to encourage residents to install private renewable-energy (RE) generators on their properties. This scheme allows participants to sell their electricity to power companies at HKD3-5/kWh, around five times the regular rate (HKE n.d.), but one that is subject to an annual review. However, the rate is fixed from the date the participants enter the FiT scheme either until the end of the project life of the owner's RE system or the end of 2033—whichever is earlier. After 2033, all the electricity generated will belong to the RE system owner. This reduces the payback period and offers an exciting incentive for people to install RE systems. As of 2020, there were 13,072 applicants to the program and 176,200 KW purchased by government and utility companies from individual solar PV array owners. The electricity generated by FiT accounted for less than 0.01 percent of the total electricity consumption in 2020.

Potential Capacity

Government predicts that only 1-1.5 percent of Hong Kong's electricity needs in 2030 can be powered by solar energy. Taking the total electricity consumption in 2019—44.8 TWh—as a framework for comparison, this is the equivalent of 0.67 TWh. Yet, other studies offer much greater estimates. According to an IEA report, rooftop solar PV can make a significant contribution to meeting electricity demand in cities; the technical potential of rooftop solar PV could provide up to 32 percent of urban electricity demand by 2050. With further policy support and investments into the development of solar energy, as well as plunging costs and rising panel efficiencies, solar energy can become even more cost effective than other forms of generation by the end of the decade.

Challenges and Opportunities

Solar has the potential to make significant contributions to the local renewable energy mix; however, there are obstacles to finding its maximum potential as calculated in the studies cited in Table 1. About a decade ago, the most significant barriers for solar energy diffusion in Hong Kong were the high initial and repair costs, the long payback period, inadequate installation

Table 1 | **Summary of Predictions on Solar Utilisation Output in 2030 as a Percentage of Demand in 2019**

STUDY	ESTIMATED ANNUAL OUTPUT (TWh) IN 2030, AS A % OF ELECTRICITY DEMAND IN 2019	LOCATION OF INSTALLATION	TECHNOLOGY	TYPE OF SOLAR RADIATION
EMSD (2002)	5.94 (13.3%)	Building rooftops	Building integrated PV (BIPV)s	Direct normal irradiance
Peng & Lu (2012)	5.98 (13.4%)	Building rooftops	Monocrystalline silicon modules	Diffuse horizontal irradiance
Wong (2015)	2.43 (5.4%) 38 (84.8%)	Building rooftops, open spaces	-	Direct normal irradiance
Wong et al. (2016)	2.66 (5.94%)	Building rooftops	Mono- and poly-crystalline silicon modules	Diffuse horizontal irradiance
WWF (2017)	3.95 (8.8%)	Reservoirs	-	Direct normal irradiance

Source: EMSD 2002; Peng & Lu 2012; Wong 2015; Wong et al. 2016; WWF 2017.

space, inadequate service infrastructure, the lack of stakeholder or community participation in energy choices, and legal and regulation constraints.

Government's introduction of the FiT Scheme in 2017 provided a much-needed push for solar energy deployment. Some projects reported an average payback period of six years if the current rates remained constant, which spurred numerous small-scale private investments in solar equipment (Chan 2019). Government says it will provide incentives until 2033; however, what happens beyond this year is unclear. While the FiT Scheme has provided some incentives and confronted the issue of long return on investment, policy support does not guarantee the ubiquitous deployment of solar energy in Hong Kong. Citywide land constraints stunt capacity factors and the average size of installations.

Furthermore, while the estimated total rooftop area of all buildings in Hong Kong is around 42.6 square kilometres, one third of this is deemed unsuitable for PV systems—for instance, the perimeter zone of roofs due to lower solar irradiance, and pitched roofs with slopes greater than 40 degrees. Excluding these areas brings the total viable rooftop area for PV systems down to 25.7 square kilometres.

Moreover, regulatory constraints, such as the cumbersome installation process of PV systems, create barriers to installing solar energy systems throughout Hong Kong. Customers must go through the regulatory hoops and involve multiple parties. They need, for instance, to obtain permission from the Buildings Department for construction; appoint a prescribed registered contractor (PRC) to submit a form outlining the intended works; appoint a registered electrical company to commence work; and submit a generating facility registration to the EMSD. Lastly, the PRC must submit a form after the completion of works to the EMSD. Additionally, installing a solar energy system on a high-rise residential building requires approval of all its owners, which is a difficult task because few owners would want to pay for the extra costs involved.

The recent introduction of one of the world's largest floating solar panel farms in Singapore is a huge step in the promotion of solar energy. With Singapore and Hong Kong both exposed to similar extreme weather events, such as typhoons and heavy monsoon rain, the success of Singapore's floating solar panel farm provides Hong Kong with some certainty that similar technology can be deployed in the city to help deal with such natural disasters. Moreover, floating solar panels could address capacity factor issues in Hong Kong, raising the potential of solar energy. Hong Kong can also follow in the footsteps of the Solar Roadmap for Singapore, prepared by a consortium led by the Solar Energy Research Institute of Singapore of the Natural University of Singapore for the Singapore government. It states that the accelerated scenario could contribute about 22 percent (2030) and 43 percent (2050) to electrical power demand around noon every day.

In the meantime, government could implement two prospective solar communities in Hong Kong—Fairview Park and Hong Lok Yuen—which have the capacity to produce substantial amounts of solar electricity. Government also needs to develop proper manufacturing and disposal protocols to limit the ecological and carbon footprint of solar panels.

Wind Energy

Current Capacity

Hong Kong has the wind energy potential to supplement its renewable-energy base. There are a few locations where the conditions are right, namely where wind power density is above 200 W/m^2 and the maximum water depth is 30 metres. Potential locations for wind farms are summarised in Figure 8. So far, Hong Kong has only a small number of wind projects, all onshore, with a total capacity of less than 1 MW. The majority of wind power comes from a single 0.8 MW Lamma Wind turbine operated by the Hong Kong Electric Company Limited. There are also a number of small-scale projects with individual turbines operating on government buildings and nongovernment structures. These installations have a limited capacity of 1-1.5 KW.

Large-scale wind power systems require vast areas of land and must be located in sparsely populated areas, if not offshore. While there are currently no offshore or large-scale wind power stations in Hong Kong, several studies have assessed the suitability of wind farm development in the city's surrounding waters. In 2006, HKE conducted a feasibility study of a 100 MW offshore wind farm with 40 sets of 2.5 MW class wind turbine units (HKE 2006). Also in 2006, CLP commissioned a feasibility study for an offshore wind farm with 50 turbines in the southeastern waters of Hong Kong that has a maximum output of 150 MW (HK

Figure 8 | **Potential Sites for Offshore Wind Development**

Source: Wong Kam Sing, 2020

Offshore Wind Limited 2006). Furthermore, CLP identified several areas where offshore wind energy stations could be developed, as highlighted in green in Figure 8.

As technology and equipment associated with wind energy generation develops and becomes more cost-effective, CLP is planning to build a 250 MW wind farm. CLP considers offshore wind energy systems a vital part of Hong Kong's future energy mix and is hoping that innovations in this area can help government meet its 2050 carbon-neutrality target. HKE is also seeking to construct an offshore wind farm southwest of Lamma Island in the short term.

Potential Capacity

Government says it is not completely ruling out the aforementioned projects in the medium term and estimates that total power generation from wind will amount to 660 GWh. Other studies offer a higher potential capacity by assessing the feasibility of wind energy development in other locations.

Challenges and Opportunities

Wind energy is well recognised as a clean alternative to conventional fossil fuel-fired power. Though wind energy does not release air pollutants and GHGs during its operations, it can potentially bring an adverse environmental impact, especially on local ecosystems by potentially reducing, fragmenting, or degrading habitats for wildlife, fish, and plants.

The construction of offshore wind farms is very likely to affect marine mammals. Activities of greatest concern are pile driving and increased vessel traffic. Moreover, as wind turbines operate, birds migrating through the area may collide with moving blades, causing higher mortality rates. In addition, the transmission of produced electricity via cables emits an electromagnetic field, which could affect the movement and navigation of species sensitive to them (Bailey et al. 2014). Both HKE and CLP have environmental permits for wind farm developments and they consider mitigation measures as part of the permit application process. However, due to the potential impact of wind power on wildlife, the power companies must continue to pay attention to and minimise their environmental impact.

A significant limitation is the various human activities in Hong Kong waters that interfere with the development of offshore wind farms. Using all 1,659 km2 of Hong Kong's waters, Li (2000) estimates that offshore wind has the

Table 2 | **Summary of Predictions on Wind Utilisation**

STUDY	ESTIMATED ANNUAL OUTPUT (GWh), AS A % OF ELECTRICITY DEMAND IN 2019	LOCATION	CAPACITY OF HYPOTHETICAL WIND FARM (MW)	ANNUAL WIND SPEED (m/s)	AVERAGE WIND POWER DENSITY (W/m^2)
EMSD (2002)	2,630 (5.9%)	Onshore rural wind farms	1,500	-	200
Lu et al. (2002)	0.032 (<1%)	Offshore - Waglan Island	NA (single turbine)	6.92	-
Gao et al. (2014)	11,280 (25.2%)	4 offshore sites	102.75	-	-
Gao et al. (2019)	14,449 (32.2%)	Southwest Lamma	100	7.03	200

Source: EMSD 2002; Lu et al. 2002; Gao et al. 2014; Gao et al. 2019.

potential to provide 40–72 percent of the city's electricity consumption. However, the total sea area available for development is reduced after factoring in the shared use of these waters with shipping, gas, electric submarine cables, and mud disposal. Marine conservation and recreational areas that are protected from any form of development also need to be counted out.

The demand and supply mismatches also render wind energy a less viable alternative. Electricity demand is high during the hot summer months (May–September) and low during the mild winter months (November–April). Yet, the seasonal variation from wind power production is the reverse, since more electricity is produced in winter than summer. This may not be a technical issue in terms of grid operations due to the diverse makeup of the fuel source, but it remains a factor for further consideration.

Although Hong Kong's average wind speed is relatively moderate, the city is frequently affected by typhoons. This poses a serious risk to offshore wind development. In 2013, Typhoon Usagi hit the Honghaiwan Wind Farm in Shanwei, Guangdong, wiping out 70 percent of its wind turbines (Winn 2013). This resulted in 100-million-yuan worth of losses and raised the question of wind farms' ability to withstand typhoons.

Aside from practical constraints, financing is another issue to address. With the high capital investments needed for wind energy production, government and the city's power companies may face financing burdens with regard to the long-time payback, high risk, and low return from wind energy projects.

Conclusion

Domestic RE is an important step for the power sector to achieve carbon neutrality but does not represent the entire solution. As shown in Table 3, aggregated domestic RE potential can only supply 10 percent of Hong Kong's electricity demand by 2050. The commissioned, planned, or potential development projects for domestic RE are summarised in Table 4. Moreover, the mismatch between demand and supply also renders solar and wind energy less viable alternatives. As such, wind and solar energy may not be able to keep up with demand. Having a diverse energy mix may mitigate supply issues in grid operations, but it cannot be disregarded altogether. Energy storage solutions, such as hydrogen storage, may be helpful in resolving supply mismatches.

Renewable energy may not be the central pillar of Hong Kong's transitioned low-carbon energy mix, but it has a crucial part to play. Government must also broaden the fuel mix option through regional collaboration to import renewable or low-carbon electricity from elsewhere, making Hong Kong's grid cleaner and more climate proof in the process.

The potential for domestic RE is less than academic projections but exceeds the existing government target. Hong Kong's potential for renewable energy far exceeds that of government's 2030 target of 3–4 percent of the energy makeup. However, whether Hong Kong can realise this technical capacity for renewables remains to be seen. If four offshore wind farms are built, wind power has a maximum output potential of 11,280 TWh per year, enough to meet 25.2 percent of Hong Kong's electricity needs. Yet it is unlikely that these plans will become a reality, at least in the short to medium term. In addition, the lack of open space hinders widespread installation of onshore windfarms; the need to accommodate shipping channels, conservation areas, undersea cables, and power cable landing points creates other obstacles facing large-scale offshore windfarms.

Regarding solar energy, academic estimates are optimistic but unrealistic. If all rooftops and reservoirs are utilised, the maximum potential is 9.93 TWh or 22.2 percent of electricity demand. Yet, land and space constraints in Hong Kong prevent high estimations of locally produced renewable energy. Hong Kong's densely populated high-rise buildings obstruct several rooftops from receiving adequate sunlight.

There is a large base of support for solar energy in the community, and government has responded to this by introducing the FiT Scheme and other grant programs. However, costs remain high, and without more widespread regulatory changes, these efforts won't be enough to allow solar to reach its real potential. Furthermore, current efforts are aimed at building small-scale, individual PV systems, which will not lead to the large-scale solar coverage that these studies are proposing.

This study established the following scenario, after a comprehensive literature review and in-depth conversation with local and international experts.

Table 3 | **Estimate of Future Potential in This Study**

TYPE OF ENERGY	% OF ELECTRICITY DEMAND IN 2030	% OF ELECTRICITY DEMAND IN 2050
Waste-to-energy (WtE)	2%	3%
Solar energy	1%	4%
Offshore wind energy	1%	3%

Source: Authors' estimates

Table 4 | **Commissioned, Planned or Potential Development for Domestic RE**

	STATUS	TYPE OF TECHNOLOGY	EXPECTED ELECTRICITY PRODUCTION	
			GWH	% OF ELECTRICITY DEMAND IN 2019
WtE	Commissioned for 2023	*Anaerobic digestion*	24	0.05%
	Commissioned for 2025	Thermal treatment with energy recovery (MSW incinerator)	480	1%
	Planning (beyond 2030)	*Anaerobic digestion*	24	0.05%
	Planning (beyond 2030)	*Anaerobic digestion*	24	0.05%
	Planning (beyond 2030)	*Anaerobic digestion*	24	0.05%
	Planning (beyond 2030)	Thermal treatment with energy recovery (MSW incinerator)	480	1%
	Planning (beyond 2030)	Thermal treatment with energy recovery (MSW incinerator)	480	1%
	Total for WtE		1,543.5	3.27%
Solar	Potential development (2030)	Solar rooftops	400	0.9%
	Potential development (2050)	Solar rooftops	1,300	3%
	Total		1,713	4.2%
Wind	Potential development (2030)	Offshore wind farm (Southwest Lamma)	175	0.4%
	Potential development (2030)	Offshore wind farm (Southeastern Waters)	410	0.92%
	Potential development (2030)	Offshore wind farm (Southeastern Waters / Waglan Island)	800	1.8%
	Total for wind energy production		1,398	3.16%
Total			4,654.5	10.63%

Source: Authors' estimate based on literature review in this Chapter.

CHAPTER 3

FOSSIL FUELS WITH CCS

In 2020, natural gas contributed 48 percent of Hong Kong's electricity generation, while coal accounted for 23 percent. Despite Hong Kong's plans to phase out all coal in the future, electricity generation from natural gas would still produce worrying amounts of emissions. If CCS technology becomes commercially available, it could abate the emissions of fossil-fuel power plants while maintaining their dispatchable power output to underpin local reliability in a flexible manner.

Use of Fossil Fuels and Potential for CCS

Currently, Hong Kong has four fossil fuel-fired power stations in operation–Castle Peak Power Station, Black Point Power Station, Penny's Bay Power Station, and Lamma Power Station. They use coal, natural gas, and oil. The current total capacity of Hong Kong's coal-fired power generation is 6,108 MW. Only one power station, CLP's Castle Peak, is dedicated to using coal. According to their power development plans, the utility companies are actively replacing coal with natural gas for power generation. An estimated 1,650 MW of coal generation capacity is planned for retirement by 2025, while day-to-day use of coal for electricity generation is expected to be phased out entirely in the 2030s. The Castle Peak facility is expected to be phased out before 2040. With two newly added gas-fired power generation units in operation, the total capacity of gas-fired power in Hong Kong is 4,210 MW. The city uses combined-cycle gas turbine (CCGT) technology for gas-fired power generation. Based on the companies' plans, gas capacity is expected to increase to 5,580 MW in 2030 (CLP 2021a; HKE 2021)

Ultra-low sulphur diesel oil is utilised at Penny's Bay and Lamma, with open-cycle oil-fired gas turbines (OCGT) used to generate electricity. The OCGT units have quick-start abilities and capacity flexibility. They are used to meet load peaks and as backup for emergency responses to contingencies. The total capacity of oil-fired power generation is 1,360 MW. HKE proposes to construct and commission up to four new oil-fired OCGTs, each with a capacity of up to 130MW, to replace their existing units at the Lamma facility (HKE 2020).

Conventional fossil fuel-fired power plants (without CCS) produce more carbon emissions than other decarbonised energy resources and are not compatible with Hong Kong's carbon neutrality vision. Through capturing, transporting, and storing CO_2 emissions, CCS technologies could abate emissions from fossil fuel-fired power plants while maintaining dispatchable power output in a flexible manner. This would be of great value to Hong Kong, where fossil fuel-based power generation is likely to perform an important role due to limited renewable energy and land resources.

Globally, there are situations where CCS facilities are applied to coal-fired, natural gas-fired, and biomass power plants (including WtE) (Global CCS Institute 2020). The Asia-Pacific is an emerging region for CCS deployment, as more countries are establishing CCS strategies and developing pilot CCS projects (Global CCS Institute 2020). But ensuring sufficient carbon storage capacity is a key challenge in CCS application. Studies in Guangdong have identified saline aquifers about 100 kilometres

offshore that would have ample capacity for centuries of storage. Technically, this could enable Hong Kong to build a decarbonised power system with CCS.

Challenges of Continued Use of Fossil Fuels and Application of CCS

In 1997, government decided against building new coal-fired power plants in an effort to reduce air pollution. Since then, gas-fired power plants have gradually replaced coal. Hong Kong has already achieved a target laid out in Government's *Climate Action Plan 2030+*, which aimed, by 2020, for natural gas to generate about half of Hong Kong's electricity, with coal falling to 25 percent (Hong Kong Steering Committee on Climate Change 2017). However, fossil fuel-fired power plants continue to dominate Hong Kong's power sector, accounting for more than 70 percent of power generation.

Replacing coal with gas has both climate and air-quality benefits. Generally, when compared with coal-fired power plants, CCGT power plants emit around half the amount of CO_2, one-third the amount of NO_x, and virtually zero SO_2. Table 5 shows the carbon and air pollutant emissions per unit of electricity output in CLP's fossil fuel-fired power plants in 2019.

According to CLP data, CO_2 emissions per kWh from the gas-fired Black Point are 0.404 kg, around 60 percent less than Castle Peak, which is coal-fired. Though Black Point emits less carbon emissions and air pollutants per unit of electricity than the coal-fired power plant, it alone cannot help Hong Kong meet its 2050 carbon-neutrality target. Reaching carbon neutrality without applying CCS technologies requires the virtual elimination of all fossil fuel-fired power generation in Hong Kong.

