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International Renewable Energy Agency

NET ZERO PATHWAYS FOR CITIES: THE CASE STUDY OF WUZHONG DISTRICT, SUZHOU, CHINA

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Contributing authors
This report was prepared, under the guidance of Dolf Gielen, by the sustainable urban energy team at IRENA's Innovation and Technology Centre. It was authored by Yong Chen (IRENA), Mashael Yazdanie, and Chenyu Zhou (Empa), Weiyang Li, Weimin Xi and Chanxia Zhu (SGCERI), with additional support from Julien Marquant and Fabia Miorelli (former IRENA colleagues).

TABLE OF CONTENTS

Figures

Tables

ABBREVIATIONS

BC	baseline case
BIPV	building-integrated photovoltaic
CCP	combined cycle power plant
CCS	carbon capture and storage
CHP	combined heat and power plant
CO_2	carbon dioxide
CP	carbon policy
GDP	gross domestic product
IGCC	integrated gasification combined cycle
NZC	net-zero CO_2 emissions
PV	photovoltaic
SD	sustainable development
SGCERI	State Grid City and Energy Research Institute

EXECUTIVE SUMMARY

In 2020, Chinese President Xi Jinping announced, at the 75th United Nations General Assembly, that China will aim to peak carbon dioxide (CO_2) emissions before 2030 and achieve carbon neutrality by 2060. At the national level, China has – over the past decade – made remarkable progress in renewable energy development, in particular in solar photovoltaics (PVs) and wind power. By the end of 2020, renewable electricity accounted for around 30% of total electricity output and 42% of national installed power generation capacity. In spite of this, fossil fuels remain dominant in Chinese energy use, including in the power sector and in end-use sectors such as transportation, buildings and industry. Cities, including their suburban areas, where the majority of these sectors' activities take place, will therefore have an important role to play in achieving the goals announced by President Xi Jinping.

In 2020, about 60% of Chinese people lived in cities. Cities already consume 85% of the total national energy supply in China and are responsible for around 70% of total national energy-related CO_2 emissions. Yet, over the next three decades, it has been projected that another 250 million people will become urban dwellers in China. How can local decision makers support the national energy transition and the achievement of the national climate objectives while sustaining local economic and social development?

This study used the Wuzhong District of Suzhou city as a case study to explore pathways towards a net-zero emissions future, particularly for those cities where the potential for renewable energy production is less abundant. The study took a unique approach. The first question probed was what options Wuzhong would have if the district used conventional emission abatement technologies to reduce its carbon emissions from its current energy mix. Considerations taken into account in answering this question included (a) the constraints district governance might face in making a dramatic and systemic change and (b) the district's limited renewable energy resources and its constraints on land use due to the ecological preservation zone it is located in.

The modelling results and scenario analyses show how Wuzhong's energy system might evolve if the technological options and decarbonisation strategies are, to a large extent, confined to conventional technological pathways. Cost-optimal scenarios demonstrate significantly lower local installed capacities, as they rely heavily on grid imports. Carbon-optimal scenarios demonstrate significantly higher investments in gas, carbon capture and storage (CCS), ground-or water-source heat pumps, and solar conversion technologies, making these scenarios more costly. The modelling exercise aimed to help local decision makers understand the limitations of the business-as-usual approach and why transformative measures might be needed.

In addition, the modelling-derived results indicate that Wuzhong would have to rely on CCS for decarbonising natural gas and coal if it focused on decarbonisation of its own generation capacity to achieve net-zero. In less ambitious scenarios, natural gas is given an important role to play. These modelling results might not be aligned with the Chinese overall policy direction and multiple constraints that may exist in China, including limited potential of natural gas resources, lack of clarity on carbon storage capacity in the region, and the technology risks of CCS. Hence, the overall outlook for the supply of natural gas would need to be further discussed, as the demand for natural gas nationwide is expected to grow dramatically following the phasing down of coal consumption. Also, a detailed feasibility analysis of CCS technologies in the Suzhou area needs to be conducted.

Given the above, the extent to which Wuzhong can adopt advanced renewable energy technologies – such as building-integrated photovoltaic (PV), city-integrated applications of solar PV, and innovative solutions such as extracting cold energy from water supply facilities – is crucial to increasing the uptake of renewables. Although waste energy resources (mainly biomass and municipal solid wastes) are fully utilised in every year of every modelled scenario, some advanced technologies might enable biodegradable feedstock to be used in a more efficient way, which might also expand the local resource spectrum; this option could be used in addition to importing underutilised wastes from neighbouring districts. The local geothermal potential and the applicability of advanced technologies for direct use of geothermal resources are also worth investigating.

In all scenarios with the conventional emission abatement approach, natural gas is given an important role to play, under the assumption that the carbon emission factors of the electricity imported from the grid to Wuzhong District are higher than those associated with local natural gas-based electricity generation. However, the grid electricity could be decarbonised faster, with greater shares of solar PV and wind power being integrated into the grid, if cities could support grid operation with more demand-side flexibility. This will, in return, affect how cities respond to the paradigm change in the Chinese power sector and will consequentially affect the carbon emission factors of national and regional grid electricity to Wuzhong.

The second step of the study looked at strategic areas enabling expansion of the decarbonisation options presented in the modelling results: building-integrated PV, demand-side flexibility, green hydrogen and urban energy planning. These areas are applicable not only for Wuzhong but in general for many districts and cities like Wuzhong with moderate local renewable energy resources and relatively high energy demand. Certainly, these strategic areas do not constitute an exhaustive list, but they do highlight the most relevant aspects that such cities or districts should look into and adjust to suit the characteristics of their localities.

Overall, the Chinese leadership has boosted its ambition and stepped up its efforts to address the climate challenges. Cities will take this as guidance and make corresponding strategies and actions plans to contribute as much as they can to achieving the national carbon peak by 2030 and carbon neutrality by 2060. However, the actions they take and the decisions they make should be based on their resources. Those without abundant local renewable energy resources could explore other options with the aim of achieving net-zero for Chinese cities in a collective and collaborative fashion.

1

INTRODUCTION

With the near-universal adoption in 2015 of the Paris Agreement – an international treaty on climate change – reaching net-zero emission of anthropogenic carbon dioxide (CO_2) around 2050 has become the key driver for the global energy transition (IPCC, 2018; UNFCCC, n.d.). Cities will play a critical role in reducing emissions as they are responsible for around three-quarters of global energy use and CO_2 emissions (Edenhofer *et al.*, 2014). Cities would, in return, be rewarded with new opportunities for industrial and business development, as well as job creation, generated by implementing innovative solutions and redesigning urban infrastructure to unlock potential for carbon emissions reduction (IRENA, 2020a).

1.1 China's new carbon targets are guiding cities' energy development

Five years after joining the Paris Agreement, Chinese President Xi Jinping announced, at the 75th United Nations General Assembly, that China will aim to achieve carbon neutrality[1] by 2060 and peak (energy-related) CO_2 emissions before 2030. These are known as the "dual carbon goals" or "30-60 goals" in China. They send a strong signal of China's commitment to accelerating efforts to address climate issues under the global framework set out by the Paris Agreement.

Over the past decade, China has made remarkable progress in renewable energy development, in particular in solar photovoltaics (PVs) and wind power. By the end of 2020, renewable electricity accounted for around 30% of total electricity output and 42% of national installed power generation capacity, according to the Chinese National Energy Administration. However, fossil fuels remain dominant in Chinese energy use, as electricity makes up only slightly more than one-quarter of final energy use at present. Therefore, decarbonising end-use sectors such as transportation, buildings and industry through electrification and through substitution of fossil fuels with renewable-based energy carriers will be crucial for China to achieve its dual carbon goals. Cities, including their suburban areas, where the majority of the key end-use sectors' activities take place, will have an important role to play.

1. Covering all greenhouse gases.

In 2020, about 60% of Chinese people lived in cities. Over the next three decades, it is projected that another 250 million people in China will become urban dwellers (CNBS, 2021). This suggests that both energy consumption and carbon emissions will increase in keeping with the growing urbanisation if substantial measures are not taken. The implications are significant, given that cities already consume 85% of the total national energy supply in China and are responsible for around 70% of total national energy-related CO_2 emissions (McKinsey & Company, 2021; SGCERI, 2019). The major challenge thus lies in how to significantly reduce emissions while providing energy to growing urban populations, given that fossil fuels are still the dominant source of energy supply in China.

The Chinese Government is developing more detailed guidance for subnational governments and sectors to follow in devising their own action plans. Decarbonisation of the building sector and the transport sector is expected to be a key area of focus under the guidance to be issued soon (Government of China, 2021). This has provided cities a clear policy direction for their future urban planning and infrastructure development.

Yet, for many, the question is how and to what extent Chinese cities can capitalise on such opportunities. A major challenge is the mismatch between the geographical distribution of the resources and the demand for energy services. Much of the excellent renewable energy resources – notably, solar and onshore wind and hydropower – are located in the northern and western parts of China, while the demand (or load centres), like cities, is concentrated in the eastern and southern regions.

Therefore, it would be easier for the northern and western cities with abundant renewables to decarbonise their energy supply and provide renewable electricity to the other regions, if the transmission capacity permits. Zhangjiakou city is one such example (see Box 1).

For many central and eastern Chinese cities (except for some coastal cities with decent offshore wind energy potential), the local potential for renewable energy resources is modest; furthermore, the available land for the deployment of utility-scale renewable energy systems is limited. Nevertheless, thanks to their geographic proximity to the load centres and continued decline in cost, there are still some cities where local renewable-based distributed energy systems present compelling options.

However, many cities have to rely on "imported" renewable electricity via the national or regional grids as a key strategy for achieving net-zero emissions. In return, those cities can provide greater flexibility to assist the integration of variable renewable energy sources by increasing electrification in end-use sectors and by upgrading local power grids and energy management systems with digitalised devices and intelligent controls. For example, in some cities globally, electric vehicles and two- and three-wheelers have been used to reduce dependency on fossil-derived transport fuels as well as to decarbonise the transportation sector. China has been making steady progress in the electrification of the transport sector. Power-to-heat is another area where cities have taken advantage of surplus renewable electricity to reduce emissions from the heating sector.

Therefore, it is crucial for local authorities to develop a long-term energy transition strategy. Such a strategy is vital to making forward-looking investment decisions today to avoid lock-in effects and future stranded assets.

BOX 1: Zhangjiakou's energy transformation with solar and wind

Zhangjiakou is a medium-sized Chinese city of 4.4 million people located in northwest Hebei Province, adjacent to Beijing. The city is abundant in renewable energy resources, including an estimated technical resource potential of 30 gigawatts (GW) for solar photovoltaics and 40 GW for wind. Over the past decade, the city has stepped up its efforts to deploy renewable energy systems. In 2017, renewables accounted for 73% of the total installed capacity in Zhangjiakou and for around 45% of the total electricity output. Nevertheless, much of the potential has yet to be exploited.

In terms of future energy demand, uncertainty remains regarding the shaping and implementation of Zhangjiakou's industrial restructuring strategy, the electrification of some end-use sectors, improvements in energy efficiency, and the enhancement and expansion of local and regional power grids. Overall, increasing local use of renewables requires greater application of innovative end-use technologies in concert with renewable energy generation.

The study Zhangjiakou Urban Energy Transformation 2050 has shown that because Zhangjiakou has undertaken an initiative to upgrade its current industrial sectors – a transformative move to a new generation of industrial development for the city – urban energy system planning must be strategically harmonised with industrial sector development to ensure that the new energy demand can be met as much as possible by renewables.

The demand for electricity needed to produce hydrogen from renewables will increase in Zhangjiakou. In addition, smart manufacturing will substitute for conventional production facilities, offering better energy and environmental performance. For energy production, including of electricity and heat, generation is located as close as possible to the loads to reduce losses during transmission. With sufficiently forward-looking strategic planning, Zhangjiakou can offer unique opportunities for businesses to reduce their environmental impact through scaled-up use of renewable energy sources.

Source: IRENA, 2019a.

1.2 Wuzhong District: A pilot on the race to net-zero

Wuzhong, located in the city of Suzhou (illustrated in Figure 1), is a rapidly developing district with a population of approximately 1.1 million (accounting for 10% of Suzhou's total population). The district has an area of 2 231 square kilometres (km^2), of which the land area is 745 km^2 and the rest is Lake Tai.

Eighty-seven per cent of the total area is classified as an ecological conservation area, including 61% of the land area. For conservation areas, stricter environmental assessment procedures and environmental regulations apply for any type of development.

The restrictions on land use have also significantly limited the availability of land for the deployment of renewable energy systems. This has narrowed the options for using local renewable energy resources, which are already limited compared with those in the northern and western areas of China.

FIGURE 1: Location of Wuzhong District in Suzhou city

Source: https://en.wikipedia.org/wiki/Suzhou.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

The district is divided into four zones: the Lake Tai touristic zone, the economic and technology development zone, the agricultural zone, and the high-tech industrial zone. The industrial and service sectors are the key pillars of Wuzhong's economic development, driving gross domestic product (GDP) growth over the past years at a rate higher than the national average. Due partly to high service sector shares in its economic structure compared with other districts in Suzhou, Wuzhong's energy intensity per unit of GDP is about 10% lower than the city average. Nevertheless, it has two energy-intensive industries: chemical fibre production and ferrous metal processing. Their shares in the total energy consumption of Wuzhong are rather modest, at 10% and 12%, respectively, because of their small scales in capacity. By contrast, the electronic equipment manufacturing industry and the textile industry, which are low in energy intensity, each account for 25% of the district's total energy use, as a result of their relatively larger production scales (Wuzhong DRC, 2020).

The district anticipates continued industrial growth in the coming years, with a focus on high-tech sectors such as robotics, smart manufacturing and the bio-medical industry, while placing high priority on ecological preservation to advance Wuzhong's green development strategy. Decarbonising the district's energy mix remains a priority. As such, Wuzhong District has the opportunity to become a model community in the race to net-zero, contributing to the realisation of the national dual carbon goals.

1.3 Objectives of this report

The overall objective of this report is to provide a framework for discussion that focuses on strategies, technologies and measures to decarbonise the energy system at the district level. This framework can help urban energy planning decision makers at the district level to engage in balanced discussions about increasing sustainable energy development towards the carbon neutrality target, preferably reaching the objective of becoming a net-zero carbon emissions district. The recommendations offered in this report are suggestive rather than prescriptive, as the situation in China is rather dynamic and energy transition technologies are rapidly evolving globally. It is important to remain flexible when developing a longer-term strategy.

The specific objectives of this report are to:

a. Provide Wuzhong District with a suite of strategic areas and specific actions that the local authorities and their energy advisors can consider as they develop their sustainable long-term energy and urban planning strategy. The recommendations facilitate achieving carbon reduction goals (carbon-peaking and carbon neutrality) by maximising the use of local renewable energy resources and increasing the share of renewable electricity on a regional level. The district would need to provide greater demand-side flexibility through sector coupling and enhanced intelligence of its energy management systems to support the grid operations.

b. Present a unique methodology that could be adopted by other districts and cities in Chinese regions where renewable energy resources are not on the top tier in terms of potential or where there are many restrictions on cities' abilities to exploit such resources (*e.g.* restrictions for ecological protection).