The transition from coal to gas significantly increases the cost of unit electricity output due to the higher associated fuel costs. The cost of power generation by natural gas is more than double that of coal (CLP 2020b). In February 2020, CLP's fuel generation costs per unit of electricity were around HK$0.70 per kWh for gas, compared with around HK$0.25 per kWh for coal (Jiang et al. 2020), indicating an equivalent CO_2 mitigation cost of HK$0.78/kg CO_2 or US$100/ton CO_2.

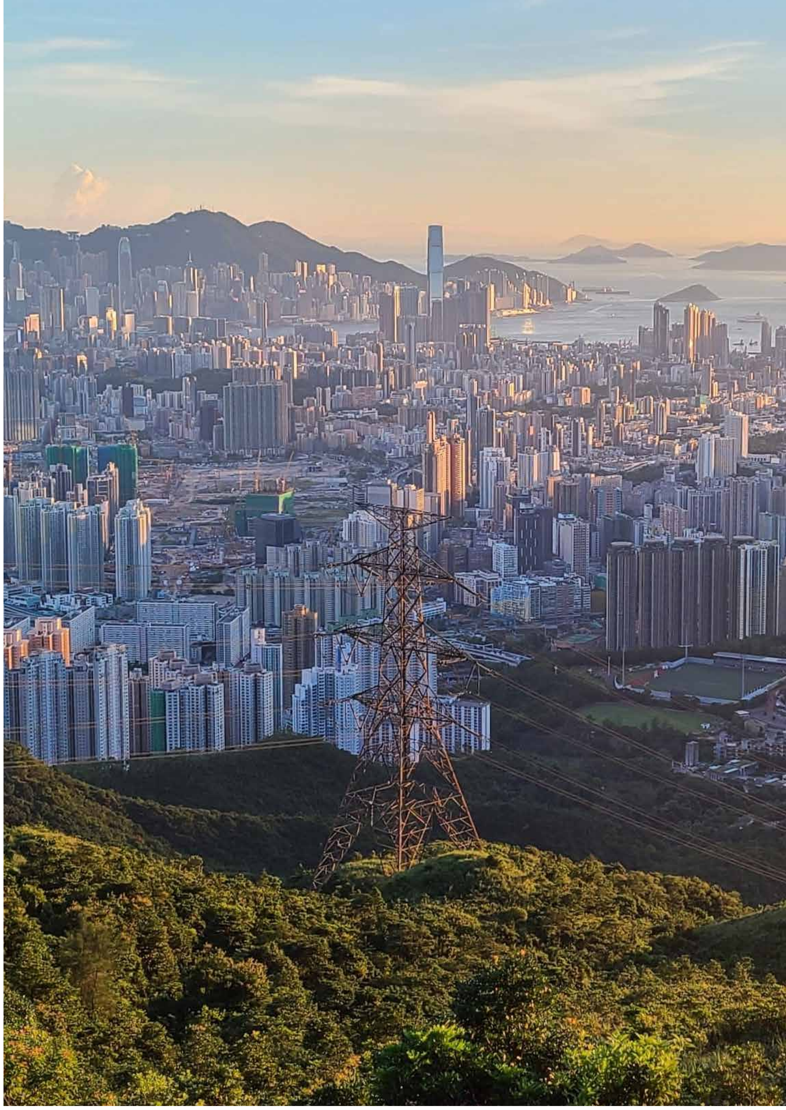
There is growing recognition that CCS is an integral part of a least-cost portfolio of technologies needed to support the decarbonisation of power systems globally. However, CCS deployment has been slow. Currently, only two commercial CCS facilities are in operation globally, which are both CCS retrofits to existing coal-fired power plants. There are no commercial CCS projects at gas-fired plants in operation today (Global CCS Institute 2020).

Table 5 | **Carbon and Air Pollutant Emissions per Unit of Electricity Output in CLP's Fossil Fuel Power Plants in 2019**

POWER STATION	FUEL	CO_2 EMISSIONS (kg/kWh)	SO_2 EMISSIONS (g/kWh)	NO_X EMISSIONS (g/kWh)	PM EMISSIONS (g/kWh)
Black Point	Gas	0.404	0.01	0.15	0.01
Castle Peak	Coal	0.983	0.26	1.08	0.04
Penny's Bay	Oil	1.719	0.01	1.77	0.03

Cost has been identified as the major challenge preventing CCS-equipped power plants from being commercially viable. These costs are associated with the capture, transportation, and storage of CO_2 emissions. The levelised costs of electricity (LCOE) from coal- and natural gas-fired power plants at different carbon capture rates show that carbon capture would increase the cost of electricity output per unit by 47.7–82.2 percent (IEA 2020a). The cost increase is dominated by the capital cost of the capture facility, usually accounting for more than half of the total cost of capture, as seen from the operating experience of the first-generation CCS retrofit plants (IEA 2020a). Additionally, the operating costs of CCS-equipped plants are much higher than conventional plants due to the efficiency penalty required to operate the capture facility. Compared with other decarbonised energy sources, such as renewables and nuclear, the cost of electricity from CCS-equipped power plants is currently substantially more expensive.

Energy penalties are another impediment to CCS deployment in the power sector. To power the operations of CCS facilities, the energy use (and air pollutants) for the same amount of electricity output is expected to increase by around 25 percent (IPCC 2005). In addition, installing CCS cannot prevent all CO_2 emissions; uncaptured emissions are estimated to be around 5–15 percent (Eldardiry and Habib 2018).



Opportunities

Carbon capture technologies can support Hong Kong's power transition towards carbon neutrality. Without carbon capture technologies, however, meeting this target would mean eliminating the use of fossil fuels for power and switching to local renewable energy and imported hydrogen. These options do not appear to be feasible on a large scale due to limited availability. The other solution is additional imported electricity from regional renewable or nuclear sources.

CCS-equipped power plants can run for lengthy periods as base load plants. They can also provide a source of dispatchable, flexible capacity to quickly respond to emergencies and help Hong Kong integrate a growing share of variable renewable energy into the power system. There are numerous studies that identify the potential of technological innovations to reduce the cost of equipping power plants with CCS technologies. The cost of CCS could fall as a result of scale and learning curve effects (IEA 2020a; Dewar and Sudmeijer 2019). But CCS is projected to be a cost-competitive option post-2040, and Mainland China isn't expected to have large-scale CCS development in the power sector until after 2035. In addition to global efforts on CCS-related research and development (R&D), strong policy support and more stringent climate targets are necessary for high market CCS penetration.

Ensuring that all fossil fuel-fired power plants built after 2020 are CCS-ready can reduce the risk of creating stranded assets. Once built, retrofitting existing facilities with CCS could be costly or even infeasible. During the project design phase, power companies should ensure that the technical requirements for CCS are considered and met. These requirements include reserving space for CO_2 capture equipment, configuring turbines appropriately, ensuring the availability of cooling water and the additional flue gas pre-treatment required before CO_2 capture. Also necessary will be dedicated access to auxiliary power.

Hong Kong is located in a potential CCS hub. High quality and sufficient storage capacity are prerequisites, and there are several large sedimentary basins in the northern South China Sea with suitable geological conditions for CO_2 storage. A previous assessment indicated that CO_2 storage capacity in the shelf area of the Pearl River Mouth Basin is 77 $GtCO_2$ at an 85 percent probability level (Zhou et al. 2013). This appears to be the most favourable storage area at present. From a source-sink matching perspective, there is satisfactory distance between Hong Kong's power plants and the storage areas. Sitting in CCS hubs and utilising shared infrastructure can also lower transportation and storage costs. Guangdong has been proactively carrying out CCUS (carbon capture, utilisation, and storage) research and demonstration pilots. In May 2019, China Resources Power's Haifeng carbon-capture test platform (CCTP), located on Guangdong's coast, began operations. The CCTP consists of two CCS-equipped coal-fired power generation units, with the capacity to capture 20,000 tonnes of CO_2 per year.

Government should proactively support CCS deployment. Government could look to provide assistance in the form of capital support, public procurement, tax credits, operation subsidies, and carbon pricing, as well as by enhancing coordination with authorities from Mainland China on CO_2 storage. To increase public awareness, government could collaborate with power companies, academics, and nongovernmental organisations to organise programs and activities to facilitate knowledge sharing, as well as to raise public awareness and acceptance around CCS.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CHAPTER 4

GREEN HYDROGEN

Hydrogen has great potential as an alternative energy source in supporting Hong Kong's carbon-neutrality goal. The utilisation of low- or zero-carbon hydrogen can reduce the city's carbon footprint, as well as strengthen its energy security, thus contributing to greater climate resilience. The power sector could benefit greatly from hydrogen's contribution to grid balancing and the management of peak load issues, thereby enhancing the reliability of the power-sector supply.

Introduction to Green Hydrogen

Hydrogen has gained traction over the past few years as it is anticipated to be a key component in the transition to a net-zero carbon emissions society (Timur and Turk 2019). Hydrogen itself is not an energy source but, rather a clean chemical energy carrier with the benefit of facilitating long-range transportation with high efficiency and stable storage over a long period of time.

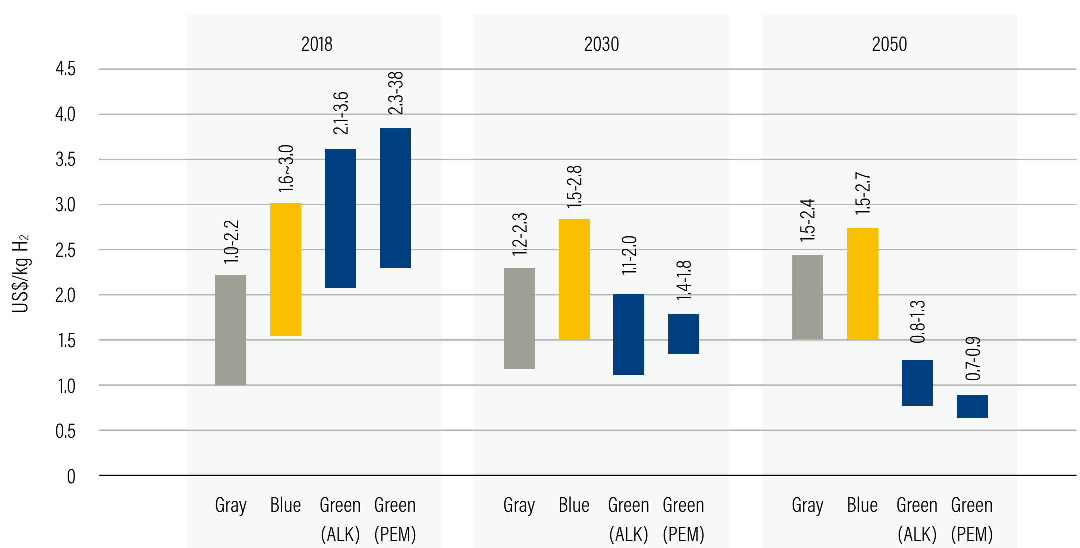
Key Hydrogen Production Technologies

Hydrogen can be generally classified into three categories, all with different levels of environmental cleanliness:

- **Grey:** Produced from fossil fuels and **high carbon**-emitting sources
- **Blue:** Produced from **low carbon**-emitting sources, such as steam methane reforming with CCUS, or other fossil fuels, such as feedstock with CCUS
- **Green:** Produced from **zero-carbon** sources, such as renewable energy via electrolysis (a process taking place in an electrolyser where zero carbon electricity is used to split water into hydrogen and oxygen)

Globally, 75 percent of hydrogen comes from natural gas reforming; 23 percent from coal gasification; and the remaining 2 percent from electrolysis (Timur and Turk 2019). Green is the goal for future hydrogen production. While the high capital and operational expenditures associated with electrolysers are the main barriers to producing entirely green hydrogen, costs are expected to decrease. With hydrogen expected to be a key technology in the move towards decarbonisation, investments in research and development are expected to rise. Electrolysers are projected to have an average 18 percent learning rate (IRENA 2020), which means there will be an 18 percent decrease in costs in the long term due to technological improvements and greater demand for electrolysers. This also means that, globally, green hydrogen is expected to become more cost competitive in comparison to grey and blue hydrogen, due to increased economies of scale of electrolysis production, as shown in Figure 9 below. Moreover, the decreasing costs of renewables will help reduce costs for electrolysis and, thus, lower the costs of 'green' hydrogen.

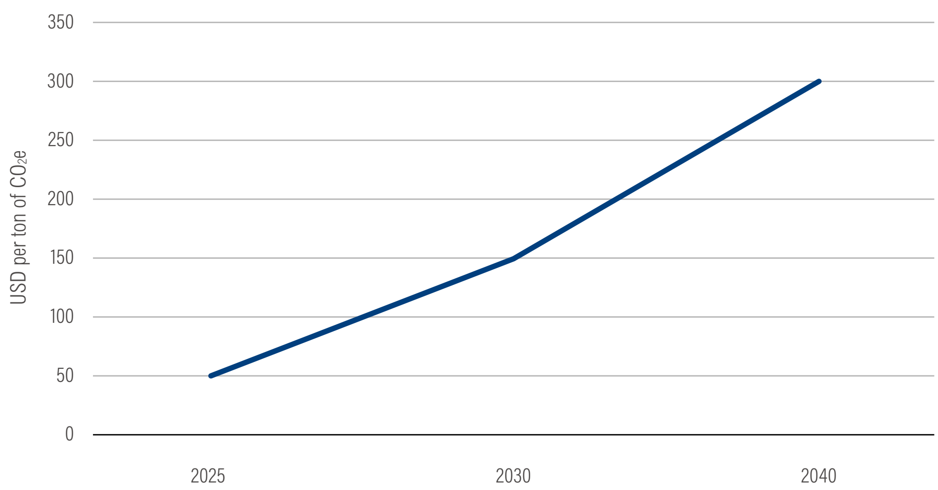
Figure 9 | **Cost-Competitive Projections for Green Hydrogen**



Renewable LCOE (US$/MWh)	30-45	18-26	14-18

Source: Anouti et al. 2020.

Figure 10 | **Timeline of Increasing Carbon Costs**



Source: Hydrogen Council and McKinsey & Company 2021.

According to cost projections, renewable hydrogen produced by electrolysis will see promising cost reductions and breakeven dynamics, due to positive projections regarding manufacturing scale, learning rates, and technological improvements (Hydrogen Council and McKinsey & Company 2021). Grey and blue hydrogen may decrease in cost competitiveness because of increasing carbon costs from the implementation of carbon pricing schemes. Globally, low-carbon hydrogen could break even with grey hydrogen by 2025–30, subject to at-scale CO_2 storage and transport infrastructure, at an expected cost of about US$35–50 per ton CO_2e, as shown in Figure 9 (Hydrogen Council and McKinsey & Company 2021). Carbon costs are set to increase globally to $300 per ton of CO_2e by 2050.

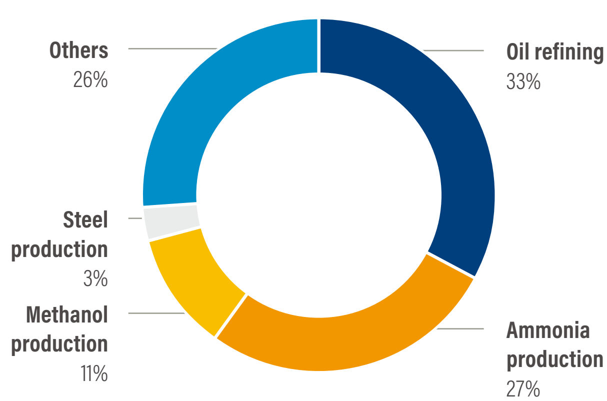
Versatility of Hydrogen

Due to the variety of sources that can be used for its production—including natural gas, coal, oil, renewables, and nuclear—hydrogen has high capacity and flexibility to improve energy security (IEA 2020b). In addition, it can be directly used or converted into other products with different potential applications such as ammonia, synthetic methane, and synthetic liquid fuels. Since it acts as an energy carrier, hydrogen produced by electrolysis could be a long-term solution that increases system stability and energy resilience; reduces costs by flattening the residual load in a power system; provides grid balancing, power backup, and releasing grid constraints; and accommodates the peak load (IEA 2020b).

Growing Industry Demand

Globally, hydrogen is mainly used in three areas: oil refinery, chemical production, and steel production, with 80 percent of its global consumption attributed to refineries and ammonia production, as shown in Figure 11 (Tlili et al. 2019). Hydrogen may also be used in the

Figure 11 | **Global Hydrogen Uses across Industries**



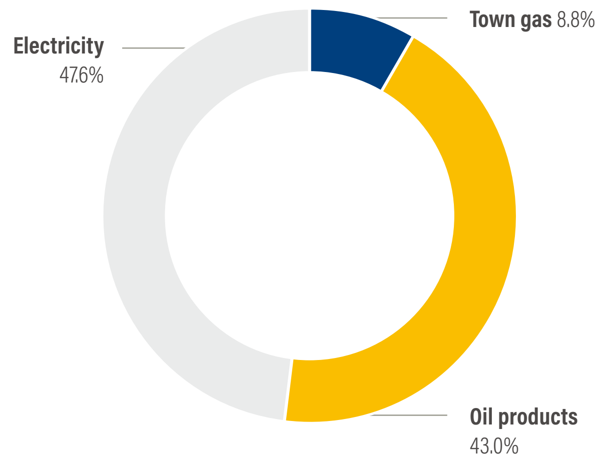
Source: Timur Gül and Dave Turk 2019.

generation of industrial high-temperature heat. Within the building sector, hydrogen can be blended with existing natural gas networks or directly utilised as pure hydrogen for a variety of end-uses, depending on infrastructure capacity.

Hong Kong could import low-cost green hydrogen as green hydrogen could then be converted into electricity through large-scale fuel cells or mixed with natural gas in domestic power plants (Anouti et al. 2020). As such, the power sector could greatly benefit from hydrogen's contribution to grid balancing and its ability to manage peak load issues.

New uses for hydrogen can also be anticipated, especially as there are currently an estimated 228 hydrogen projects across the value chain globally, worth more than $300 billion, through to 2030 (Hydrogen Council and McKinsey & Company 2021).

Figure 12 | **Hong Kong's Final Energy Demand in 2019**



Source: Based on data from the Census and Statistics Department.

Hydrogen Transportation and Storage Options

There are multiple transport options for hydrogen, including retrofitted pipelines and natural gas blending for shorter distances; shipping hydrogen in the form of ammonia, gas tanks, or liquefied; or new and retrofitted sub-sea transmission pipelines for longer distances. Hydrogen storage capacity is also promising. Hydrogen can be stored long term, either compressed overground, liquefied in tanks, or underground in salt caverns, depleted natural gas or oil reservoirs, and aquifers (Ren et al. 2020).

Potential of Green Hydrogen Use in Hong Kong

In Hong Kong, green hydrogen has great potential as an alternative energy carrier in supporting Hong Kong's carbon neutrality goal.