2

METHODOLOGY

This study takes a two-step approach to address the challenges that Wuzhong District faces during its transition towards a net-zero carbon future. The first step is to explore what options Wuzhong would have if the district used conventional emission abatement technologies to reduce its carbon emissions, considering Wuzhong's limited potential for local renewable energy resources and its currently dominant fossil fuel consumption. A long-term optimisation energy system model was built to construct multiple planning scenarios. The scenario results show how the emissions from the current generation fleet can be reduced as much as possible through conventional approaches such as efficiency improvements, fuel switching, and modest increases in the use of local renewable energy resources. This will help local decision makers understand the limitations of the business-as-usual approach and why transformative measures might be needed.

The second step focuses on discussion of a suite of emerging innovative solutions that could help the district further change course towards a low to net-zero carbon energy system. This is followed by general recommendations to Wuzhong on addressing challenges in these areas.

2.1 Model

Model built for Wuzhong District

A long-term energy system model of the Wuzhong District was built using OSeMOSYS to identify low-carbon emission planning pathways under different scenarios. The model aims to provide analytical insights into long-term technology capacity investment and dispatch planning for the energy system under cost and carbon minimisation objectives.

The cost and carbon minimisation objectives are specified as follows:

$$NPV = \sum_{i \in years} (1+d)^{Y-i} * C_i$$

$$TE = \sum_{i \in years} E_i$$

where:
NPV is the net present value of the total cost
TE is the total emissions
$years$ is the set of modelling years
Y is the starting year
d is the annual discount rate
C_i is the total system cost in year
E_i is the total emissions in year

The objective function (total cost and/or carbon) is minimised subject to constraints, which can be specified to include bounds on technology capacities, operation and capacity factors, as well as resource potential. Balanced constraints ensure that energy demands are satisfied by installed technology capacities in each time period and time slice.

Structural scope

The structural scope of the built model is summarised in Table 1.

TABLE 1: Model structural scope

ASPECT	DETAILS
Sectors	• Industrial • Services/commercial • Residential • Transportation
End-use energy demand	• Electricity • Heat (process, space, hot water) • Space cooling • Transport
Energy imports (external to the model)	• Electricity (regional/national grid, by sector) • Natural gas (by sector) • Coal • Oil (transport)
Local energy resources	• Biomass (waste) • Solar
Modelling horizon	2020-2050
Intra-annual time period	3 years
Inter-annual time slice	24-hour periods for three representative seasonal days (summer, winter, intermediate)
Optimisation goal	Cost or CO_2 emission minimisation

Technology scope

The scope of energy conversion technologies under consideration is described in Table 2 by output or functional category. These technologies include the existing and future investment technology options in the model. Detailed descriptions of these technology categories and their advantages, disadvantages and key parameters are well documented by the International Energy Agency's ETSAP programme (IEA-ETSAP, 2014).

TABLE 2: Model energy conversion technology options and associated outputs or functions

TECHNOLOGY	ELECTRICITY	DISTRICT AND PROCESS HEAT (IND.)	SPACE HEAT (SER./RES.)	SPACE COOLING (SER./RES.)	HOT WATER (SER./RES.)	H_2	CCS	STORAGE	TRANSPORTATION	DISTRICT NETWORK
Centralised technologies										
Coal CHP	X	X								
Coal boilers		X								
Coal IGCC CCS		X					X			
Gas CCP	X									
Gas CCP CCS	X						X			
Gas CHP	X	X								
Regional electricity grid import	X									
Waste CHP	X	X								
Waste CHP CCS	X	X					X			
Waste CCP	X	X								
Waste boiler plant		X								
Waste incineration plant	X									
Electrolyser						X				
Biomass gasification						X				
Hydrogen (H_2) storage								X		
Decentralised technologies										
PV	X									
Small gas CHP (ind.)	X	X								
Small fuel cell CHP (ind.)	X	X								
Electric space heater (ser./res.)			X							
Electric water heater (ser./res.)					X					
Electric boiler (ser./res.)			X		X					
Gas boiler (ser./res.)			X		X					
Gas water heater (ser./res.)					X					
Gas boiler (ind.)		X								
Waste boiler (ind.)		X								
Air conditioner (ser./res.)				X						
Air-source heat pump (ser./res.)			X	X						

TECHNOLOGY	ELECTRICITY	DISTRICT AND PROCESS HEAT (IND.)	SPACE HEAT (SER./RES.)	SPACE COOLING (SER./RES.)	HOT WATER (SER./RES.)	H_2	CCS	STORAGE	TRANSPORTATION	DISTRICT NETWORK
Central air-source heat pump (ser./res.)			X	X	X					
Ground- or water-source heat pump (ser.)			X	X						
Central ground- or water-source heat pump (ser.)			X	X	X					
Solar thermal (ser./res.)			X		X					
Batteries								X		
Heat storage								X		
Internal combustion engine vehicle									X	
Battery-electric vehicle									X	
Fuel cell vehicle									X	
Networks										
Electricity distribution network (losses)										X
District heating network (losses)										X

CCP = combined cycle power plant; CCS = carbon capture and storage; CHP = combined heat and power plant; ind. = industrial; IGCC = integrated gasification combined cycle; PV = photovoltaic; res. = residential; ser. = services.