Current Local Circumstances for Hydrogen Utilisation

Currently, Hong Kong uses hydrogen as a constituent of town gas in its power system, although it is not green or zero-carbon. Town gas currently accounts for about 8.5 percent of the city's final energy requirements (Figure 12) (CSD 2020a). Town gas is produced from naphtha and natural gas under the catalytic rich gas process mainly at the Tai Po Plant, in which hydrogen occupies 46–52 percent of its composition (Hong Kong and China Gas Company Limited 2020). Town gas is transmitted through underground pressured pipelines, providing energy to more than 1.9 million customers (Hong Kong and China Gas Company Limited 2020). The utilisation of low- or zero-carbon hydrogen could reduce the carbon footprint of these sectors, as well as strengthen Hong Kong's energy security and, thus, climate resiliency. However, Hong Kong is lagging here, because it would require a change in the manufacturing process, regulatory restrictions, financial barriers, and policy support gaps.

Moving Hong Kong towards Hydrogen Utilisation

Part of the challenge is that current safety standards and guidelines around the usage and handling of hydrogen are outdated. Hong Kong's Dangerous Goods (General) Regulations (Cap. 295, Chapter 5) state that the maximum quantity of hydrogen permitted to enter the city without a license is one cylinder (Hong Kong e-Legislation 1964). Further to that, compressed or refrigerated liquid hydrogen, as well as fuel cell cartridges, are only permitted in Hong Kong at the general level of 75 units and at the industrial level of 150 units (Hong Kong e-Legislation 1964). The maximum package size for fuel cell cartridges is 120 ml (Hong Kong e-Legislation 1964). Moreover, hydrogen in a metal hydride storage system is not permitted. With regulatory restrictions limiting the usage of hydrogen as an alternative form of energy in Hong Kong, the city will fall behind.

Government has pledged to achieve carbon neutrality by 2050. To that end, it has established a HK$200 million ($25.8 million) Green Tech Fund based on recommendations from the Hong Kong Sustainable Development Council's report on medium- to long-term decarbonisation (Low 2020). While Hong Kong has indicated that its 2030 fuel mix will include a larger proportion of natural gas over nuclear power and that coal will gradually be phased out, there has been no indication yet by government that it will implement hydrogen technologies (Low 2020). Without an explicit hydrogen road map, Hong Kong will lag. Globally, direct subsidies from local and national governments have helped accelerate the adoption of renewable technologies (Denman et al. 2021) and enabled a steep annual learning curve for the growth of renewable energy capacity—35 percent for solar PV and 30 percent for offshore wind energy—over the past 10 years (Hydrogen Council 2021). If government were to provide similar support in the form of direct subsidies and promote green funding priorities for hydrogen technologies, Hong Kong could enable a similar learning curve for the growth and efficiency of hydrogen technologies (Denman et al. 2021). High costs associated with hydrogen technologies could also decrease if measures, such as the enactment of carbon pricing, were implemented (Turner et al. 2021). For example, a carbon price could aid the transition to hydrogen-based energy and improve the competitiveness of low- or zero-carbon emission technologies more generally.

Co-combusting hydrogen with natural gas in Hong Kong's three new CCGTs—which are either in operation or commissioned to begin operations within the next three years—may also be a viable option to aid peak load management and grid balancing. With upgrades, retrofits, and life extensions, hydrogen can be used in newer CCGTs and would emit zero SO_2, PM, CO_2, and NO_x emissions. However, emission levels may be the same as that from current CCGTs if flame temperatures are not controlled during combustion (Campbell 2020). Moreover, making any new fossil fuel-fired power plant built after 2020 hydrogen-ready will support onshore hydrogen production within Hong Kong.

Hydrogen can also be converted from renewable energy. However, as Hong Kong has limited green hydrogen facilities and land to produce its own renewable energy, it will likely have to import supplies from Australia, the Middle East, or Mainland China. In the process of importing hydrogen, it will be important to use hydrogen-based transport technologies, such as hydrogen fuel cell heavy-duty vehicles and shipping vessels to prevent embodied carbon emissions. Shipping hydrogen from renewable energy hubs in Australia or the Middle East would cost $9–10/kg H_2. In order to receive imported hydrogen, Hong Kong could implement a floating dock similar to the one being built in Hong Kong waters for receiving imported liquefied natural gas (LNG) (Timur and Turk 2019; Lau 2020).

Incorporating Hydrogen into Hong Kong's Energy Demand

A range of energy scenarios by other external energy research organisations predict that hydrogen-based energy will cover 7–29 percent of global energy demand by 2050, as shown in Table 6. Taking these different scenarios into account, we assume that Hong Kong's hydrogen supply within the total energy demand should remain unchanged. However, as green hydrogen is still an emerging technology, there is still uncertainty regarding its technological development and utilisation within Hong Kong's fuel mix. This report examines the impact of green hydrogen technologies where they contribute towards 15–30 percent of power generation.

Table 6 | **Summary of Global Hydrogen Demand Forecasts**

REPORT/SCENARIO NAME	ORGANISATION	FORECASTS FOR HYDROGEN AS A PERCENTAGE OF TOTAL ENERGY DEMAND IN 2050	DATE PUBLISHED
Net Zero Energy Scenario	International Energy Agency	13%	May 2021
Final Energy Demand, ETC 2050 Indicative Scenario	Energy Transitions Commission	13%	April 2021
World Energy Transitions Outlook 1.5°C Pathway	International Renewable Energy Agency	12%	Jan 2021
New Energy Outlook: Climate Scenario	BloombergNEF	25%	Oct 2020
Energy Outlook 2020 Edition: Rapid Scenario	BP	7%	2020
Energy Outlook 2020 Edition: Net-Zero Scenario	BP	16%	2020
The Role of Clean Hydrogen in the Future Energy Systems of Japan and Germany: German Scenarios	adelphi	8-11%	Sept 2019
The Role of Clean Hydrogen in the Future Energy Systems of Japan and Germany: Japanese Scenarios	adelphi	9-22%	Sept 2019
Hydrogen Roadmap Europe	Fuel Cells and Hydrogen Joint Undertaking	24%	Jan 2019
The Vision Scenario for the European Union: 2017 Update for the EU-28	Öko-Institut e.V	20%	Feb 2018
Eurogas Scenario	Eurogas	29%	n.d.
Average 2050 EU Final Energy Consumption	Joint Research Commission	10-23%	n.d.

Source: IEA 2021; Energy Transitions Commission 2021; Bloomberg 2020; BP 2020; adelphi 2019; Fuel Cells and Hydrogen Joint Undertaking 2019; Öko-Institut e.V 2018; Eurogas 2020; Joint Research Commission 2019.

Challenges and Opportunities in Adopting Hydrogen

Hydrogen has huge potential in satisfying power issues in Hong Kong, such as peak loads, grid balancing, natural gas blending, transport, and energy security. As such, government must incorporate hydrogen technologies into its plan to move towards net-zero carbon emissions. The application of hydrogen in Hong Kong does not come without challenges, though.

Hydrogen utilisation on its own relies on advanced technologies. In particular, the storage and transport of hydrogen is especially difficult, relative to other fuels. Apart from storing hydrogen in fuel cells, it can be transported in gaseous and liquefied forms, both with their own advantages and disadvantages. As a gas, hydrogen can be transported within a compressed gas tube trailer or through pipelines.

Moreover, hydrogen's production costs are sometimes considered redundant due to an existing alternative energy carrier: electricity. The cost of producing hydrogen by electrolysis is also particularly high due to the high cost of electrolysers, as well as the electrical costs of producing low-carbon hydrogen, which could account for 60 percent of the total cost (IEA 2020b).

In Hong Kong, due to land limitations, it may be difficult to construct hydrogen production and storage facilities, as well as renewable energy production facilities. As a result, government would likely need to import the majority of the city's hydrogen needs to balance excess renewable energy production in other parts of the world. Potential sources of hydrogen imports include Australia, the Middle East, and Mainland China.

From Town Gas to Clean Energy

Town Gas in Hong Kong and the Status Quo

In Hong Kong, town gas is produced solely by the Hong Kong and China Gas Company Limited (HKCG). The city's consumption of town gas in 2019 (8,208.33 GWh) was 10.25 percent of the total energy consumption. More than 283,000 units of gas appliances were sold to 1.91 million customer accounts that year (Hong Kong and China Gas Company Limited 2020). The residential sector accounted for about 60 percent of consumption, followed by commercial (34 percent) and industrial (6 percent). Currently, town gas is produced mainly from natural gas and naphtha in Hong Kong, with a small portion from landfill gas. As for the final composition of the city's town gas, the major chemical components are hydrogen (46.3–51.8 percent), methane (28.2–30.7 percent), carbon dioxide (16.3–19.9 percent), small amounts of carbon monoxide (1.0–3.1 percent), and nitrogen and oxygen (< 3.3 percent) (Hong Kong and China Gas Company Limited 2020). The GHG emissions factor of town gas is 3.117 kg CO_2e/unit in Hong Kong.[5] This means that town gas was responsible for 1.919 million tonnes of CO_2e and at least 4.73 percent of the city's total GHG emissions that year. By comparison, the natural gas that produces the same amount of energy as one unit of town gas would emit 2.498 kg CO_2e (U.S. Energy Information Administration 2021a).[6] HKCG has a target to reduce carbon intensity by 30 percent from 2005 levels by 2020, shifting from a 100 percent naphtha fuel supply to a near dedicated natural gas supply, apart from 5 percent from landfill gas.

The Move to Clean Energy

In Hong Kong, town gas is produced at two facilities: the Tai Po Plant and the Ma Tau Kok Plant. The process of producing and using town gas results in considerable GHG emissions, but these emissions are avoidable with existing electrification products or more advanced hydrogen technologies. Therefore, aligning with *Towards a Better Hong Kong: Pathways to Net-Zero Carbon Emissions by 2050*, this report recommends replacing town gas with zero-carbon electricity or clean hydrogen.

Approach 1: Electrification (zero-carbon electricity)

The gas-dependent cooking habits of Hong Kong residents pose challenges for the electrification of energy use. Since cooking in China mostly requires a powerful stove to pan fry or deep-fry, residents prefer to use town gas rather than electricity for cooking and water heating (Tso and Yau 2003; Li et al. 2014). Thus, electric stoves are uncommon. If people's cooking preferences can adapt to electric stoves, aside from reducing their reliance on town gas, this could produce less heat in kitchens, thereby improving working conditions and reducing the energy required for air conditioning, as well as changing the source of fuel.

The Hong Kong EPS model shows that town gas and liquefied petroleum gas (LPG) consumption could be reduced by 82 percent, compared with 2017 levels, if sufficient near-zero carbon electricity sources are used and Chinese cooking preferences adapt. A potential solution is a gas ban, which would reduce carbon emissions. However, side effects should be considered:

- Electric stoves and electricity are more expensive than gas stoves and gas, which could place added burdens on residents and small businesses.
- Employees of gas companies and related industries may lose their jobs or need to be retrained.
- The electrification transition would require an expansion of the power capacity. Based on 2017 data, electricity output would need to increase by 22 percent to replace all town gas and non-transport LPG. This increase is substantial but could be achieved well before 2050 if the switch occurs soon.

Approach 2: Hydrogen (blue and green hydrogen)

Hydrogen is a desirable energy alternative, as it can be used in existing natural gas or gas pipelines and can provide energy to customers by pipeline. However, problems with mass production and transport remain.

The United Kingdom provides Hong Kong with a suitable case study for a hydrogen energy transition, as it has a similar preference for gas. The UK-based Northern Gas Networks (NGN) seeks a shift from natural gas to hydrogen. They have proposed an alternative approach that would require much smaller, more manageable upgrades: Change the fuel used in the gas network to hydrogen. In 2016, NGN proposed the H21 Leeds City Gate Project. It was launched to evaluate the feasibility, from both a technical and economic viewpoint, of converting the existing natural gas network in Leeds, one of Britain's largest cities, to 100 percent hydrogen. The project plans to take natural gas from the North Sea and convert it to hydrogen using steam methane reformers. The carbon dioxide produced in the process could be captured and stored in underground salt caverns to avoid its release into the atmosphere. The hydrogen could then be distributed in gas pipelines.

The high initial cost of constructing hydrogen pipelines is a major obstacle to the expansion of hydrogen pipeline delivery infrastructure. Transporting gaseous hydrogen through existing pipelines is a low-cost option, but several concerns arise about the conversion of pipelines transporting natural gas to those that could transport hydrogen: the potential for hydrogen to embrittle the steel and welds of the pipeline and the need for current pipeline facilities to be reinforced to control hydrogen leaks (U.S. Department of Energy n.d.).

A study from the U.S. Department of Energy National Renewable Energy Laboratory (Melaina et al. 2013) also found that, when implemented at relatively low concentrations (5–15 percent hydrogen by volume), this strategy for storing and delivering renewable energy appears to be feasible without significantly increasing the risks associated with the utilisation of the gas mixture in end-use equipment. However, the durability of certain metal tubes may be reduced when they are exposed to hydrogen for extended periods of time, especially at high concentrations and pressures. In addition, the energy density of hydrogen is also about three times lower than that of methane, which means that, as the percentage of hydrogen rises, the volume of energy delivered through the same pipe decreases.

In general, three main challenges remain for Hong Kong's town gas-to-hydrogen transition: producing and guaranteeing a stable supply of zero-carbon hydrogen, transporting hydrogen, and retrofitting gas terminal appliances.

The clean hydrogen approach almost eliminates possible GHG emissions, both in terms of production and consumption, and is undoubtedly the ideal solution from an environmental point of view. At the same time, the hydrogen solution has a much lower impact on local employment since the hydrogen substitution approach would still require the existing pipeline system and associated repair upgrades, together with a modification of all end-use appliances. For Hong Kong's energy sector, switching to hydrogen would have synergies with the power-sector transition, given the economic scale of the hydrogen supply and the shared infrastructure.

The Expansion of Hydrogen across Industries

Hydrogen is a versatile resource. Hence, demand is expected to rise across a variety of sectors.

For transport, when used in fuel cells, hydrogen generates no exhaust emissions and can help reduce local air pollution, shorten refuelling times, and reduce the added weight of energy stored within the vehicle. Fuel cell vehicles (FCVs) can also operate at a higher efficiency than combustion engines and can convert chemical energy in the fuel to electrical energy with efficiencies of up to 60 percent. Moreover, for a densely populated city like Hong Kong, FCVs are inherently quiet and ideal in traffic (Campbell 2020). However, the use of hydrogen in transport will depend on whether it can become a cost-competitive option in comparison to battery electric vehicles. Hydrogen may also be used more extensively in shipping and aviation. As a major trading hub, hydrogen usage in these two sectors will be extremely important in reducing Hong Kong's carbon emissions associated with international trade—currently 62 percent of the total. (Yau et al. 2018).

Off-grid construction sites may also benefit from fuel cells. Diesel generators are often used at off-grid construction sites to power their operations, producing heavy carbon emissions. However, a zero-emission hydrogen fuel generator capable of providing enough power for an entire off-grid construction site could entirely remove the need for diesel generators.

Another use would be hydrogen fuel cell systems, rather than diesel generators, to power data centres at large technology or banking companies. It's becoming more difficult to gain permits for diesel generators, especially at the hyperscale required for data centres. For example, Microsoft is aiming at carbon neutrality by 2030 and is conducting research into the large-scale and extended use of hydrogen fuel cells for data centres. However, with so much uncertainty still around hydrogen-based energy technologies, diesel generators will be needed as backup generators.

CHAPTER 5

REGIONAL COLLABORATION ON LOW-CARBON ENERGY

Hong Kong should work with Guangdong Province and aspire for the Greater Bay Area to lead efforts in China to achieve carbon neutrality by 2050.

Collaborative Potential with Mainland China on Low-Carbon Energy

Hong Kong lacks local primary energy sources. Both CLP and HKE import primary energy, which is then converted locally into electricity or gas for final consumption (Hong Kong Institution of Engineers 2014). The total amount of natural gas imported from Mainland China in 2020 was 3.88 million tonnes. In terms of carbon-free electricity in Hong Kong, imported nuclear energy from Daya Bay in Guangdong provides the largest share, providing about a quarter of total power demand. CLP is connected to Mainland China through its Clean Energy Transmission System (CETS), while HKE does not currently have power linkages.

Moreover, constrained by limited land and natural resources, Hong Kong does not boast favourable conditions for large-scale commercialised renewable energy generation to meet the local energy demand. In light of this, government should consider entering into joint-venture partnerships with energy generators in Mainland China to decarbonise the city's power system.

In a public engagement document issued in 2019 regarding a decarbonisation strategy for Hong Kong, the Sustainable Development Council suggested that, upon the completion of the CETS, Hong Kong would have the "capability and flexibility to use more zero-carbon energy from the China Southern Grid (CSG) of up to 30-35 percent of the fuel mix" (Council for Sustainable Development 2019). We recommend that Government monitor policy and technological developments in China pertaining to low-carbon energy and proactively seek opportunities to establish joint-venture projects to decarbonise Hong Kong's power system.

There should be many opportunities to collaborate with Mainland China on low-carbon energy because its energy sector is moving towards decarbonisation following the central government's call for an energy transition. By the end of 2020, power-generation capacity from non-fossil fuels was about 954 GW, accounting for around 43 percent of the total installed capacity (China Electricity Council 2021). Electricity generation from non-fossil fuels was approximately 2,449 TWh, accounting for just under a third of the total electricity generation in 2020; wind and solar combined provided around 9.5 percent, up from 3.9 percent in 2015 (China Electricity Council 2021).

Looking ahead, the Chinese government's 14th Five-Year Plan (2021–2025) proposes a 13.5 percent reduction in energy intensity and an 18 percent reduction in CO_2 emissions intensity (Liu et al. 2021). The plan further proposes to increase the share of non-fossil fuel energy in total energy consumption to around 20 percent in 2025. The mainland is also committed to achieving over 1,200 GW installed solar and wind power capacity, compared with 475 GW in 2020. After a series of power-sector reforms in March 2015, interprovincial and provincial electricity trading centres have been established, with the objective of facilitating mid- and long-term trading and interprovincial electricity exchanges. A regional trading centre of note is the Guangzhou Power Exchange Centre, which covers interprovincial transactions in the CSG region. There are two main types of interprovincial trade in Mainland China's power market: generators reaching direct power purchase agreements with provincial grid companies, and provincial grid companies selling to other grid companies in neighbouring provinces.

Although opportunities exist for collaboration on low-carbon energy development, the Hong Kong public prefer local generation over grid purchases from Mainland China (ENB 2015). The lack of support for grid purchasing was due to loss of local control over the power sector, over-dependency on the Mainland, and loss of local employment and career development opportunities.

However, imports from Mainland China do not necessarily mean a surrender of local control. In this Chapter, we focus on exploring the potential for Hong Kong of purchasing low-carbon electricity from the Mainland through negotiating power purchase agreements (PPAs) with specific generators under a joint venture model. A PPA is a legal contract between a power generator and a power purchaser, where the two parties can negotiate the sale and purchase of energy on an agreed upon price structure for a fixed period of time.

Opportunities for Hong Kong to Import Decarbonised Electricity

Development of Low-Carbon Energy in Neighbouring Guangdong Province

By the end of 2020, Guangdong's installed power-generation capacity totaled around 141 GW, of which local thermal power (coal, gas, etc.) accounted for the largest proportion (67.7 percent). Nuclear (11.4 percent) was second and hydropower (11.2 percent) third. In addition, wind and solar energy accounted for 9.7 percent. Aside from hydropower, other non-fossil fuels—including nuclear, wind, and solar energy—experienced different levels of growth. Additions in nuclear and solar installations were the most remarkable in 2020.

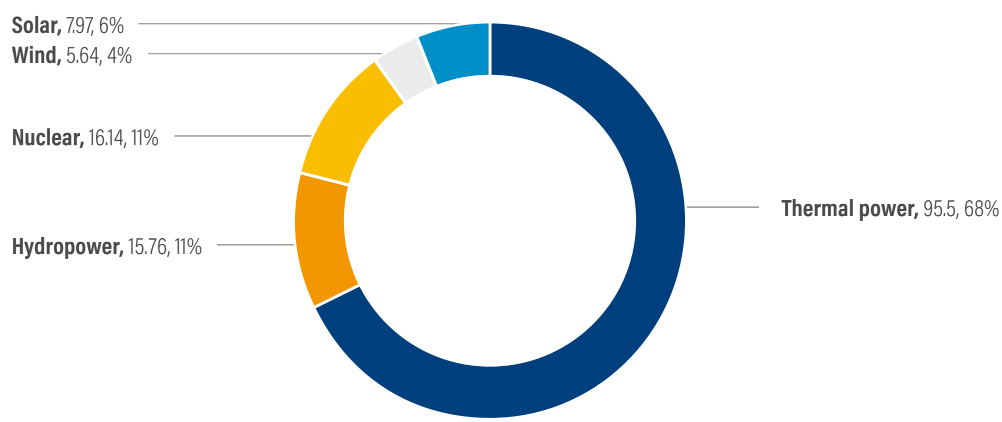
In addition to local power generation, imported electricity from other provinces, such as Yunnan through the west-to-east electricity corridor project, provides about 30 percent of Guangdong's power demand. In 2018, Guangdong imported 192.3 TWh of electricity, of which 117.5 TWh came from Yunnan's hydropower. Aside from increasing interprovincial renewable energy, Guangdong has prioritised the development of local nuclear and offshore power sources to achieve a decarbonised power system. This is an opportunity for Hong Kong to expand its imported decarbonised energy.

The first consideration is what *kinds* of agreements with power generators in Mainland China would bring the most benefit to Hong Kong. The central question that Government needs to address is how Hong Kong can negotiate and compete with cities on the mainland for decarbonised energy resources. While the number of renewable and nuclear energy developments will increase substantially, energy demand in Guangdong is also rising, especially with the continuing development of the Greater Bay Area. Government needs to swiftly negotiate an agreement with the central government so that power companies can begin discussions on securing decarbonised energy for the city.

For Hong Kong to buy energy from Mainland China, whether nuclear or renewable, the power companies will have to enter into PPAs with the CSG or individual power generators. We suggest two types of power purchase:

Negotiating PPAs to secure imported electricity from the mid- to long-term energy market. Mid- to long-term energy markets use direct-purchase contracts for bulk energy to specify the volume and price of energy traded (Cao et al. 2019). These contracts are signed through power exchange centres, with a time scale of a few days, one month, one year, or even longer. Customers purchasing energy on the mid- to long-term market will pay the generator directly for energy and pay the grid company a regulated fee. This means that if Hong Kong is to pursue this option, the power companies will have to pay for energy based on an agreed price, as well

Figure 13 | **Guangdong Province's Installed Capacity by Source in 2020 (GW)**



Source: Department of Science and Technology of Guangdong Province 2021.

as pay CSG a rate per MWh from individual power generators.

Negotiating joint-venture contracts over power generation assets and supply contracts for power purchase. Under this arrangement, parties to the contract, in this case a Hong Kong power company and a power generator in Mainland China, agree to jointly invest, build, and manage energy projects. This grants Hong Kong some degree of control over generation capacity. For the actual use of the electricity generated, supply contracts also need to be negotiated.

The joint-venture contract model has already been tried and tested in Hong Kong through the Daya Bay Nuclear Power Station. CLP is a 25 percent equity partner of the Guangdong Nuclear Power Joint Venture Company Limited. It also has a 12.5 percent stake in the Daya Bay Nuclear Power Operations and Management Company Limited, which is responsible for the management of operations (CLP, n.d.a.). The share of nuclear energy that can be exported to Hong Kong is agreed upon in supply contracts (CLP 2013).

Compared with PPAs negotiated on the mid- to long-term energy market, the joint-venture contract plus PPA model enables better control of generation capacity. The power companies can exert a greater degree of influence over the operations of the power stations in Mainland China, as opposed to being the dependent party in a buyer-seller arrangement through a PPA. Joint-venture contracts are more acceptable to the public as they allow greater autonomy and governance terms over energy for Hong Kong. Building on the success of Daya Bay, Hong Kong can consider replicating the joint venture contract model to meet its future energy demands. Though the model has thus far been applied to nuclear energy, it could also be feasible for new large-scale renewable energy projects.

Nuclear as a Technically Feasible, Commercially Viable, and Available Decarbonised Option

There is potential for Hong Kong to import more nuclear energy from Guangdong as part

Box 1 | CLP and Guangdong Daya Bay Nuclear Power Station

Daya Bay is located in Dapeng, a sub-district of Shenzhen in Guangdong Province. The nuclear power plant is the first of its kind in Mainland China. It is one of the earliest and largest joint-venture projects launched under the Open-Door Policy. CLP has a 25 percent stake in the nuclear power station (CLP, n.d.a.).

The station produces some 15 billion kWh of electricity per year, of which 70 percent is imported by CLP into its system in Hong Kong. In 2009, the supply contract was extended until 2034. To ensure that cleaner and more cost-competitive energy is provided to Hong Kong, Daya Bay needs to increase its electricity supply to Hong Kong from 70 percent to around 80 percent from late-2014 to 2023 (CLP, n.d.b.; 2021b).

The cost of the electricity from Daya Bay in 2020 was HK$6,380 million (HK$6,456 million in 2019). It's estimated that the total amount of electricity (purchased or generated by CLP) would have been around 12.24 TWh in 2020 (12.01 TWh in 2019). Thus, the estimated cost for the electricity from Daya Bay was about 0.521 HKD/kWh in 2020 (0.538 HKD/kWh in 2019) (CLP 2021b).

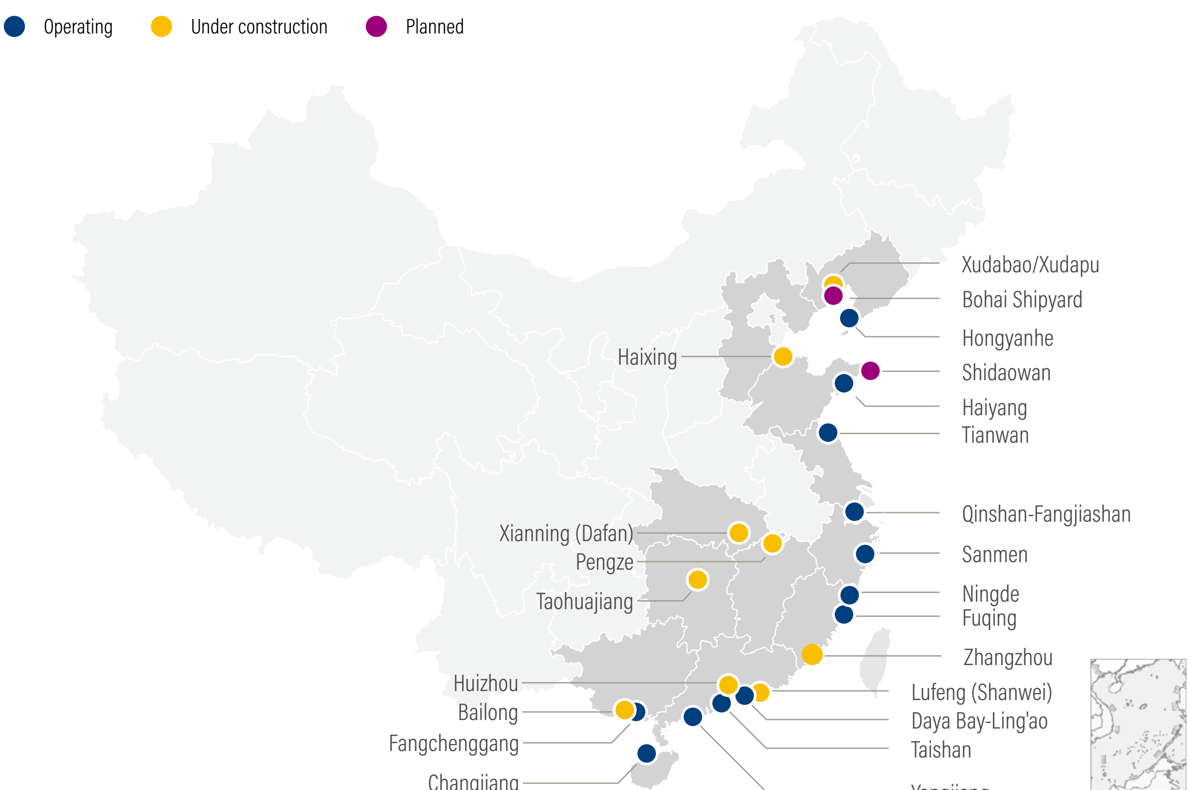
- **Equity Interest**
  CLP—25 percent
  Guangdong Nuclear Investment Company, Ltd.—75 percent
- **Ownership**
  Guangdong Nuclear Power Joint Venture Company, Limited
- **Gross Capacity**
  1,968 MW (2 x 984 MW)
- **Capacity Purchase**
  1,577 MW
- **Estimated Unit Price**
  2020: 0.521 HKD/kWh
  2019: 0.538 HKD/kWh

of its clean energy transition. The Sustainable Development Council, in its report following the 2019 public engagement on Hong Kong's Decarbonisation Strategy, suggests that nuclear energy can be a viable "transitional solution to climate change" and can help stabilise or reduce emissions in the short to medium term (Council for Sustainable Development 2020).

China's 14th Five-Year Plan aims for nuclear generation capacity to reach 70 GW by 2025, which represents a significant increase from 50 GW in 2020 (Stringer and Koh 2021). To put it into context, the additional power generated is the equivalent to having 20 additional nuclear reactors. Guangdong is the leading province in China in terms of nuclear power. It has four nuclear power plants and a total capacity of 16.1 GW. As of 2019, 11 nuclear power plants around Hong Kong were either operational or in the planning stage. Aside from Daya Bay, Ling Ao Nuclear Power Plant, with a capacity of 3,914 MWe, is the closest to the city, positioned approximately 50 kilometres away. (World Nuclear Association 2021). Another facility in focus is the Huizhou Taipingling Nuclear Power Plant, which was approved for construction in early 2019. The first phase of the project, expected to be operational in 2025–6, will have a capacity of 2,400 MWe (IAEA 2021a; 2021b). In September 2020, Guangdong set a provincial installed capacity target of 18.5 GW by 2025. To diversify Hong Kong's low-carbon energy sources, an option could be to import greater volumes of nuclear energy from the power plants that will be operational in the city's vicinity.

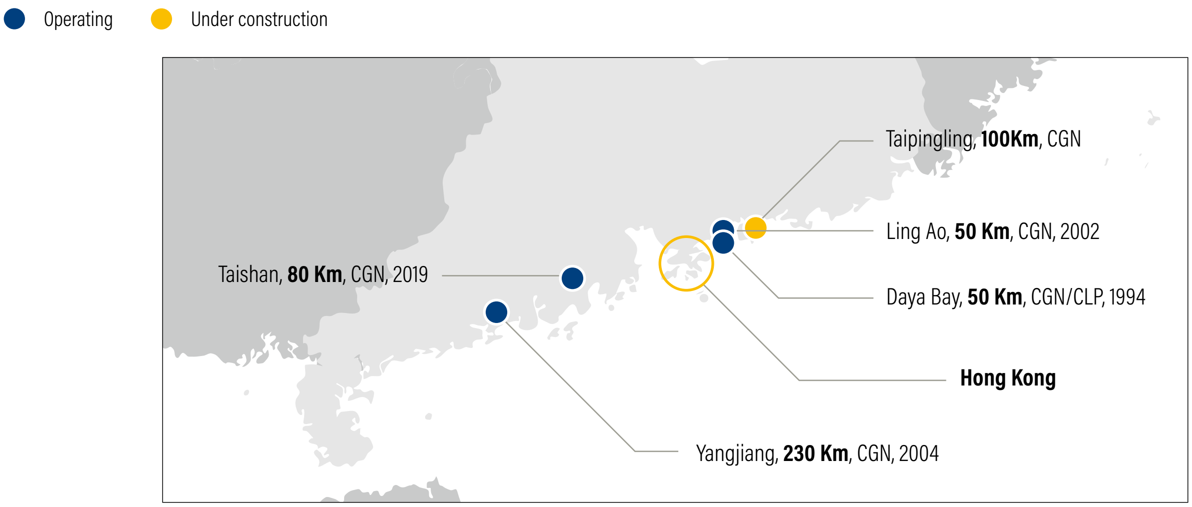
Following the 2011 Fukushima nuclear disaster, the Chinese government pledged to use advanced third-generation nuclear technology to enhance safety. Third-generation nuclear technology uses high-performance equipment and materials and has higher standards in safety design. However, it brings a higher capital cost. Analysis shows that in the 14th Five-Year Plan period (2021–2025), except for Liaoning Province,

Figure 14 | **Distribution of Nuclear Power Plants in China**



Source: World Nuclear Association 2021.

Figure 15 | **Location of Nuclear Power Plants Close to Hong Kong**



Source: National Nuclear Safety Administration n.d.

the economics of third-generation nuclear will be less competitive than fossil fuel-fired power plants (Song et al. 2021). In the long term, with improvements in third-generation nuclear technology, the LCOE of nuclear power should be competitive with coal power by 2030. Moreover, the CO_2 emissions reduction potential of nuclear power is greater than coal power with CCS, while the avoided CO_2 costs of nuclear power are much lower (Xu et al. 2018).

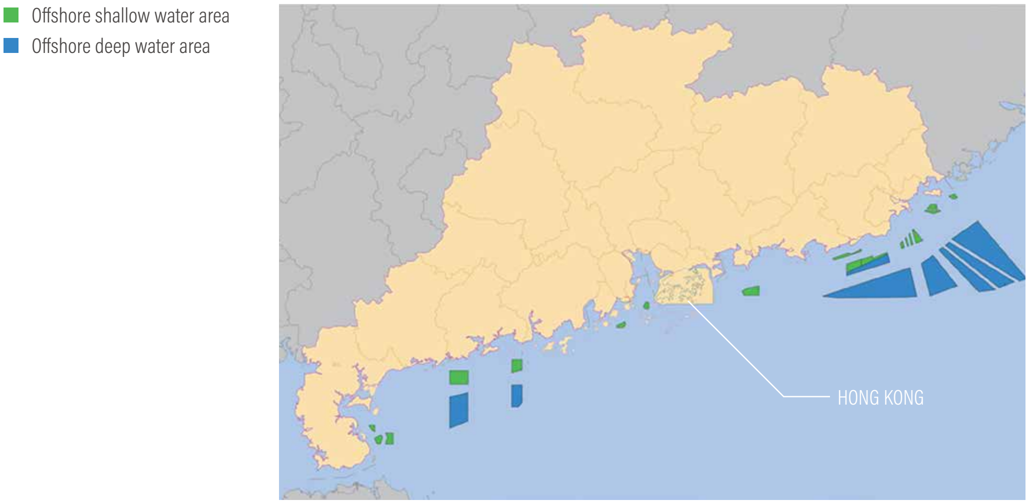
Nuclear safety is seen as a crucial part of national security and an important area of discussion in environmental protection. Unlike fossil fuel-fired power plants, nuclear power plants do not produce air pollution or carbon dioxide during their operational periods. Major environmental concerns involve the creation of radioactive waste, such as uranium mill tailings and spent (used) reactor fuel. These can remain radioactive and dangerous to human health for thousands of years (U.S. Energy Information Administration 2021b). With third-generation reactors, nuclear power has become much safer (World Nuclear Association 2020).

Offshore Wind as a Promising, Economically Effective, and Available Option

Offshore wind power is a feasible and attractive option with substantial potential for Guangdong. The estimated offshore energy potential in Guangdong (1,584.4 TWh) is 2.8 times its electricity demand (561.0 TWh) and is 35.9 times Hong Kong's electricity demand (44.1 TWh) (Sherman et al. 2020). By the end of 2020, Guangdong had about 1 GW of grid-connected installed offshore wind capacity and 8 GW of capacity under construction (China Southern Power Grid 2021). This was half the province's goal of 2 GW installed capacity by 2020 in its offshore wind power development plan (2017–2030). Guangdong's September 2020 *Action Plan for Cultivating New Energy Strategic Emerging Industrial Clusters* set a provincial target of 15 GW for installed offshore wind by 2025. It also plans for wind power to reach grid parity in the same year, meaning that wind power needs to become as or less expensive than coal and other more conventional sources of electricity by 2025. This would go a long way to helping Guangdong reach its target of 30 GW installed capacity by 2030.

Offshore wind energy projects have the potential to interconnect with Hong Kong. An example is the Guishan Offshore Windfarm, which began generating power in March 2018. With an installed capacity of 198 MW, it currently supplies power to a few small islands in Hong Hong's vicinity, as well as Zhuhai city on the mainland. Connection is by submarine cable and distributed

Figure 16 | **Guangdong Province Offshore Wind Power Planning Site 2017–2030**



Source: Guangdong DRC, 2018

through a 110 kV step-up substation (Zhuhai Municipal Government 2018).

The Guishan Offshore Windfarm is important because it is located a mere 20 kilometres from Hong Kong International Airport on Lantau Island. This presents a promising opportunity for interconnections through submarine power cables to both power companies. However, a PPA between Hong Kong and the owners (Southern Offshore Wind Power Joint Development) is unlikely at this stage. Despite its ideal location, the capacity of this wind farm is already being used by neighbouring islands and Zhuhai.

The Guishan Offshore Wind Farm was set up as a pilot project for Guangdong during the 12th Five-Year Plan period (2011–2015). As provincial authorities have stepped up their commitment to developing renewable energy, it's likely that similar projects will be announced in the near future. Government and the power companies need to monitor the development of renewable energy projects in Guangdong so as to seize opportunities for new renewable energy interconnections, whether through a PPA in the mid- to long-term energy market or through negotiating a joint venture with a supply contract arrangement.