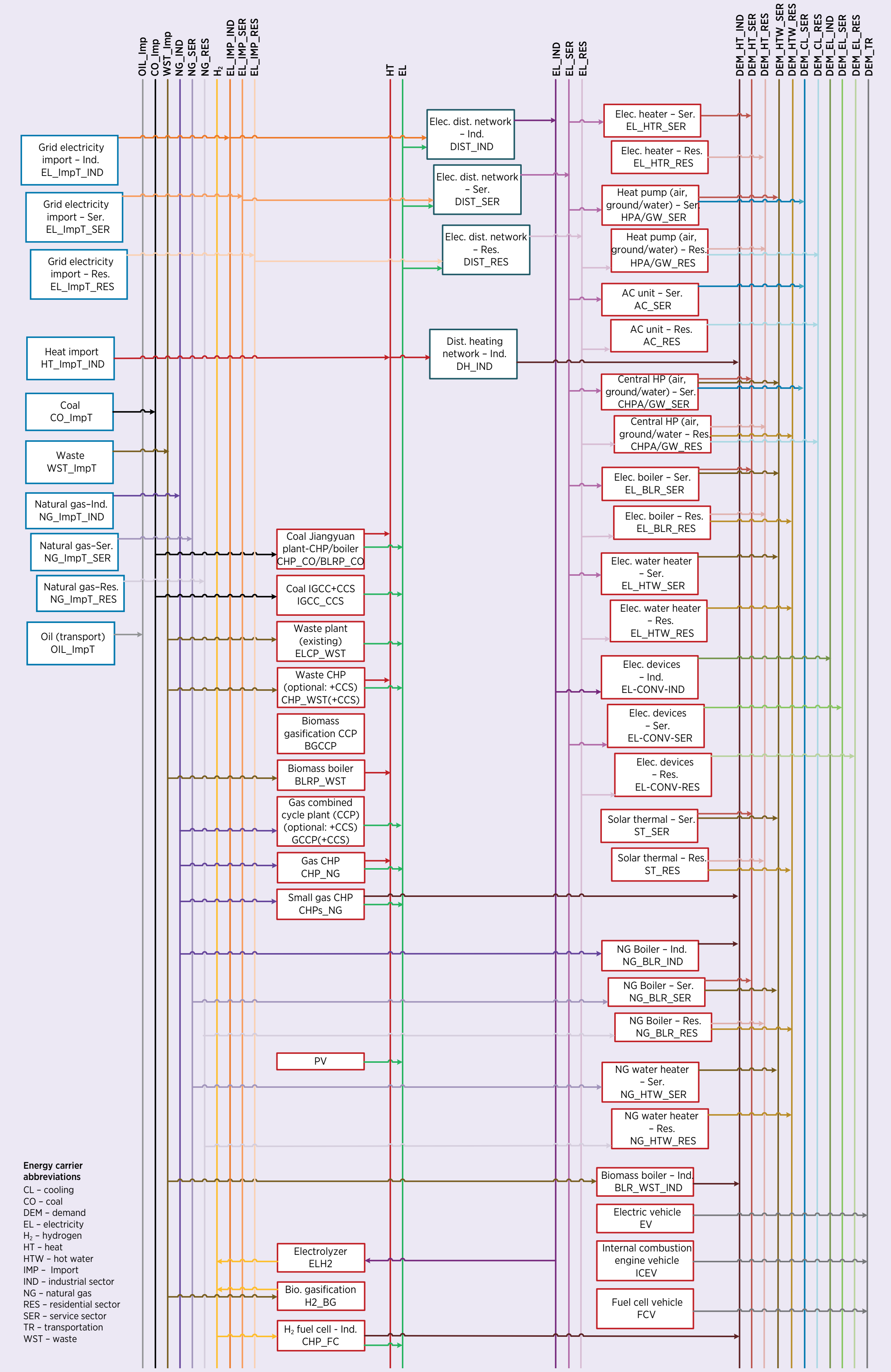
Reference energy system diagram

The model structure, including energy imports, conversion technologies, end-use energy demands, and the transformation pathways that connect them, is depicted in Figure 2.

2.2 Data constraints, estimation and assumptions

As with many countries, the availability and accessibility of energy data in China can be a greater challenge at the district level than at the national or provincial levels. This is in part due to the lack of sound energy statistics systems for urban energy system planning, which is – albeit rising worldwide – still relatively novel for local authorities, particularly in the Chinese energy governance regime. The challenges are often attributed to the need for higher data granularity within cities for energy analysis and planning. Such highly granular data are hard to acquire for various reasons (*e.g.* privacy issues). In addition, when the shares of variable renewable energy sources increase in the energy mix, the need for more detailed data on both the supply and demand side becomes greater.

FIGURE 2: Model reference energy system diagram



To fill gaps in data collection for this study, proxy data, historical trends and other publicly available and published data were adapted to fit Wuzhong's profile. These data have been calibrated with supplied reference data. Assumptions were also made on the basis of the expert knowledge and insights obtained for this study, particularly for projecting future demands. The methods, assumptions and resulting data inputs applied in the model are detailed in the following sections.

Creation of hourly demand profiles

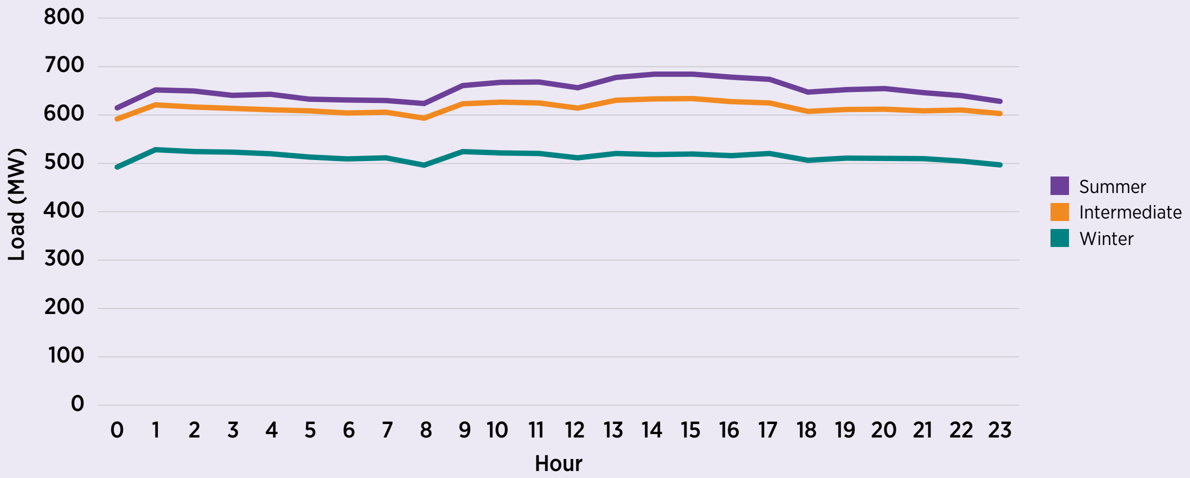
The total hourly load profile for the district was provided by the State Grid City and Energy Research Institute (SGCERI). The data were disaggregated by sector and end-use demand type. The following subsections summarise the approach and the key results.

Electricity demand for industrial sector

The hourly industrial load profile was created from hourly data for the industrial sector of a district whose industrial structure is similar to that of Wuzhong.[2] The data indicate a baseload consumption pattern. We adopted this hourly baseload profile as a reasonable approximation for our model.

Figure 3 indicates a baseload consumption pattern, providing a reasonable approximation for the model.

FIGURE 3: Hourly electricity demand profile – industrial sector



Electricity demand for service and residential sectors

The total electricity load profile for the service and residential sectors is derived from the total electricity load profile in 2017 minus the hourly industry electricity load, followed by further disaggregation based on the residential and service load profiles. The resulting profiles are adjusted to match available annual total electricity consumption data. Figure 4 represents the hourly electricity demand profile for the service sector; Figure 5 shows the profile for the residential sector.

2. Data were provided by SGCERI.

FIGURE 4: Hourly electricity demand profile – service sector

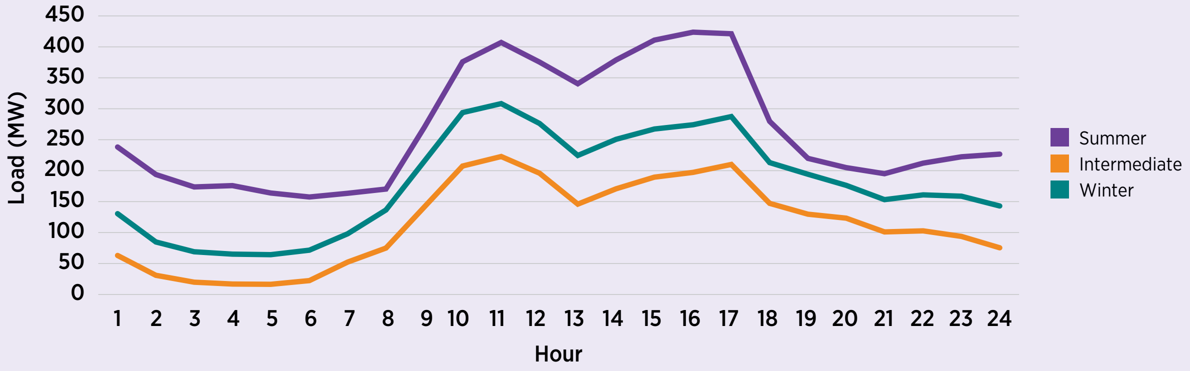
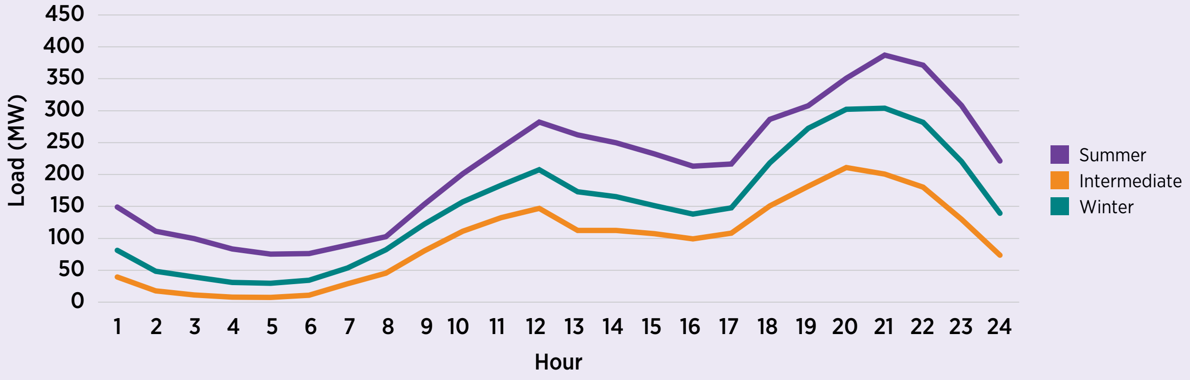