5.3. Challenges

Contingency Arrangements

Hong Kong prides itself on the reliability of its power grid, with both power companies boasting over 99.99 percent reliability. It is essential for Hong Kong to have backup generators or reserve margins for generation that can kick in during an emergency. Local backup power supplies already exist. Within CLP's portfolio of power-generation facilities, Penny's Bay Power Station serves as a support facility that can be started in just 12 minutes. With a capacity of 300 MW, it can act as a backup in case of interruptions or in times of peak demand (CLP 2021b). Regarding HKE power assets, the oil-fired open-cycle gas turbine units at HKE's Lamma Power Station are designed for peak-lopping and meeting any emergency operational requirements.

More reserve capacity may be needed in the future. This will be determined by three primary factors:

- **Increased reliance on renewable energy**: The variable nature of renewable energy means that even with sophisticated battery storage technology some uncertainties and supply fluctuations may exist. With a significantly longer lifespan and easier scalability than lithium ion batteries, flow batteries are a promising storage technology that can provide flexibility. However, they are yet to be utilised in Hong Kong's power system due to high capital costs.

- **Increased reliance on Mainland China**: Future sources of energy will likely come from Mainland China, considering the land and resource constraints in Hong Kong. This reliance potentially compromises Hong Kong's energy independence, given that part of its energy supply would be out of the city's control, and power purchase would be subject to prices offered by Mainland entities.

- **Escalating threats posed by climate change**: Hazards associated with climate change will pose increasing risks to energy security. Extreme weather, such as typhoons and storm surges, as well as secondary weather events, like landslides and flooding, can disrupt power generation and transmission, leading to fluctuations in the power supply. For example, Macau suffered from widespread blackouts during Typhoon Hato in 2017. Its power company, Companhia de Electricidade de Macau, stated that its electricity supply from Mainland China (which provides 80 percent of the city's needs) was interrupted due to the typhoon, and some of its local power supply facilities were damaged by floods (*Macau Post* 2017). The impact of extreme weather events will only become more frequent and intense over time, so there need to be flexible options that can limit power outages and help maintain resilience. More diversity in the location of mainland generation plants, as well as multiple and direct transmission corridors to Hong Kong, can help mitigate these risks. Another solution is to enhance reserve capacity in Hong Kong. The power companies could keep power stations that have reached their end of life as backup generation facilities, only firing them up when absolutely necessary. Having more contingency options in place would be preferable from an energy security perspective.

Transmission Infrastructure

HK's existing transmission connections with Mainland China

At present, CLP is linked to Mainland China through its Clean Energy Transmission System (CETS). CLP's power imports come from two sources:

- Daya Bay Nuclear Power Station. Since 1994, CLP has been connected to the mainland by a dedicated link to Daya Bay in Guangdong. The station, powered by two pressurised water reactors, produces 15 billion kWh of electricity per year, of which around 70–80 percent is shipped to Hong Kong (CLP n.d.b.).

- China Southern Power Grid (CSG): CLP also has the contractual right to use 600 MW from Phase 1 of the Guangzhou Pumped Storage Power Station. The station is a pumped storage plant for power transfer, where hydro technology is used to store CLP's energy generated by other power stations in the CSG (CLP 2020a). When necessary, CLP can release its energy from storage.

The CSG's power system is interconnected with Hong Kong through four 400 kV lines. There are also seven 132 kV lines that are used to export electricity to load centres in Guangdong (EB 2015). In 2018, government approved the enhancement of the CETS, which is expected to be completed in 2025. The enhancements entail replacing 160 kilometres of overhead transmission line circuits to increase overall transmission capacity by 900 MW (Wong 2019). According to a CLP press release, this project will not only enhance transmission capacity and reliability, but will also increase flexibility for increased imports of zero-carbon energy in the future (CLP 2018).

Connections between Hong Kong and Mainland China

Governments in the Greater Bay Area appear willing to enhance and expand their electricity transmission networks. In *Outline Development Plan for the Guangdong-Hong Kong-Macao Greater Bay Area*, there is a Chapter on the development of an Energy Security Protection System (Hong Kong Constitutional and Mainland Affairs Bureau 2019). This Chapter describes the need to strengthen energy storage and transport systems, ensure the "safe and stable supply of energy to Hong Kong," and explore "ways to improve the electricity transmission networks and gas pipelines from Guangdong to Hong Kong."

If Hong Kong is to import a larger proportion of low-carbon energy, there will need to be further upgrades to the existing transmission infrastructure. CLP's current upgrade to the CETS, which will add 900 MW of capacity, is most likely insufficient. In 2015, government suggested that new power interconnections from CSG could be built through submarine cable circuits, linking to CLP in New Territories East and to HKE on Hong Kong Island East (EB 2015). However, this does not escape the issue of the growing energy demand in Shenzhen, which takes up much of CSG's capacity and thus limits new physical connections. CLP and HKE are cognisant of this constraint and further note that, *even if* a new connection was possible, the process would require a timeline of at least 10 years.

Another issue, in terms of interconnections between CSG and the Hong Kong power grid, is the interconnections between CSG and HKE. Currently, HKE is not importing any electricity from the mainland, instead relying solely on local power generation. In 2014, at the Hong Kong Institution of Engineers Annual Seminar, a representative from HKE remarked that reliability was a large concern because HKE and CSG are not currently interconnected. If HKE were to import electricity from the mainland, electricity consumers on Hong Kong Island might have to rely on a single transmission path for their renewable energy needs through the CLP network (Hong Kong Institution of Engineers 2014). Whether HKE should be connected to CSG through CLP is an idea deserving further consideration and requiring deeper reflection about the structure of the SCA. It is equally possible for HKE to independently construct a power cable for dedicated renewable energy generation sites or nuclear power plants in Mainland China. This would, however, require 8 to 10 years and extensive negotiations and involve many logistical challenges. If HKE wants to explore the possibility of importing from Mainland China, perhaps at the same time that CLP wants to add further capacity for zero-carbon imports, the process needs to start now.

Article 26 of the SCA calls for cooperation between government and the companies in a future interconnection study. This study, which is yet to be published, is expected to consider the "detailed arrangements for strengthening the interconnection between Mainland China and Hong Kong." It aims to investigate "the technical feasibility; the implications to the overall performance of the power supply, including safety, reliability, tariffs, and environmental performance; efficiency of the power system; cost and benefit to consumers; and the impact to the companies." The study is especially interested in Guangdong, as opposed to Mainland China in general, as the province's proximity to the city makes the interconnection more feasible.

Importing Power from Mainland China

Supply reliability

Hong Kong has one of the world's most reliable power systems. This is largely because it is controlled by two power companies, including its power generation plants, infrastructure networks, and power assets. Below is a table comparing the reliability of the power supply of Hong Kong and other urban areas supplied by CSG. As the supply reliability of CSG differs from city to city and by area (rural or urban), the point of comparison taken is an average reliability rate in 50 major cities across the CSG network.

Table 7 | **The Supply Reliability of HKE, CLP, and CSG**

	HKE (2020)	CLP (2020)	50 CITIES USING CSG'S SUPPLY (China Electricity Council, 2020)
Reliability (%)	CLP (2020)	>99.995	99.931
Power outage (minutes)		1.44	60

Source: HKE 2020; CLP 2020.

CSG has extensive experience in long-distance transmission: The company transmits power across five provincial-level regions in China—Guangdong, Guangxi, Yunnan, Guizhou, and Hainan. It also exports electricity to Macao and countries such as Vietnam, Laos, and Myanmar (China Southern Power Grid n.d.). Notwithstanding its experience, the CSG's extensive transmission network means that there is a greater possibility for cascading blackouts across transmission lines. Connecting the Hong Kong grid with a relatively less reliable power supply through a long transmission network that may be subject to adverse weather conditions and accidents could create higher reliability risks for the city. The difference between one minute and one hour of power outages is not negligible. In comparison, building a dedicated circuit with a specific power station is likely to be more reliable, as it is easier to monitor one asset and one infrastructure network than to ensure the reliability of an entire power grid.

There have been positive signs that CSG is committed to increasing its reliability and resilience against natural disasters. Between 2018 and 2022, CSG is investing over 170 billion yuan to improve the disaster-prevention capacity of the grid, and it has also committed to reducing power outages in central urban areas to less than 30 minutes per year (Zheng 2019). China is also actively developing an ultra-high-voltage AC-DC power grid connecting all six regional grids. Hong Kong should pay close attention to technical and infrastructural efforts to improve reliability (Fairley 2019).[7] Furthermore, according to the *Greater Bay Area Outline Development Plan*, there are plans to improve energy storage and transport systems. These developments are crucial in determining the future feasibility of connecting with the mainland's power grid.

Another key component of reliability is maintenance, especially in the event of an emergency, such as a natural disaster. This is a definite concern for nuclear energy, especially with accidents in recent memory, most prominently in Japan in 2011, as mentioned earlier. Safety standards in nuclear power are continually rising, though. The Taipingling Nuclear Power Plant, currently under construction, is based on China's local Hualong third-generation pressurised water nuclear reactor standards. In case of an emergency, the plant can automatically shut down fission reactions and cool down the reactor cores to safe levels within 72 hours to avoid a meltdown (*Asia Times* Staff 2019).

For renewables, reliability could be compromised in the case of extreme weather, such as typhoons. For wind energy systems in particular, violent winds could create significant stress conditions on the turbines, affecting their blades and transmission systems. Currently, technology is being upgraded. The V117-4.2 typhoon-resistant turbine, originally developed by Vestas Wind System, will be deployed at the Akita Noshiro Offshore Wind Farm Project in Japan and is expected to commence operations in 2022 (MHI Vestas Offshore Wind 2020). The turbine will be able to withstand wind speeds of up to 57 m/s, or 205.2 km/h, which is approximately the wind speed of a signal 8 typhoon. When wind speeds exceed 30 m/s, the wind turbine will typically stop generating power and will transition to a mode to withstand high winds (Wood 2020). These innovations need to be on the radar of government and the power companies to ensure that power infrastructure remains robust.

Competition for energy resources

Competition for energy resources can compromise electricity supply reliability in Hong Kong. Many cities in the Greater Bay Area, including Hong Kong, share similar objectives in relation to power. Aside from ensuring energy security, many have aligned themselves with provincial decarbonisation targets. Therefore, it is likely that all locations will be competing for the same carbon energy sources. Government needs to weigh its options for zero-carbon energy as soon as possible to secure energy for the city. It should also remain open-minded about importing energy resources from elsewhere, especially if it is cost-effective and reliable.

Regulatory Challenges

Hong Kong does not have the authority to regulate the operations of generators and networks in Mainland China. This makes it difficult for government to be able to exercise administrative oversight and ensure that safety and reliability standards are harmonised. It is unlikely that guaranteeing the power supply to Hong Kong is a high priority for CSG or the central government when discussing regulatory changes, while it is likely that local operators will not be involved in high-level discussions. This may lead to unfavourable regulatory changes for Hong Kong.

Costs

Building interconnections with Mainland China will enable Hong Kong to use more cost effective and low-carbon energy resources; however, it will bring additional capital costs. The cost increases will mainly come from the construction and maintenance of cable networks for long-distance power transmission and upgrades in existing transmission networks to ensure the security of energy supply. Costs may also come from maintaining backup generator capacity in Hong Kong in the event of cascading blackouts along the CSG power transmission network.

The Hong Kong Government, in its 2015 consultation, stated its concern regarding the possibility that the city might become a captive buyer in the power market (EB 2015). This could potentially be the case if Hong Kong connects directly to the CSG grid; as energy demand grows, the city will have to continue to rely on the grid and accept mainland prices. However, our recommended means of collaboration with the mainland could mitigate concerns about Hong Kong becoming a captive buyer. If Hong Kong's power companies can sign PPAs with specific power plants and form joint ventures with power generators, in theory, they will have a larger sway in the negotiation process and discussions about price stability. A relatively successful agreement that has been concluded is the Memorandum of Understanding between the National Energy Administration and the Hong Kong Special Administrative Region Government on the Supply of Natural Gas and Electricity to Hong Kong. It facilitates and protects a stable supply of nuclear energy and natural gas into the city (China National Energy Administration and Hong Kong Special Administrative Region 2008). Moreover, a PPA is a medium- to long-term hedging strategy to reduce price volatility.

Public Opinion

The Hong Kong public is worried about the increased use of nuclear energy. Six months after the nuclear accident in Japan, a survey was conducted in Hong Kong to gauge public opinion on the issue. At the time, in September 2011, only 15 percent of those surveyed believed that Hong Kong should increase its imports of nuclear energy by 2020 (Friends of the Earth et al. 2011). About half thought that the city's nuclear power supply should remain unchanged, and a quarter felt it should decrease. Sixty-one percent of respondents thought that the future development of the power sector should instead prioritise renewable energy.

More specifically, Hong Kong residents appear to be most concerned about the threats posed by power plants close to the city in the case of a nuclear incident. Voices are especially prominent in view of the many power plants that Guangdong is constructing or planning to construct along its coastline, especially those that lie quite close to Hong Kong. While the Daya Bay Nuclear Power Plant has survived several large-scale typhoons in recent years, such as Mangkhut in 2018, there are still lingering concerns that a natural disaster on the mainland could affect livelihoods and even survival in Hong Kong. Disruptions from storm surges and sea level rises will only intensify with climate change.

To assuage concerns, government must maintain constant communication with the Guangdong authorities regarding the performance of nuclear power plants and ensure that Hong Kong is protected as much as possible from future potential threats. Government and the power companies will need to communicate to Hong Kong residents the exact nature of any PPA and keep the discussion process transparent. There must be extensive plans on how Hong Kong can retain control over its power sector, and government must also conduct multiple rounds of consultations at different stages of the decision-making process to ensure the greatest degree of inclusion.

PART III

NET-ZERO PATHWAYS

CHAPTER 6

PATHWAYS TO A NET-ZERO EMISSIONS POWER SYSTEM

This Chapter examines the possible pathways to a net-zero carbon power system by 2050 while meeting future energy demand and improving today's levels of energy security. In order to compare various pathways and understand their impact on Hong Kong's power system, we evaluate the economic impact, environmental impact, health impact, and energy diversity of each one. Based on these assessments, together with additional stakeholder consultations, we explore five pathways that could help achieve a deep decarbonised power system for Hong Kong by 2050.

Five Scenarios for Potential Energy Mixes

Scenario Setting

Based on an analysis of the feasibility, opportunities, and challenges of these available technologies in Chapters 2 through 5, and through round tables and one-on-one meetings with stakeholders, we developed five scenarios to demonstrate different combinations of available options. These decarbonisation scenarios were developed based on the following criteria:

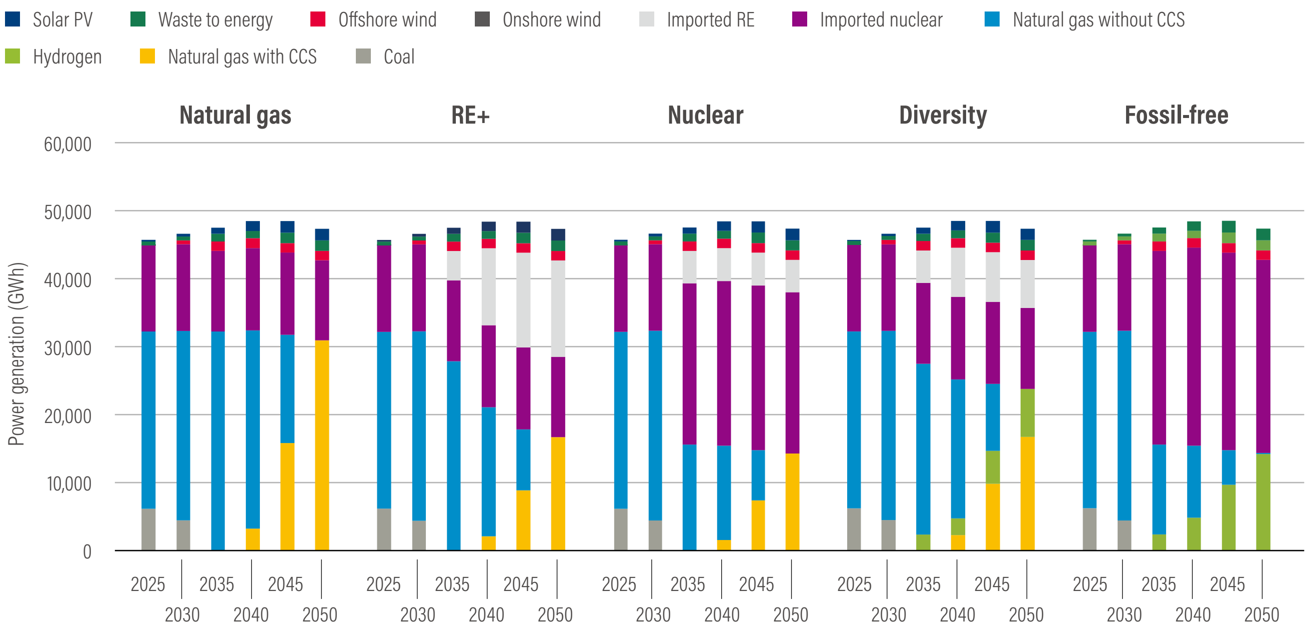
- GHG emissions from power systems will be net zero (or near zero) by 2050, and the air pollutants will be significantly reduced.
- The power system is capable of meeting the power demand in Hong Kong.
- The proposed energy option must be credible and plausible, in accordance with local policies and expert judgements.

We then compared the impact of these scenarios with CO_2 emissions, cost, air pollutants and health incidences, and energy diversity.
In this analysis, we assume that existing power plants will operate until the end of their life cycle, and the coal that is routinely used to generate electricity will be phased out by 2030. After the retirement of existing power plants, new power plants will need to be built in order to increase the power supply and meet steadily increasing power demand. Local renewable energy, including waste-to-energy, will be utilised at its highest potential, which is 10 percent for all scenarios, based on our evaluation in Chapters 2–5. Key features of each scenario are reflected in each scenario title:

- **Scenario 1—Natural Gas**: This scenario's energy mix is closest to the current situation. It consists of 25 percent imported nuclear, 65 percent natural gas, and 10 percent local renewables. As a result, CCS must be installed for the power system to achieve the carbon-neutrality target. The offshore LNG terminal being constructed in Hong Kong waters will further improve Hong Kong's long-term natural gas supply stability by diversifying supply sources and will enable procurement of natural gas at competitive prices from the global market (CLP n.d.c).
- **Scenario 2—Renewable Energy**: The share of imported renewable electricity (mainly offshore wind power) by 2050 will increase significantly from zero to 30 percent; whereas the rest of the energy mix will consist of 35 percent natural gas with CCS, 25 percent imported nuclear power, and 10 percent local renewable energy. This is dependent on the construction of offshore wind farms in Hong Kong's eastern waters.
- **Scenario 3—Nuclear**: The share of imported nuclear energy will increase from the current 28 percent to 50 percent by 2050; whereas the rest of the energy mix will consist of 30 percent natural gas with CCS, 10 percent imported renewable energy (offshore wind power), and 10 percent local renewable energy. This scenario assumes that greater interconnections and joint ventures between Hong Kong and Mainland China will be pursued for greater shares of imported nuclear energy.
- **Scenario 4—Diversity**: Energy sources are most diversified in this scenario, and hydrogen is an important emerging new energy source. The power-generation mix in 2050 will comprise 15 percent hydrogen-based energy, 35 percent natural gas with CCS, 25 percent imported nuclear, 15 percent imported renewable energy (offshore wind power), and 10 percent local renewable energy. In this scenario, hydrogen will presumably be imported from Australia, the Middle East, or Mainland China.
- **Scenario 5—Fossil-Free**: In this scenario, Hong Kong will be powered by 100 percent non-fossil fuel sources without CCS. The power generation mix in 2050 will comprise 60 percent imported nuclear, 30 percent local hydrogen-based power, and 10 percent local renewable energy. Assumptions on imported nuclear and hydrogen are similar to scenarios 3 and 4.

The power generation composition for each scenario during 2025–2050 is summarised in Figure 17.

Figure 17 | **Evolution of the Power Generation Mix Assumed across Scenarios**



Source: Authors' assumptions for the scenario analysis.

Calculation of the Levelised Cost of Electricity

The unit cost of electricity generation in the five scenarios is compared using the levelised cost of electricity (LCOE) and system costs. The LCOE is an estimate of the revenue required to build and operate a generator over a specified cost recovery period. It can be considered as the breakeven point for an electrical power station; that is, the interest rate at which future cash flows are discounted used in calculating LCOE is 3 percent. By presenting a breakeven point, the estimated LCOE does not capture the permitted return rate on net fixed assets, which is 8 percent in the current SCA. The parameters used in calculating the LCOE of each technology (except for hydrogen) are drawn from the IEA World Energy Outlook 2020's assumption for China and adjusted based on consultations with local experts and other relevant studies according to Hong Kong's local conditions. The cost of electricity generated from hydrogen is calculated based on the view that H_2 turbines would have similar construction costs as well as similar operating expenses (OpEx), and similar efficiency to CCGT (Goldman Sachs 2020). Future fuel cost estimates are from BloombergNEF and the Hydrogen Council.

System costs refer to the expense of integrating an individual power plant into an existing power system, including grid costs (linked to grid reinforcement and extension), balancing, and profile (Samadi 2017). A power system with more variable renewable energy would need more dispatchable electricity generation capacity and backup capacity; as a result, it will have higher system costs.

Calculation of Air Pollution-Related Deaths

To assess the health impact caused by air pollution, a standard approach is to first estimate the change in the ground-level concentration of various pollutants under different scenarios and then estimate the associated health impact, such as premature mortality and various respiratory diseases, using an epidemiological concentration-response function. Based on these, factors such as the cost of medicines, inpatient treatment, and lost working hours can be aggregated to compute the total economic loss. In this report, we used a simplified approach to calculate the cost of health-related incidents with the factors applied in the Energy Policy Solutions' latest 3.0 version and focused exclusively on premature mortalities caused by air pollution, as premature mortality represents 97 percent of the monetised cost of emissions in Hong Kong (Energy Innovation n.d.). We first estimated the number of premature mortalities in each scenario and then multiplied it by a localised Value of Statistical Life for Hong Kong—evaluated at 23.6 million HKD per statistical life (in 2019 HKD)—to estimate the total economic losses due to pollutant emissions in the different scenarios.

Evaluation of Energy Diversity

The security of supply from the electricity system is another important dimension in evaluating scenarios. The decarbonised power system also brings new uncertainties to the security of the system, such as the growing penetration of non-dispatchable capacity, which could increase the risk of supply interruptions. Maintaining the security of Hong Kong's power system is among the highest priorities. The low diversity of power generation options, ageing infrastructure, and inadequate generation capacity can lead to a vulnerable power system. In this report, energy diversity is measured using the Shannon-Wiener diversity index, which is frequently used to measure security of supply and electricity generation, reflecting the diversity of the system (Johansson et al. 2012).

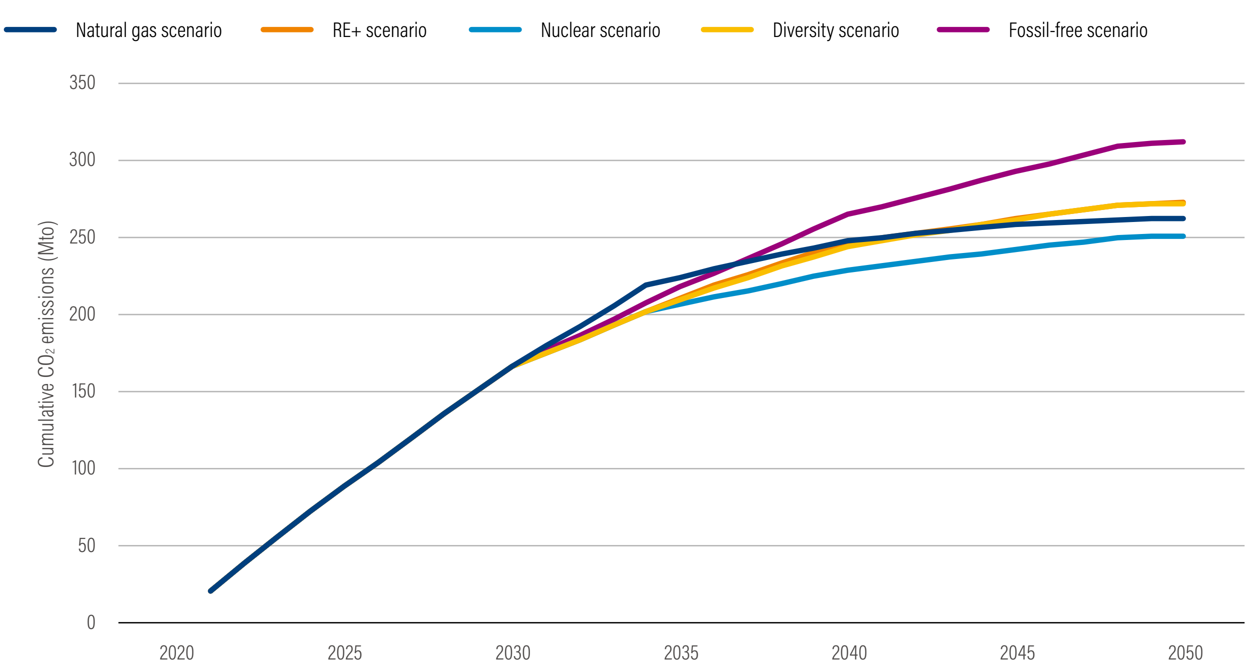
Evaluation of Impacts on Climate, Economy, Environment, and Health in the Five Scenarios

To compare the cost-effectiveness of the different scenarios, we examine the cost impact, environmental impact, and health impact for each one.

Climate Impact: CO_2 Emissions

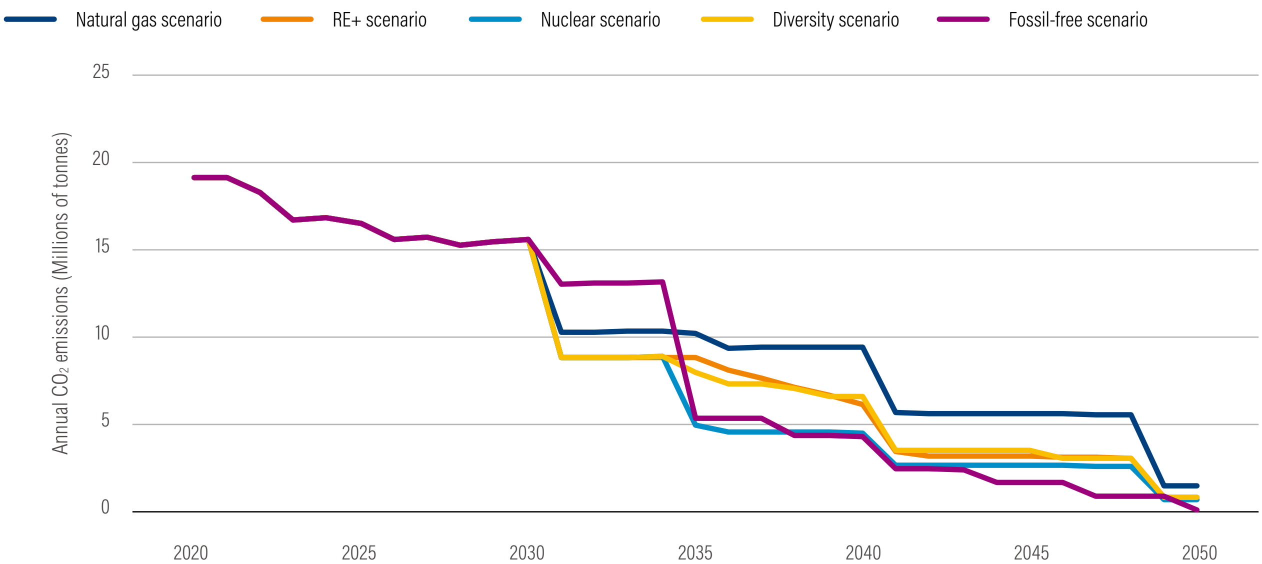
From the perspective of cumulative emissions, scenarios with a higher share of fossil fuels have higher emissions, and those with a higher share of nuclear and renewable energies have less emissions. Although different routes lead to the same goal, the cumulative emissions under the Natural Gas and Fossil-Free scenarios will be quite different—50 million tonnes of

Figure 18 | **Cumulative CO_2 Emissions under Different Scenarios**



Source: Calculated by the project team

Figure 19 | **Annual CO_2 Emissions under Different Scenarios**



Source: Calculation of the project team.

CO_2 (see Figure 18). The rise in temperatures brought about by climate change is affected by cumulative emissions. In this respect, the Nuclear and Fossil-Free scenarios deliver substantially earlier and enable larger cuts in emissions than the other options.

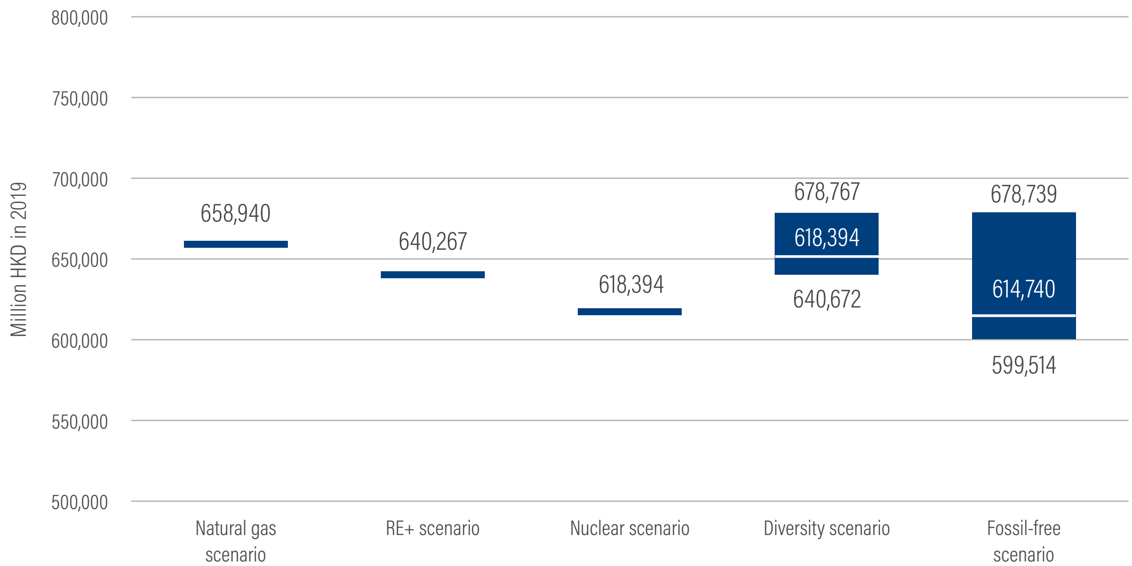
Although all pathways are designed to help Hong Kong achieve net-zero emissions, the annual emissions-reduction potential varies across scenarios over time. CO_2 emissions will be zero by 2050 only under the Fossil-Free scenario because all sources are from non-fossil fuel energy by 2050. Other scenarios will still have residual emissions that need to be offset by forest carbon sinks or by purchasing offset credits. The Natural Gas scenario will have the largest demand in this regard—1 million tonnes of CO_2 emissions in 2050 because of the energy penalty[8] and uncaptured emissions of CCS. Figure 19 shows the annual CO_2 emissions under each scenario. Under the Natural Gas scenario, the rate of decline in emissions from the power sector will gradually increase from 2036 because we assume that CCS will not be applied until 2036, and the application of CCS technology will be implemented through steps from the pilot to large-scale application. The Nuclear and Fossil-Free scenarios assume that the use of imported nuclear energy will be increased to 60 percent of the total electricity demand by 2035, so emissions will drop significantly in 2035.

Economic Impact: Cost of Electricity

Our estimated average total LCOE (including system costs) by 2050 in the Fossil-Free and Nuclear scenarios are similar, at 0.68 and 0.72 HKD/kWh, respectively, close to the current LCOE level, at 0.65 HKD/kWh. The total LCOE is estimated to be higher in the Natural Gas, RE+, and Diversity scenarios (approximately 0.78-0.87 HKD/kWh), which is much higher than the current level.

The costs of green hydrogen will have an impact on the average LCOE in hydrogen-related scenarios, namely Diversity and Fossil-Free. The projected average LCOE estimates are highly sensitive to the underlying data and assumptions. The future delivered costs of hydrogen are highly uncertain at this stage due to the early development of green hydrogen generation technologies and global transportation infrastructure. This is why LCOE and cumulative costs for the Diversity and Fossil-Free scenarios are a range in figures 20 and 21. The delivered costs of hydrogen

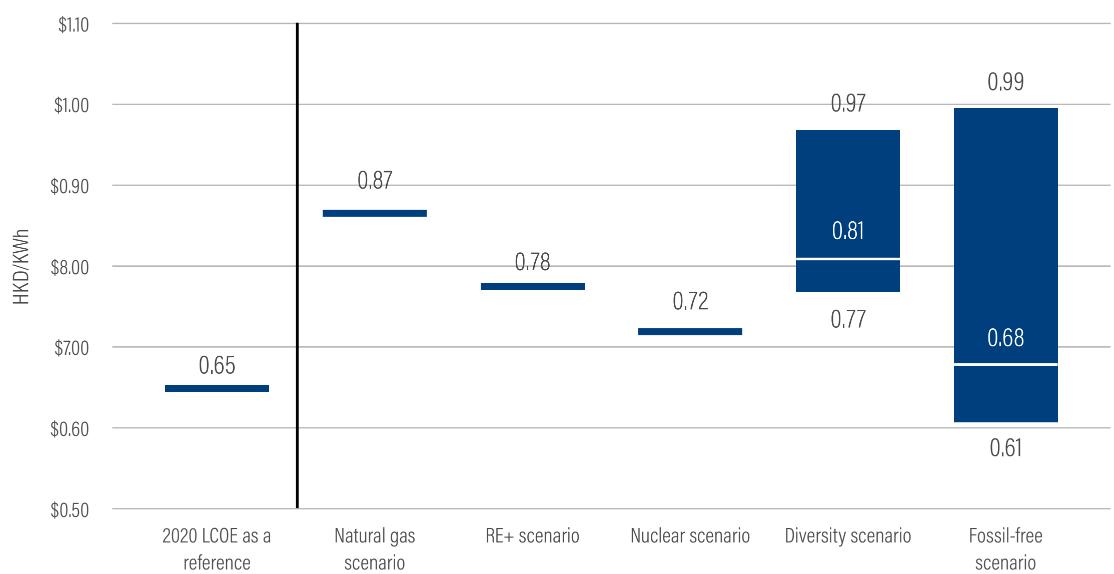
Figure 20 | **Projected Average Unit Costs of Electricity across Scenarios**



Note: Costs for the Diversity and Fossil-Free scenarios are shown as a range—including a highest level, a lowest level, and an average level—because hydrogen technologies are applied in these two scenarios and there is great uncertainty in the cost of hydrogen. The parameters used in calculating the LCOE of each technology (except for hydrogen) are drawn from the IEA *World Energy Outlook 2020*'s assumption for China and adjusted according to Hong Kong's local conditions; the cost of electricity generated from hydrogen is calculated based on the view that H_2 turbines would have similar construction costs, similar OpEx, and efficiency to CCGT (Goldman Sachs 2020). Future fuel costs are estimated by BloombergNEF and the Hydrogen Council. A discount rate of 3 percent is used.

Source: Calculated by the project team.

Figure 21 | **Projected Cumulative Costs of Electricity across Scenarios**



Note: Costs for the Diversity and the Fossil-Free scenarios are shown as a range—including a highest level, a lowest level, and an average level—because hydrogen technologies are applied in these two scenarios and there is great uncertainty in the cost of hydrogen. The parameters used in calculating the LCOE of each technology (except for hydrogen) are drawn from the IEA World Energy Outlook 2020's assumption for China and adjusted according to Hong Kong's local conditions; the cost of electricity generated from hydrogen is calculated based on the view that H_2 turbines would have similar construction costs, similar OpEx, and similar efficiency to CCGT (Goldman Sachs 2020). Future fuel costs are estimated by BloombergNEF and the Hydrogen Council.

Source: Calculated by the project team

are estimated to range between 14.9 and 52.0 USD/MMBtu by 2030; and 11.2 and 39.0 USD/MMBtu in 2040 (BloombergNEF 2020; Hydrogen Council and McKinsey & Company 2021). With hydrogen costing more, the Diversity and Fossil-Free scenarios would be less economically competitive, with an average total LCOE respectively of 0.97 and 0.99 HKD/kWh by 2050; this is 20–46 percent higher than the estimated average numbers. With a lower cost of hydrogen, the economic feasibility of the Diversity and Fossil-Free scenarios would be significantly improved, making the Fossil-Free scenario very competitive in terms of cost.