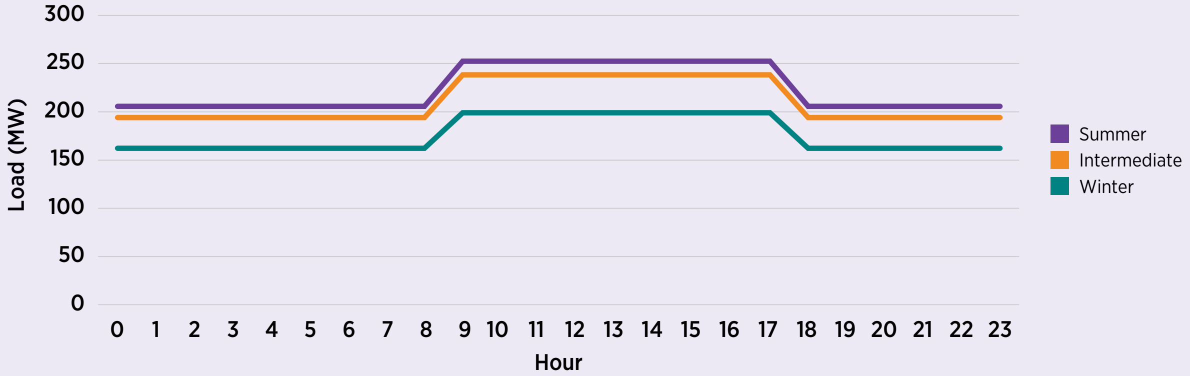
FIGURE 5: Hourly electricity demand profile – residential sector



Process heating demand for industrial sector

The industrial process heat load profiles were generated by applying the ratios of process heating load among the different seasons to the seasonal shares of the industry electricity load shown in Figure 3. The hourly load curve (Figure 6) represents a typical day of operation for a regional heating system in industry (Li *et al.*, 2018). This is calibrated with the total process heating demand.

FIGURE 6: Process heating demand profile – industrial sector



Space heating and cooling demand for service and residential sectors

Space heating and cooling is only considered for the service and residential sectors, since these demands not comparable to industry. Since Wuzhong (located in an area where heating systems are not required in China) has a mild winter season, the space heating demand is small compared with northern areas in China. The district heating in Wuzhong is mainly used by industrial end-users, while for service and residential sector consumers, we assume that space heating is entirely met by electricity in the base year; this is also assumed for space cooling (China Power, 2019). Moreover, we approximate that space heating and cooling is used in, respectively, winter and summer seasons only (based on dominant seasonal usage). The hourly load profile for cooling is based on proxy data from Nanjing, a nearby city (Jiang, 2003). The data are calibrated to match the total seasonal electricity load profile. The resulting demand profiles for space heating and cooling in each sector are given in Figures 7-10.

FIGURE 7: Space heating demand profile – service sector

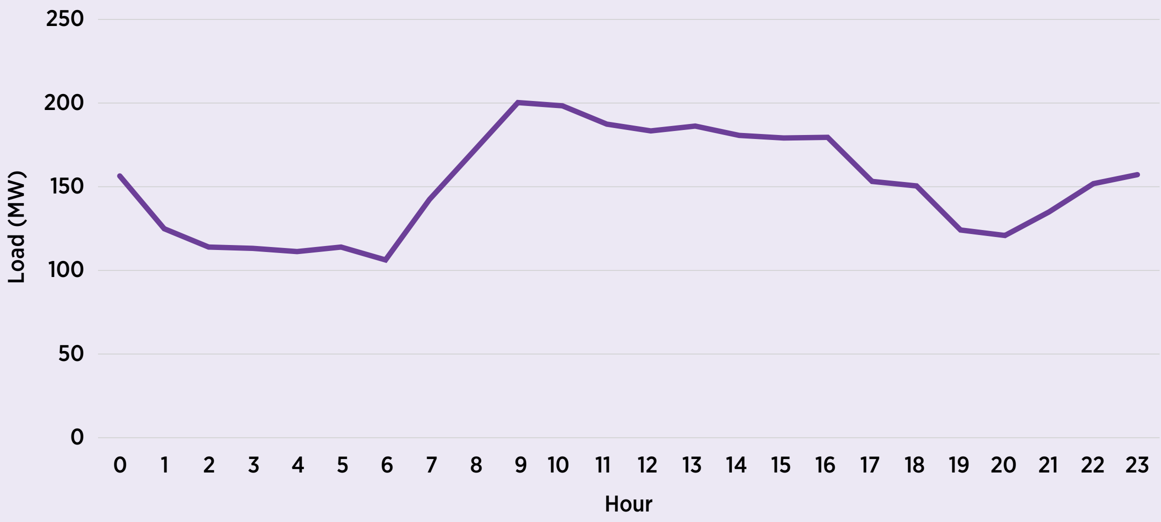


FIGURE 8: Space heating demand profile – residential sector

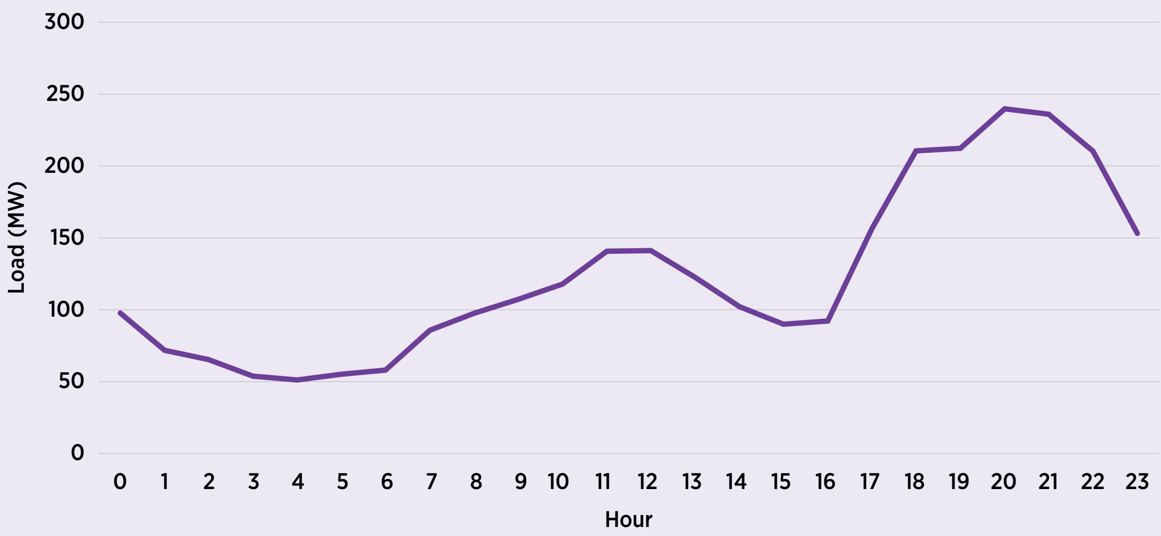


FIGURE 9: Space cooling demand profile – service sector

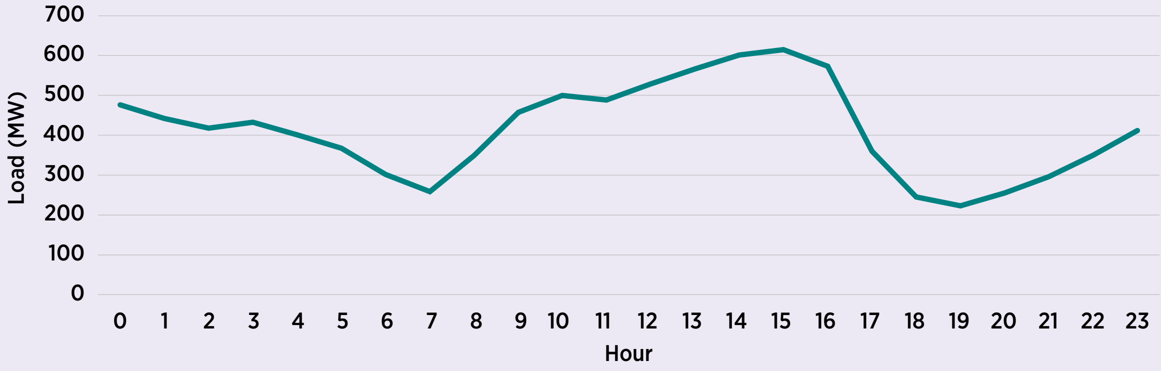
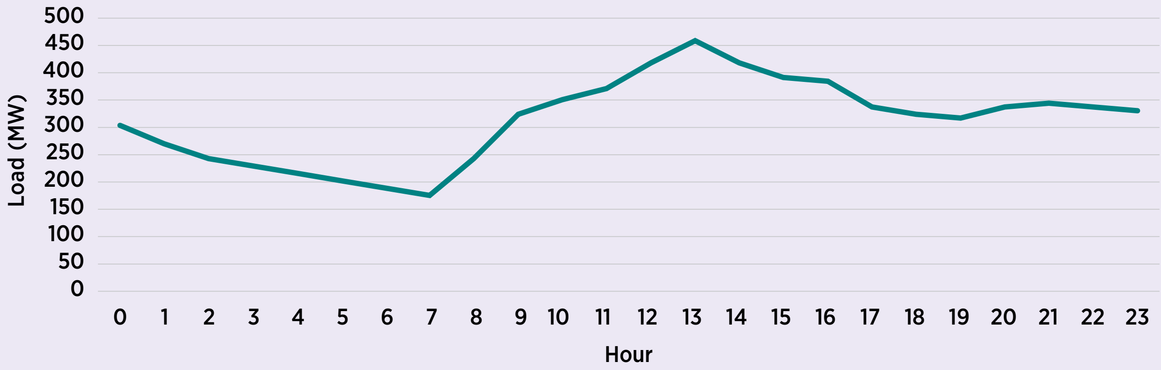


FIGURE 10: Space cooling demand profile – residential sector



Hot water demand for service and residential sectors

Hot water demand is considered only for the service and residential sectors. Total hot water demand is approximated using average parameters and the population in Wuzhong, summarised in Table 3 (Zhang, Chen and Liang, 2006).

TABLE 3: Parameters applied to calculate annual residential hot water demand

PARAMETER	VALUE
Local hot water supply system (L/person·day)	40
Specific heat capacity of water (J/kg·°C)	4 187
Days in year 2017	365
Population of Wuzhong in 2017 (million people)	1.1295
Density of water (kg/L)	1
Average temperature of running water (°C)	15
Average temperature of hot water (°C)	40

Source: Zhang, Chen and Liang, 2006.

Hourly hot water load profiles are based on hot water profiles for residential and service or commercial buildings (Fuentes, Arce and Salom, 2018). These curves are adjusted to match the total hot water demand. The resulting profiles in the service and residential sectors are shown in Figures 11 and 12, respectively.

FIGURE 11: Hot water demand profile – service sector

FIGURE 12: Hot water demand profile – residential sector

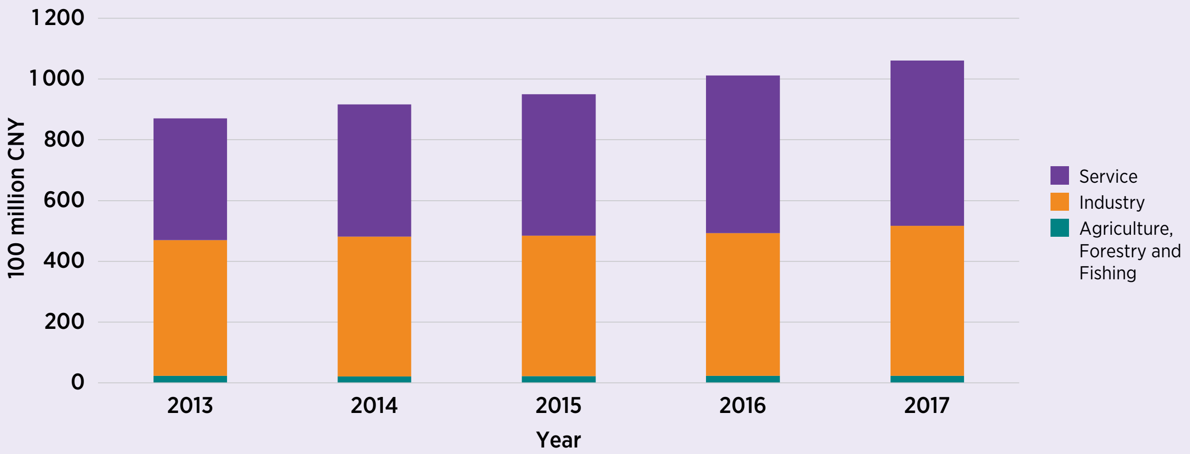
Demand projections

Energy demand is predicted over the modelling time horizon until 2050. The exponential smoothing method is used to project data using SPSS Statistics software (Brown, 1956; IBM, n.d.; Liu, 2012). Demand projections and assumptions are presented in the following sections by energy carrier type.

Electricity for industry and service sectors

Industry and service electricity demand projections are based on historical GDP growth trends (as shown in Figure 13) and predicted demands in 2025 provided by SGCERI. Data from the years 2017-2025 are used to project demand until 2050 using the exponential smoothing model in SPSS. This approach assumes GDP follows a roughly logarithmic growth trend in the future, in accordance with historical trends.

FIGURE 13: GDP growth in Wuzhong District, 2013-2017

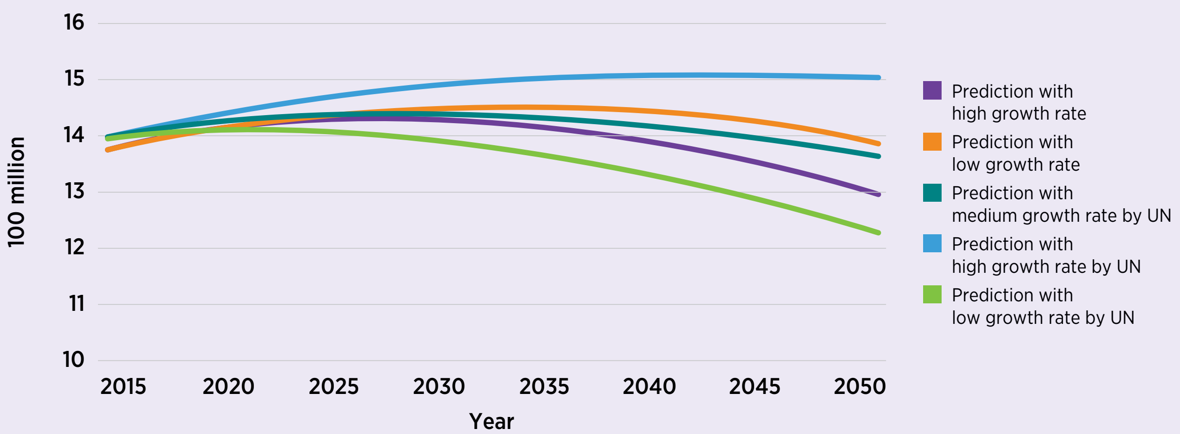


Source: SGCERI, 2019.