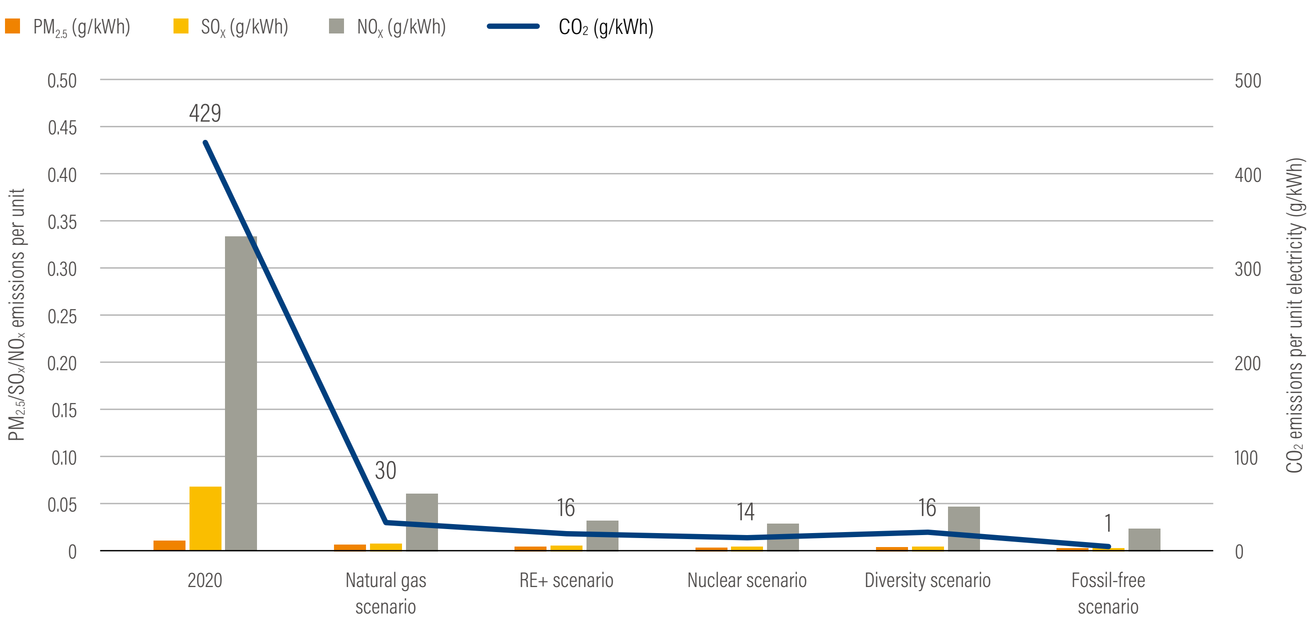
Cumulative costs are similar to the LCOE analysis. In summary, based on existing technological cost projections, scenarios with a greater proportion of nuclear would be more economically feasible for Hong Kong; those with a higher ratio of emerging technologies, such as CCS and hydrogen, would be less competitive.

Environmental and Health Impacts: Air Pollutants and Health Incidences

In addition to carbon dioxide, air pollution is a major indicator when measuring the environmental impact of particular power generation fuel mixes. Emissions of air pollutants are estimated by multiplying electricity generation per technology by emissions per kWh.

Using renewables and green hydrogen for power generation and increasing imported nuclear demonstrate significant environmental benefits, since they reduce the need to burn local fossil fuels. The use of CCS could largely reduce carbon dioxide emissions from local fossil fuel combustion, but energy penalties from the operations of carbon capture would increase air pollutant emissions—such as SO_2, NO_x and PM—imposing a more direct impact on local air quality and public health. As shown in Figure 22, under the RE+ and Nuclear scenarios, the high

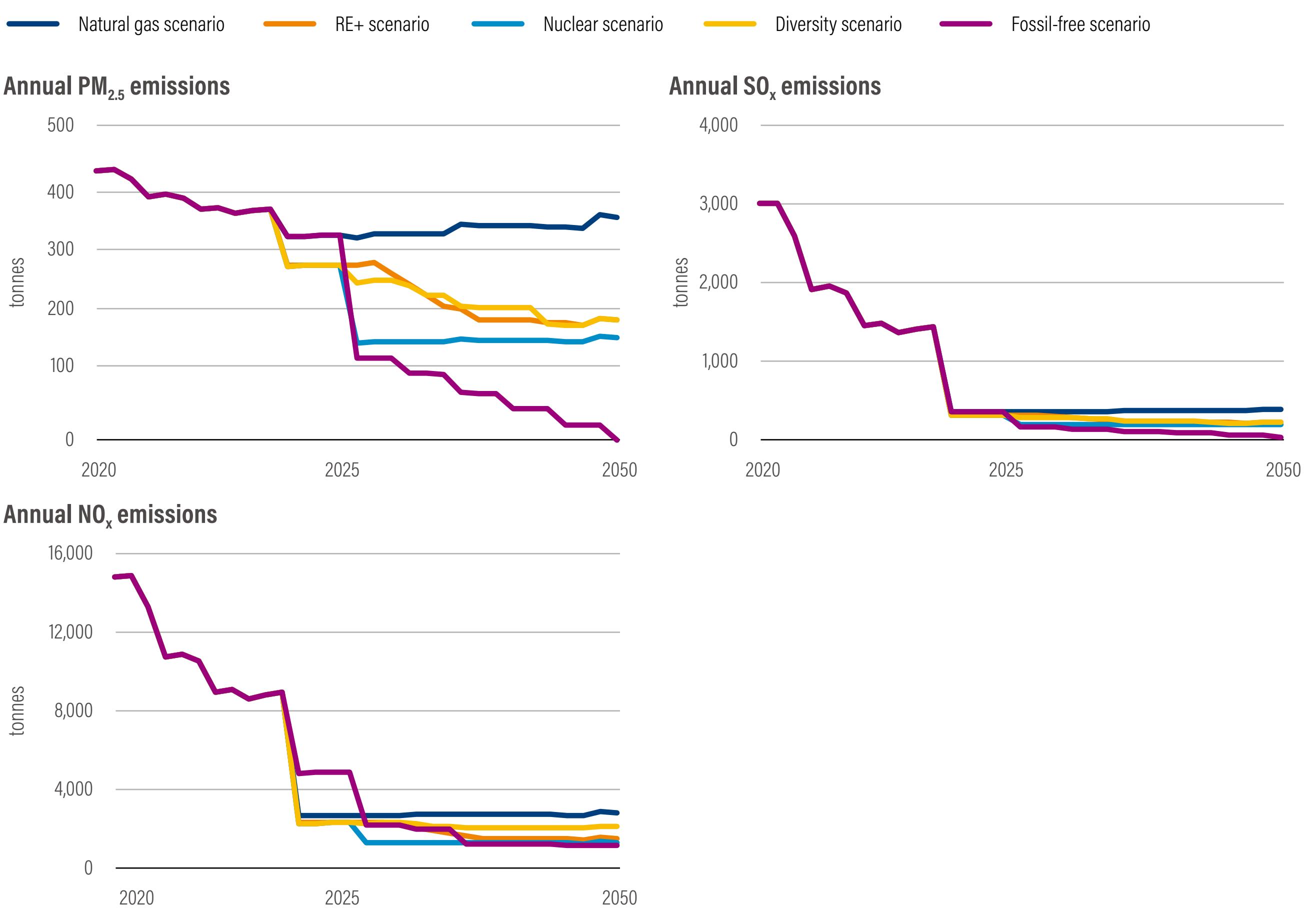
Figure 22 | **Carbon Dioxide and Air Pollutant Emissions per Unit of Electricity Output in Various Pathways**



Note: Emissions are estimated by multiplying electricity generation per technology by emissions per kWh. The emissions' factors for existing fossil fuel-fired power plants are drawn from the CLP Information Kit.

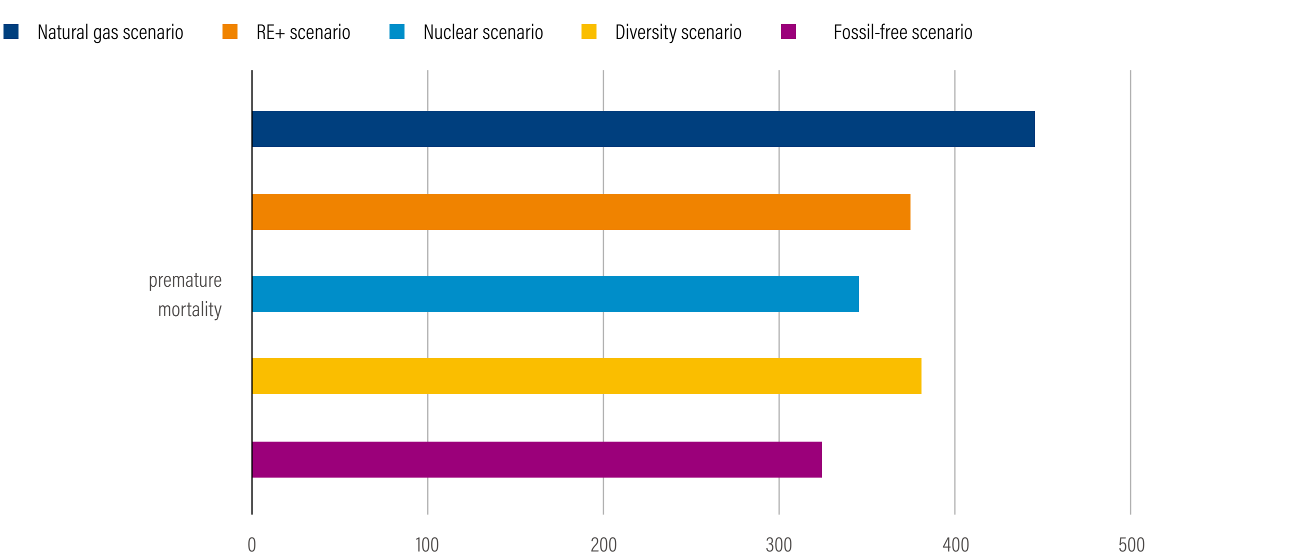
Source: Calculated by the project team

Figure 23 | Annual Air Pollutant Emissions across Different Scenarios



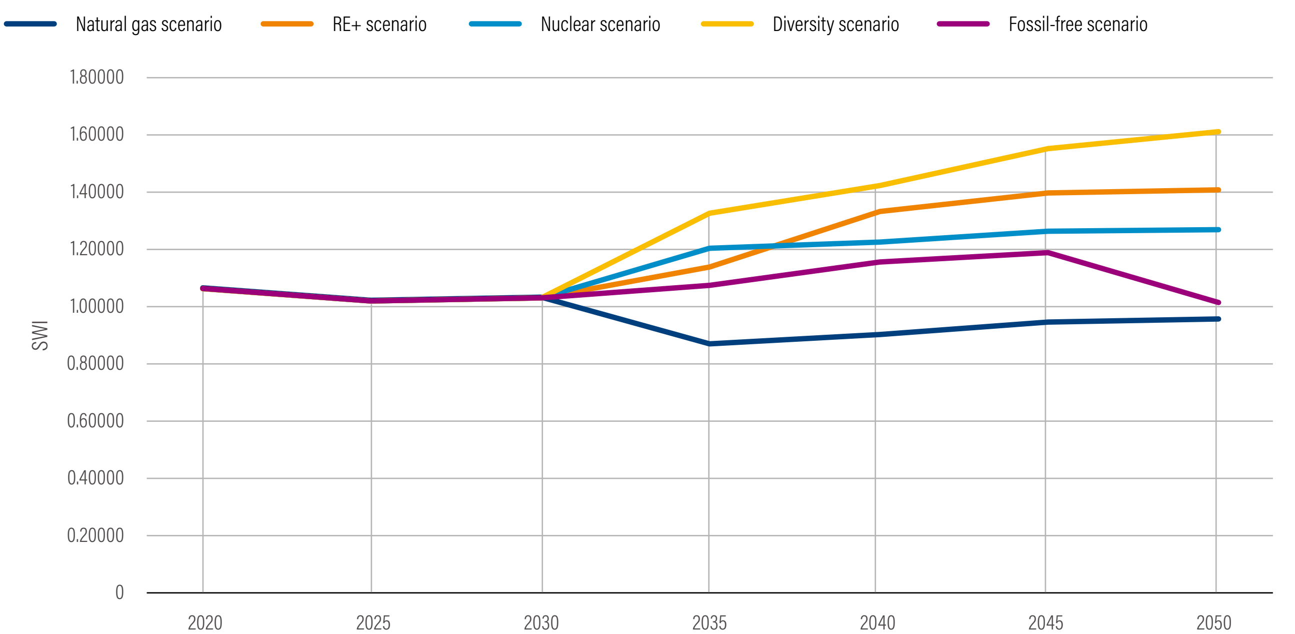
Source: Calculated by the project team.

Figure 24 | Cumulative Power Generation—Caused Air Pollution-Related Deaths in Various Pathways from 2021 to 2050



Source: Calculated by the project team.

Figure 25 | **Evolution of Each Scenario's Shannon-Wiener Diversity Index**



Source: Calculated by the project team.

ratio of imported nuclear or renewable energy for power generation would mostly eliminate air pollutant emissions; under the Fossil-Free scenario, air pollutant emissions per unit of electricity output by 2050 will be close to zero.

Our results (Figure 23) show that the Natural Gas scenario is the poorest performer in terms of reducing air pollution-related deaths. Overall, shifting away from the Natural Gas scenario can save around 1.5-2.9 billion HKD, based on 2019 prices.

Energy Diversification

In the short term, as shown in Figure 25, in all scenarios, the energy diversity of Hong Kong's power system is expected to drop before 2030 due to the increasing reliance on natural gas for electricity generation. In the long term, all scenarios, except Natural Gas and Fossil-Free, demonstrate significant improvement in the diversification of Hong Kong's power system, compared with today's levels. It is worth noting that Hong Kong's utility companies are also considering increasing natural gas terminals and importing nuclear power from different nuclear power plants to reduce their dependence on a single source, which could benefit Hong Kong's energy diversity.

Conclusions

This Chapter examines the performance of the five scenarios in terms of cost, air pollution, health, and energy diversity. Table 8 shows that the five scenarios perform differently against these criteria and no single scenario outperforms the others in all aspects. We lay out these options for the Hong Kong Government's consideration towards achieving its 2050 carbon neutrality goal.

In terms of **climate mitigation**, the Nuclear scenario has the lowest cumulative carbon emissions because it involves a one-time switch to a large-scale decarbonised energy source. The Fossil-Free scenario presents a pathway with the second-least cumulative carbon dioxide emissions and will lead to net-zero carbon emissions by 2050. The RE+, Nuclear, and Diversity scenarios will all bring carbon dioxide emissions in 2050 to less than 5 percent of today's levels. The Natural Gas scenario has the

Table 8 | **Comparison of Different Scenarios**

TECHNOLOGY YEAR		NATURAL GAS SCENARIO	RE+ SCENARIO	NUCLEAR SCENARIO	DIVERSITY SCENARIO	FOSSIL-FREE SCENARIO
Share of technologies in 2050	Natural gas with CCS	65%	35%	30%	35%	-
	Local RE	10%	10%	10%	10%	10%
	Imported RE	-	30%	10%	15%	-
	Nuclear	25%	25%	50%	25%	60%
	Hydrogen	-	-	-	15%	30%
Evaluation Criteria	Feasibility—technological maturity	No for CCS	No for CCS	No for CCS	No for CCS and hydrogen	No for hydrogen
	Economic competitiveness (ranked by avg. LCOE in 2050)	$$$$$	$$$	$$	$$$$	$
	Carbon and air pollutant emissions	High	Medium	Low	Medium	Low
	Associated health concerns	High	Medium	Low	Medium	Low
		Low	Medium	Medium	High	Low

Note: $ represents the lowest cost compared with the other scenarios; $$$$$ represents the highest cost compared with the other scenarios.

Source: Scenarios energy mix in 2050 are authors' assumption, evaluation criteria are calculation results of the project team.

highest cumulative emissions because it uses fossil fuels more than the other scenarios, as well as the energy penalties from the use of CCS.

From a **technical readiness** perspective, all the scenarios rely at different levels on the development of early-stage technologies, such as natural gas-fired power plants equipped with CCS and green hydrogen, which are still not commercially viable. This poses higher transition uncertainties. The Natural Gas and Diversity scenarios rely on these technologies for 50–65 percent of the total power generation mix, and the RE+, Nuclear, and Fossil-Free scenarios rely less on these technologies—between 30 and 35 percent.

In terms of **cost-effectiveness**, increasing imports of nuclear energy could help Hong Kong achieve its carbon neutrality goal while avoiding the higher costs associated with early development technologies. Based on existing research and estimates for the future cost of various decarbonised power-generation technologies, uncertainty mainly centres on the future price of green hydrogen and CCS technologies. Based on the current projection for the technologies, the Nuclear and Fossil-Free scenarios perform better economically.

It is evident that both **renewables** and **nuclear** energy have great potential for Hong Kong's future decarbonisation. While renewables are cleaner, more environmentally conscious, and more publicly accepted, nuclear should not be ruled out as an important option for the city, given its reliability and that it's a relatively mature technology. These options are not mutually exclusive. Instead, government and the two power companies should consider a wider diversification of the city's fuel mix and sources of power supply today, in order to ward against future supply disruptions and heighten the energy security in preparation for adverse events.

Domestic **gas-fired plants with CCS** could provide local dispatchable electricity sources and would avoid most carbon emissions. However, high costs are hindering this option from entering mainstream use in the short term. In the long-run, however, costs are expected to drop with global and regional R&D efforts on technological development and increasing investment in building infrastructure for carbon transport and storage. A high degree of reliance on CCS for deep decarbonisation may delay Hong Kong's power transformation, leading to higher cumulative carbon emissions and adverse health benefits. Also, due to energy penalties, the associated NO_x and SO_2 emissions would still have negative environmental and health impacts.

Currently, powering the base load using green hydrogen is challenging due to limited supplies and high fuel costs. Successfully utilising hydrogen in Hong Kong's power sector depends on global efforts in green hydrogen technology development and deployment. In the long-run, hydrogen-based energy can play an important role in Hong Kong's power system, including providing backup power, meeting peak demand, and serving as a means of long-term energy storage. The delivered costs of hydrogen could largely affect the power-generation costs of electricity in Hong Kong.

CHAPTER 7

RECOMMENDATIONS

In the Hong Kong Climate Action Plan 2050, government has pledged to increase the share of renewable energy (waste-to-energy, solar, and offshore wind) in Hong Kong's fuel mix to 7.5–10 percent by 2030 and to 15 percent gradually thereafter. Government has further committed to consider regional cooperation through offshore projects and joint ventures towards the large-scale development of nuclear and green hydrogen. The evaluation of these technological options in this report can inform government's planning and implementation of these targets.

Building on our analysis of decarbonised technology options for Hong Kong, this report has offered several possible pathways towards a net-zero power system. As government considers how to decarbonise the city's power system, which could be through one of the five scenarios or different combinations of them, it also needs to revisit possible pathways from time to time to keep in line with technological and market developments. In any case, at present, it is critical for government to act ambitiously and decisively towards a carbon-neutral power system. Any delay will lead to a carbon lock-in, which will eventually lead to larger cumulative emissions and jeopardise Hong Kong's carbon-neutrality vision. It will also hamper Hong Kong's leadership as one of the world's most advanced cities and an important international financial centre.