Electricity for residential sector

Residential electricity demand is assumed to increase with the population growth in Wuzhong. The population growth is based on a national high population growth projection by the United Nations, presented in Figure 14 (Liang, 2019). A high growth trend is assumed using inputs from SGCERI, which indicate that Wuzhong expects higher than national average population growth as it is a rapidly developing district.

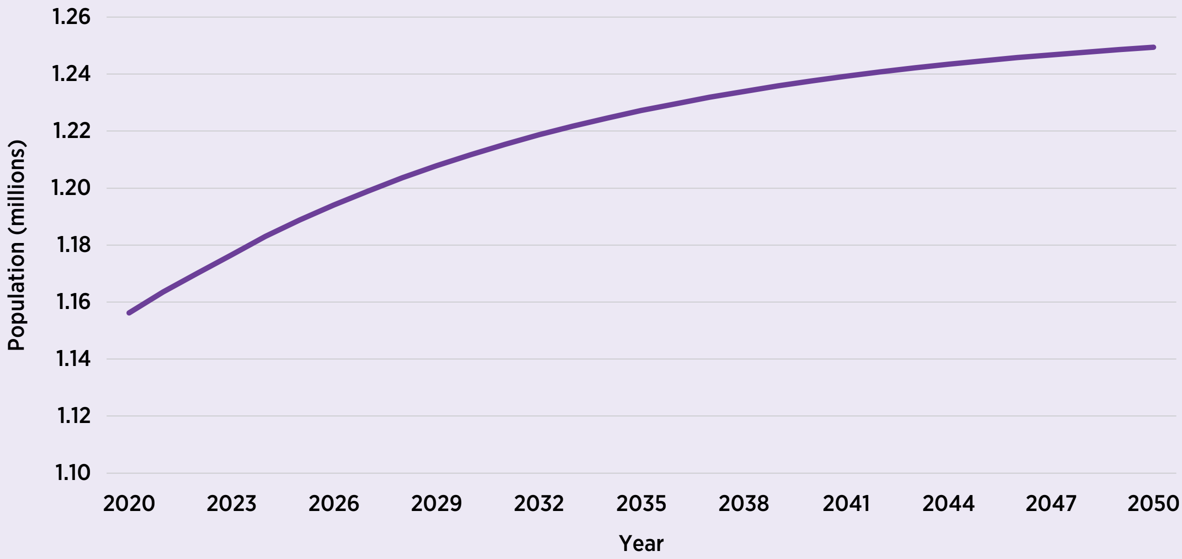
FIGURE 14: National Chinese population scenarios



Source: based on UN data (UNDESA, 2019).

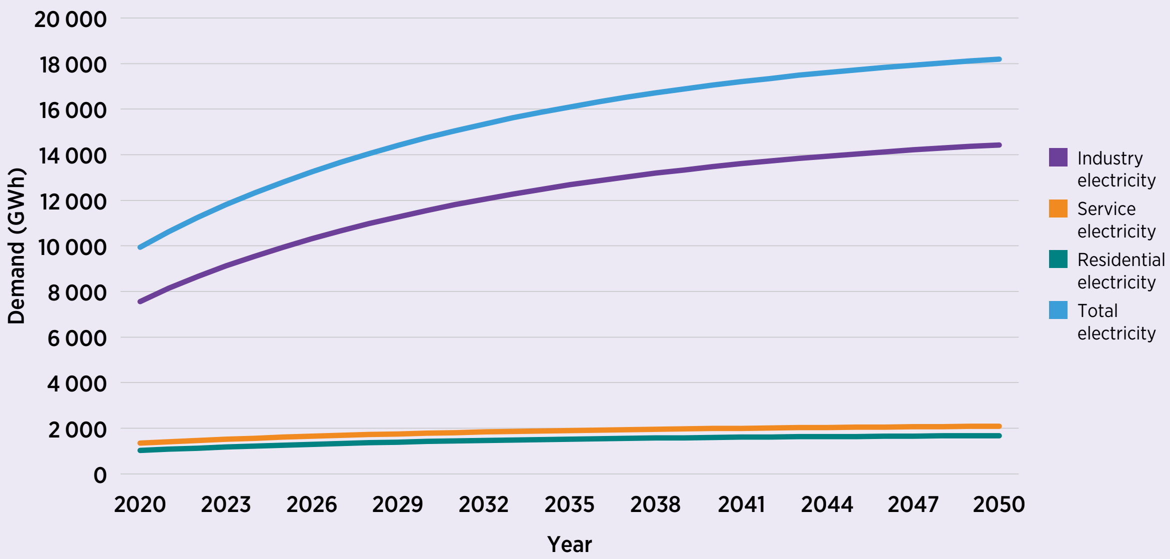
The resulting population growth trend for the Wuzhong District is given in Figure 15.

FIGURE 15: Population growth for the Wuzhong District



The resulting electricity demand predictions across sectors are presented in Figure 16.

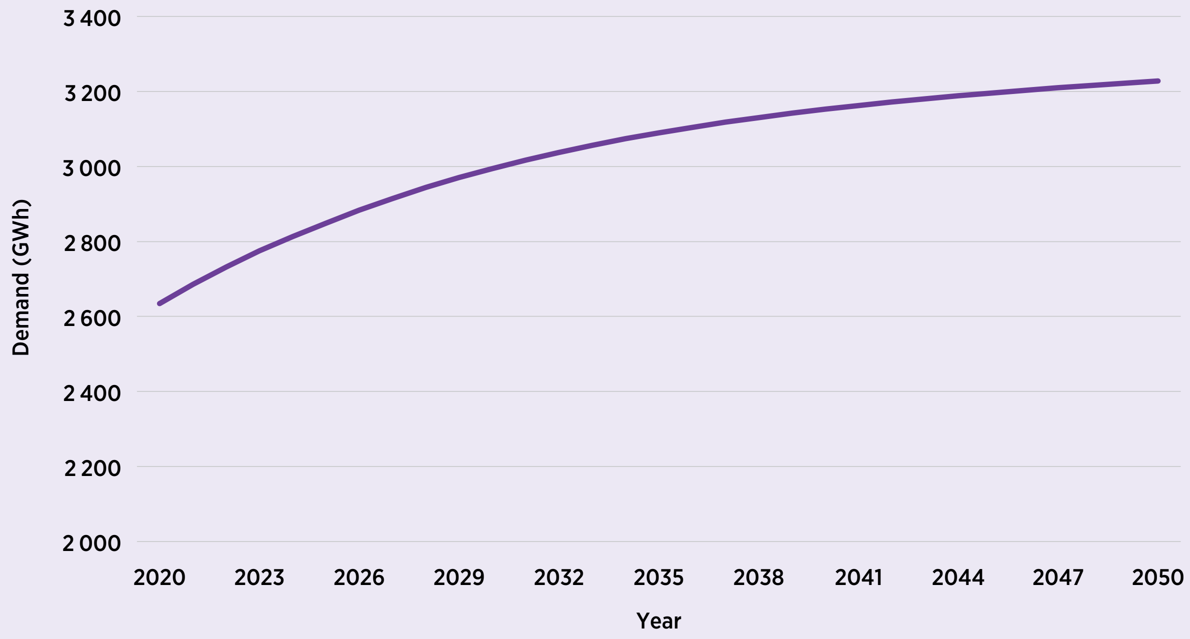
FIGURE 16: Electricity demand projections across sectors



Process heating for industrial sector

Industrial process heat demand is assumed to increase with industrial electricity demand growth, as we assume that the increase in electricity demand is reflective of growth in this sector, in general. The resulting projection is shown in Figure 17.