We make the following recommendations for immediate implementation. We call these no-regret actions. Regardless of which pathway government chooses, it should consider these recommendations for immediate implementation.

Recommendation 1: Scale-up domestic wind and solar energy.

Many studies (see Chapter 2) indicate that Hong Kong's renewable energy potential is much greater than the current government target of 3–4 percent of total energy consumption. This paper estimates it to be as high as 10 percent. Regardless of which pathway is chosen, government should utilise domestic renewable energy resources as much as possible. To do so, we recommend the following actions over the **next 12 to 24 months**:

Conduct a new study with the power companies to comprehensively examine Hong Kong's renewable energy resources. While there have been other studies on renewable energy in Hong Kong in the context of solar PV systems or the FiT scheme, none are as comprehensive as the EMSD's 2004 *Study on the Potential Applications of Renewable Energy in Hong Kong*. Based on technological advancements in the past 20 years, government should not only renew this research, but conduct

more feasibility studies into some of the stalled or earmarked projects. Given the upward trend in solar and wind technology efficiency, government should conduct an annual review of Hong Kong's renewable energy potential and cost and business model and update its renewable-energy targets according to the latest developments in renewable technology.

Incentivise renewable energy investment and promote an innovative application model and business model. Since 2018, the Government Green Bond Programme has provided funding for green public works projects. Government should introduce more financial incentives, such as fiscal and taxation mechanisms, to encourage both utility and non-utility companies to develop renewable energy alternatives. Government could also consider subsidising the initial costs of renewable-energy development.

Recommendation 2: Further scale up waste-to-energy facilities.

WtE technology offers a solution to address both waste management and GHG emission issues. Whilst reducing the generation of waste, Hong Kong should optimise the utilisation of WtE, which is an invaluable domestic renewable resource. To scale up WtE in Hong Kong, we recommend that government consider the following actions over the **coming 12 to 36 months**:

Use SCAs to ramp up WtE development. Government may include a WtE target in the SCAs as their statutory duty and request both power companies to develop WtE facilities in their plant sites. For instance, Castle Peak and Lamma Island can be potential sites for two or three more incinerators.

Enhance public awareness of WtE facilities. Inclusive decision-making is key to implementing WtE in Hong Kong. Much of the public backlash, which resulted from previous efforts to push for incinerations, came from the failure to consult with residents near the proposed sites. Government should properly address residents' concerns about air pollution, odours, and worsened environmental quality by increasing the transparency of the construction process and by offering real-time air quality monitoring.

Recommendation 3: Explore opportunities for regional collaboration on renewable and nuclear energy development with Mainland China.

Constrained by land and natural resources, Hong Kong does not have favourable conditions for large-scale renewable energy development. One option to help with decarbonising Hong Kong's power system is to expand the import of renewable and nuclear energy from Mainland China. Building new nuclear power plants and offshore wind projects are top of Guangdong's energy development agenda and could provide opportunities for Hong Kong to increase its imported clean energy via regional collaborations. Currently, nuclear energy from the Daya Bay Nuclear Power Plant in Guangdong provides the largest source of zero-carbon electricity, which is around a quarter of the total power demand for Hong Kong (CLP 2021b). To further explore this option, government should consider the following actions over the **next 12 to 24 months**:

Explore the feasibility of importing renewable and nuclear energy from Guangdong. In addition to technical feasibility, it is important that central and provincial authorities on the mainland understand the potential for Hong Kong to import greater volumes of zero-carbon electricity from Mainland China. This exploration should seek mechanisms that can maximise the agency of local power companies to prevent Hong Kong from being a captive buyer. Government should actively seek opportunities to establish joint-venture partnerships with power generators in an arrangement similar to CLP's current partnership with Daya Bay.

Explore the feasibility of greater interconnection for Hong Kong with the China Southern Grid. Complementing the above recommendation to import more renewable and nuclear energy from Guangdong, interconnection between Hong Kong and the China Southern Grid is essential. Government should explore the feasibility of long-distance interconnections and potential routes for power cables. It is vital to engage with the public to seek their opinion as this can lead to better informed and comprehensive decisions.

Recommendation 4: Explore the potential of using large-scale green hydrogen.

With hydrogen becoming an important technology in realising a net-zero carbon society, it has huge potential in satisfying Hong Kong's peak load and grid-balancing issues, as well as ensuring its energy security. However, hydrogen utilisation still has a lot of challenges. For example, storage and transport are especially difficult, and the costs associated with producing green hydrogen are also particularly high. As such, government should consider the following actions over the **next 12 to 24 months**:

Establish a cross-agency task force to develop a green hydrogen strategy for Hong Kong. The task force must focus on a long-term strategy for the large-scale deployment of green hydrogen in Hong Kong. This strategy should also include a quantitative risk assessment and a hazard-and-operability analysis of hydrogen technologies, including safe handling of hydrogen, standards in hydrogen purity, and verifiable certification for life-cycle GHG emissions. The task force should include representatives from government and different business sectors across the entire value chain of green hydrogen production, transport, and utilisation.

Building on this recommendation, in the **next three to five years**, government may consider.

Encouraging green hydrogen technology development. Incentives could include providing subsidies for green hydrogen research and development, enacting carbon pricing to allow green hydrogen to become more cost-competitive and facilitating public-private partnerships between government and CLP, HKE, or property developers. Government may also consider facilitating regional partnerships

with potential green hydrogen exporters, such as Mainland China, Australia, and countries in the Middle East. In addition, it is important to conduct an analysis on matters related to hydrogen imports, such as monitoring global price changes and assessing the feasibility of using a floating import and storage dock, similar to Hong Kong's new LNG floating dock, for hydrogen.

Recommendation 5: Enhance grid balancing to accommodate a broader energy mix.

Grid balancing becomes more challenging as a higher percentage of supply moves to multiple sources of energy, including nuclear, wind, and solar energy. Hong Kong needs to look at all options, including better interconnections within Hong Kong, enhanced interconnection with the China Southern Grid, and an increased storage capacity. Government should consider the following action in the next 12 to 24 months:

Carry out a detailed study with the power companies to identify measures to enhance grid balancing. This may include new investments in alternative sources of system reliability and flexibility in response to the shift from a dispatchable generation-dominated power system to one with more renewable power. To balance electricity supply and demand, especially with more renewable energy, Hong Kong's power system will need more flexibility, which can be provided by a mix of supply- and demand-side options, including flexible conventional generation, new transmission, and more responsive loads.

Recommendation 6: Explore the possibility of CCS technology deployment.

There is growing recognition that CCS is an integral part of a least-cost portfolio of technologies and is needed to support the decarbonisation of power systems globally. Without CCS, meeting Hong Kong's carbon-neutrality target means eliminating the use of fossil fuels (Fossil-Free Scenario in Chapter 6). Cost remains the biggest challenge in preventing CCS-equipped power plants from being commercially viable. This consists of costs related to capturing, transporting, and storing CO_2 emissions. While a large-scale deployment of CCS is still uncertain, we believe Hong Kong should do the following in the **coming 5 to 10 years**:

Ensure that all fossil fuel-based power plants built after 2020 are CCS-ready. Once built, retrofitting existing facilities with CCS would be very costly or even infeasible. During the project design phase, power companies should ensure that the technical requirements for CCS are considered and met. These requirements include reserving space for CO_2 capturing equipment, configuring the turbine, ensuring the availability of cooling water and the additional flue gas pre-treatment required before CO_2 capture, as well as dedicated auxiliary power systems. Government could also require proposals from CCS-ready power plants.

Actively engage in the regional CCS development projects. High quality and sufficient storage capacity are prerequisites for CCS development. From a source-sink matching perspective, the distance between Hong Kong's power plants and the storage areas is deemed reasonable. While the future development of CCS is still uncertain, government and the utility companies should start to actively engage in regional CCS development projects, including those in Guangdong. This will help ensure better planning for future CCS deployment.

Recommendation 7: Increase the electrification of Hong Kong society.

Although this report focuses on reducing emissions in the power industry, 45 percent of Hong Kong's final energy demand is still satisfied by fossil fuels. Hence, the decarbonisation of power needs to be considered in conjunction with electrification. Government should promote electrification in Hong Kong alongside its decarbonisation of the power system to break dependency on fossil fuels and cut carbon emissions. Detailed recommendations regarding the electrification of the transport and building sectors can be found in other reports. Only through a holistic, whole-society approach can Hong Kong achieve carbon neutrality before 2050.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ANNEX
SCENARIO SETTING

Table A-1 | **Scenario setting**

SCENARIO	ASSUMPTIONS ON THE TECHNOLOGY ADOPTION IN ADDITION TO THE EXISTING PLANNED CAPACITY
Natural Gas Scenario	
Natural gas	Build new CCGT plants by 2031 to replace the retired coal-fired power plants. CCS will be gradually applied by 2035.
Imported nuclear	Maintain the current level of imported nuclear power in the total electricity mix.
RE+ Scenario	
Imported RE	Start to import RE for 10 percent of the total demand in 2031 and achieve 30 percent in the early 2040s.
Natural gas	Build new CCGT power plants at the end of 2040s. CCS will be gradually applied by 2035.
Imported nuclear	Maintain the current level of imported nuclear power in the total electricity mix.
Nuclear Scenario	
Imported RE	Start to import RE for 10 percent of the total demand in 2031.
Natural gas	Reduce NG power plant use compared to current capacity level, and install new capacity by the end of 2040s. CCS will be gradually applied by 2035.
Imported nuclear	Double the current level of imported nuclear power by 2035.
Diversity Scenario	
Imported RE	Increase imported RE to 10 percent in 2030, achieve 15 percent in 2040, and then maintain this level.
Natural gas	Reduce NG power plant use between 2030 and 2037, install new capacity by 2040. CCS will be gradually applied by 2035.
Imported nuclear	Maintain the current level of imported nuclear power in the total electricity mix.
Green hydrogen	Start to use hydrogen in 2035 and gradually increase its use to achieve 15 percent by 2050.
Fossil-Free Scenario	
Natural gas	Reduce NG power plant use between 2031 and 2050.
Green hydrogen	Start to use 'green' hydrogen in 2035 (co-combustion in CCGT) and gradually increase its use to achieve 15 percent by 2050.
Imported nuclear	Increase imported nuclear to 60 percent of the total power demand by 2034.

Table A-2 | **Techno-Economic Parameters 1**

TECHNOLOGY	YEAR	LIFETIME (YEARS)	CAPITAL COST ($/KW)[a]	CAPACITY FACTOR (%)[a,d]	ANNUAL O&M COST ($/KW-YR)[a]	HEAT RATE (BTU/KWH)[a,b,c]	FUEL COST ($/MMBTU)[c,f]	LEVELIZED COST OF ENERGY (HKD/KWH)	SYSTEM COSTS (HKD/KWH)[h]
Coal	2019	40	700	30	30	11006	3.8	0.509	0.045
Coal	2030	40	700	30	30	11006	3.8	0.509	0.045
Coal	2040	40	700	30	30	11006	3.8	0.509	0.045
CCGT	2019	40	560	57	20	7742	7.7	0.749	0.045
CCGT	2030	40	560	57	20	5986	7.7	0.667	0.045
CCGT	2040	40	560	57	20	5783	7.7	0.655	0.045
CCGT + CCS	2019	40	2200	50	70	6964	7.7	0.952	0.045
CCGT + CCS	2030	40	2100	50	70	6824	7.7	0.936	0.045
CCGT + CCS	2040	40	1800	50	60	6824	7.7	0.895	0.045
Solar	2019	25	790	10	12	3412	0	0.5	0.2
Solar	2030	25	520	10	12	3412	0	0.365	0.2
Solar	2040	25	450	10	12	3412	0	0.33	0.336
Wind onshore	2019	25	1220	21	30	3412	0	0.429	0.209
Wind onshore	2030	25	1180	22	28	3412	0	0.389	0.209
Wind onshore	2040	25	1140	23	28	3412	0	0.364	0.345
Wind offshore	2019	25	3000	32	75	3412	0	0.691	0.209
Wind offshore	2030	25	1920	38	55	3412	0	0.389	0.209
Wind offshore	2040	25	1640	44	50	3412	0	0.293	0.345
Nuclear	2019	60	2600	80	120	10340	2.3	0.426	0.045
Nuclear	2030	60	2750	80	120	10340	2.3	0.432	0.045
Nuclear	2040	60	2500	80	120	10340	2.3	0.422	0.045
WTE	2019			78				2.63	0.045

Table A-2 | **Techno-Economic Parameters 2**

TECHNOLOGY	YEAR	LIFETIME (YEARS)	CAPITAL COST ($/KW)[a]	CAPACITY FACTOR (%)[a,d]	ANNUAL O&M COST ($/KW-YR)[a]	HEAT RATE (BTU/KWH)[a,b,c]	FUEL COST ($/MMBTU)[c,f]	LEVELIZED COST OF ENERGY (HKD/KWH)	SYSTEM COSTS (HKD/KWH)[h]
WTE	2030			78				2.821	0.045
WTE	2040			78				2.788	0.045
Hydrogen-gas turbine	2030	40	560	60	20	5986	22.3	1.094	0.045
Hydrogen-gas turbine	2040	40	560	60	20	5986	16.7	0.824	0.045
Hydrogen-gas turbine – lower fuel cost	2030	40	560	60	20	5986	14.9	0.753	0.045
Hydrogen-gas turbine – lower fuel cost	2040	40	560	60	20	5986	11.2	0.58	0.045
Hydrogen-gas turbine – higher fuel cost	2030	40	560	60	20	5986	52	2.463	0.045
Hydrogen-gas turbine – higher fuel cost	2040	40	560	60	20	5986	39	1.865	0.045

Sources and key assumptions: [a] IEA 2020, World Energy Outlook's assumption—Stated Policies Scenario for China: lifetime, capital cost, capacity factor (nuclear and onshore wind), annual O&M, heat rate (for 2030 and 2040).
[b] EPS Hong Kong: heat rate for existing (2019) coal and natural gas power plant.
[c] Fossil fuel costs are based on HKE's fuel price in 2017 (HKE 2019).
[d] Capacity factor: solar and onshore wind power estimates based on Guangdong Province; coal and gas are based on Hong Kong's local power plants.
[e] IEA's CCGT parameters for H_2 gas turbine, as Goldman Sachs report points out, H_2 turbines would have similar construction costs, similar OpEx, and similar efficiency to CCGT (Gandolfi et al. 2020).
[f] H_2 price is based on BNEF and Hydrogen Council (BloombergNEF 2020; Hydrogen Council and McKinsey & Company 2021).
[g] LCOE for WtE is drawn from Hong Kong EPS.
[h] System costs are drawn from *The Social Costs of Electricity Generation—Categorising Different Types of Costs and Evaluating Their Respective Relevance with Currency Exchange* (Samadi 2017).

Source: IEA 2020; HKE 2019; Gandolfi et al. 2020; BloombergNEF 2020; Hydrogen Council and McKinsey & Company 2021; Samadi 2017.

ENDNOTES

1. Hong Kong 2050 Is Now, a Hong Kong-based platform for education, collaboration, and action on the climate crisis, seeks to inspire ambitious target-setting, induce behavioural change, and mobilise collective action towards a carbon-neutral Hong Kong. For more information: https://www.hk2050isnow.org/.
2. The report, *Towards a Better Hong Kong: Pathways to Net-Zero Carbon Emissions by 2050*, can be found at https://www.wri.org.cn/en/report/2020/06/Hong-Kong-2050-Policy-Report-EN.
3. In Hong Kong, town gas is produced from naphtha and natural gas. Its major components are hydrogen, methane, carbon dioxide, and a small amount of carbon monoxide. More information can be found at https://www.emsd.gov.hk/en/gas_safety/gas_safety_tips_to_users/types_of_domestic_fuel_gases_and_their_properties/.
4. The Hong Kong Energy Policy Simulator (Hong Kong EPS) is a version of the Energy Policy Simulator, https://www.energypolicy.solutions/, an open source, system-dynamics computer model. The EPS can estimate the effects of various policies on many indicators, such as emissions, financial metrics, electricity system structure, deployment of different types of vehicles, as well as many other data. The Hong Kong EPS was developed in 2020. For more detailed information in regards to the methods, data, and results, please see the related publication, "Hong Kong Energy Policy Simulator: Methods, Data, and Scenario Results for 2050," https://www.wri.org.cn/sites/default/files/Hong%20Kong%20EPS_Final20191220.pdf.
5. The carbon intensity of town gas production in Hong Kong is 0.564 kg CO_2e/unit of town gas, and the carbon intensity of town gas usage is 2.553 kg CO_2e/unit. According to HKCG, one unit of town gas = 48 MJ, and 1 TJ = 1,000,000 MJ. According to *HK Carbon Emission Estimation Guidelines* (2010), burning one unit of town gas will produce 2.549 kg CO_2, 0.0446 g CH_4, 0.0099 g N_2O. (The carbon emission factor is 2.553 kg CO_2e/unit; taking production into consideration, it is 3.117 kg CO_2e/unit.)
6. The average carbon dioxide coefficient of natural gas is 0.0549 kg CO_2 per cubic foot (EIA 2019c). One cubic foot of natural gas could provide 1,000 BTU's energy, which is 1.055 MJ. So, 48 MJ of natural gas brings 2.498 kg CO_2e.
7. For instance, the State Grid has deployed a fibre-optic control network that automatically rebalances supply and demand and can boost line voltage within 200 milliseconds of a voltage drop. This network allows delivery of hydropower to operate at its designed capacity more reliably.
8. Energy penalty is defined as the fraction of fuel that must be dedicated to CCS for a fixed quantity of work output.

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World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

Our Challenge
Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision
We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach
COUNT IT
We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT
We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure that our outcomes will be bold and enduring.

SCALE IT
We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.

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Civic Exchange is an independent Hong Kong public-policy think tank established in 2000 with a vision to shape a livable and sustainable Hong Kong. Its mission is to engage society and influence public policy through in-depth research, dialogue, and the development of practical solutions. With research covering four areas—environmental, economic, social, and governance—Civic Exchange has been ranked among the top 50 environmental think tanks in the world by the Lauder Institute at the University of Pennsylvania since 2011.

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"Hong Kong 2050 Is Now" galvanises collective action in science, media, business and policy towards a carbon-neutral Hong Kong by 2050. This initiative of Civic Exchange, World Resources Institute, and the ADM Capital Foundation aims to build a broad-based collective platform for driving action in Hong Kong in response to the 2018 Intergovernmental Panel on Climate Change (IPCC) report on Global Warming of 1.5°C. According to that report, without urgent, large-scale action, global warming is likely to reach 1.5°C above pre-industrial levels, with potentially significant and dangerous consequences for the world. We believe that a decarbonised city is people-centric, more livable, healthier and successful. That's what we want for Hong Kong.

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