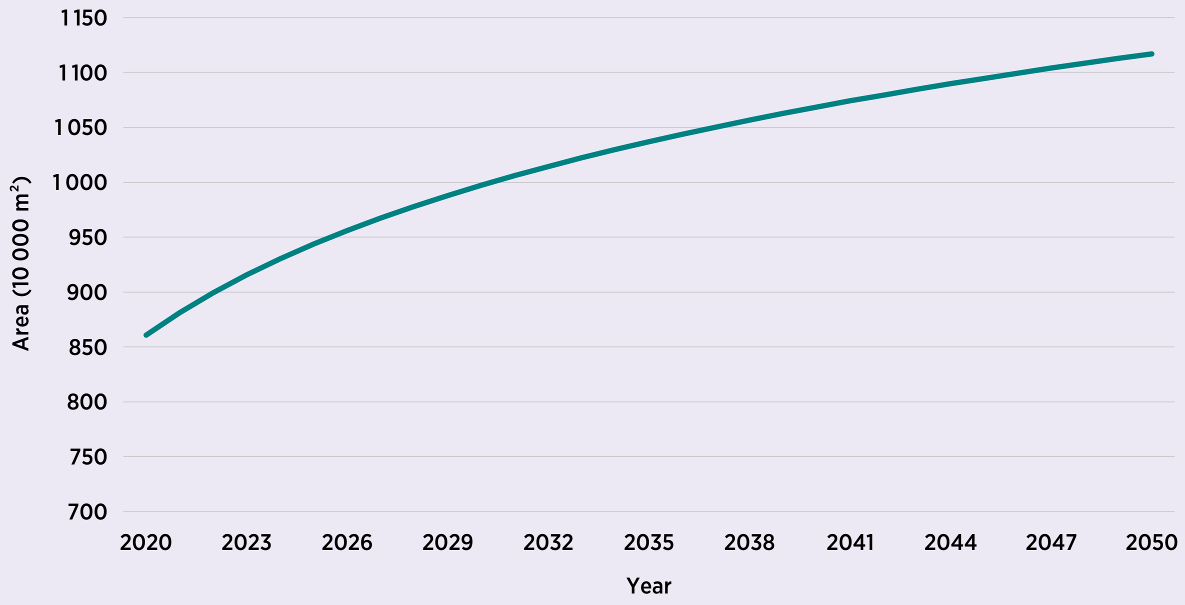
FIGURE 17: Process heat demand projection – industrial sector



Space heating and cooling for service and residential sectors

Space heating and cooling demand is assumed to increase with building area growth. Building area is projected using historical building area growth data and by applying a logarithmic curve fit (based on historical trends). The resulting building area growth trend is shown in Figure 18.

FIGURE 18: Building area growth for Wuzhong District



Projections in space heating and cooling demands are shown in Figures 19 and 20.

FIGURE 19: Space heating demand projections – service and residential sectors

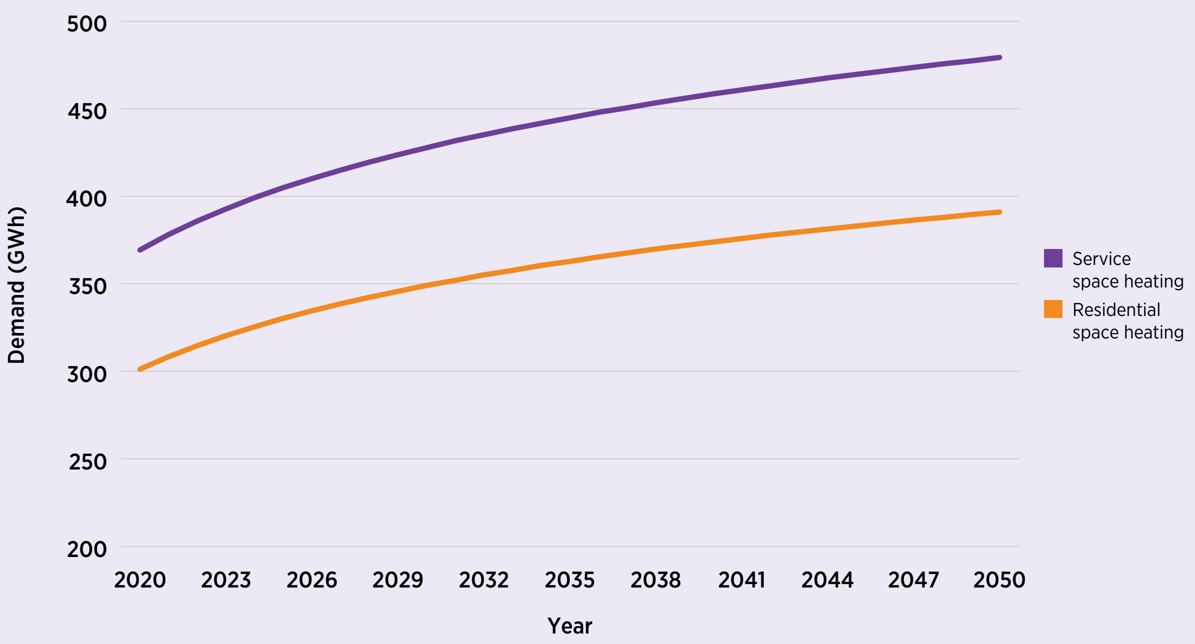
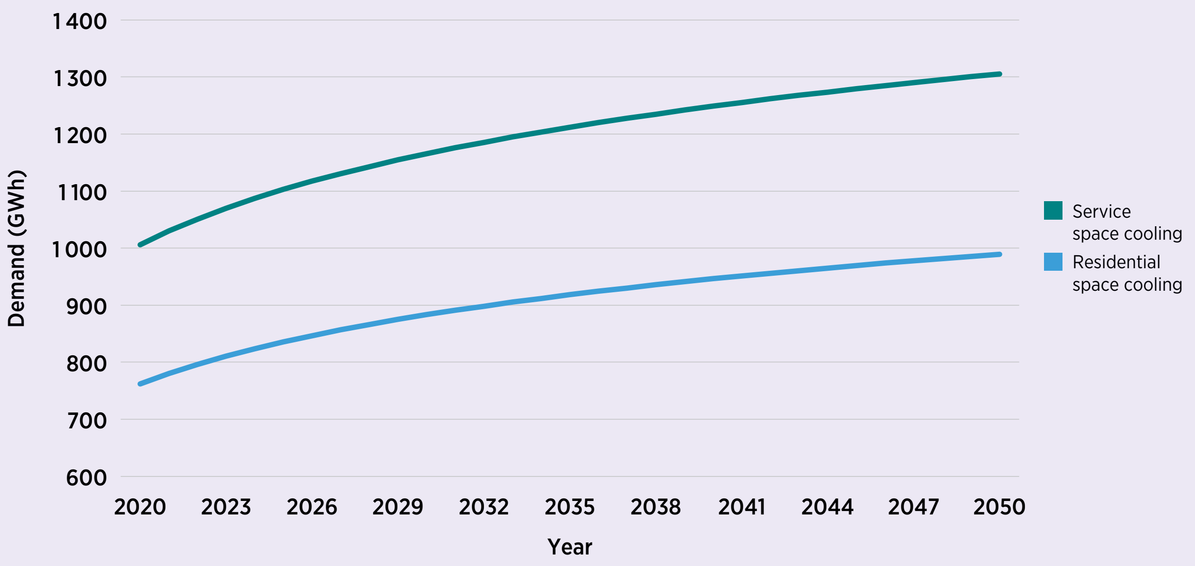


FIGURE 20: Space cooling demand projections – service and residential sectors



Hot water for service and residential sectors

Hot water demand is projected on the basis of the population growth in Wuzhong (see Figure 15), as we assume hot water demand generally scales per capita. The resulting projections are shown in Figure 21.

Aggregated projected demand for all energy services

The total demand projection for all energy services in the Wuzhong District is illustrated in Figure 22.

FIGURE 21: Hot water demand projections – service and residential sectors

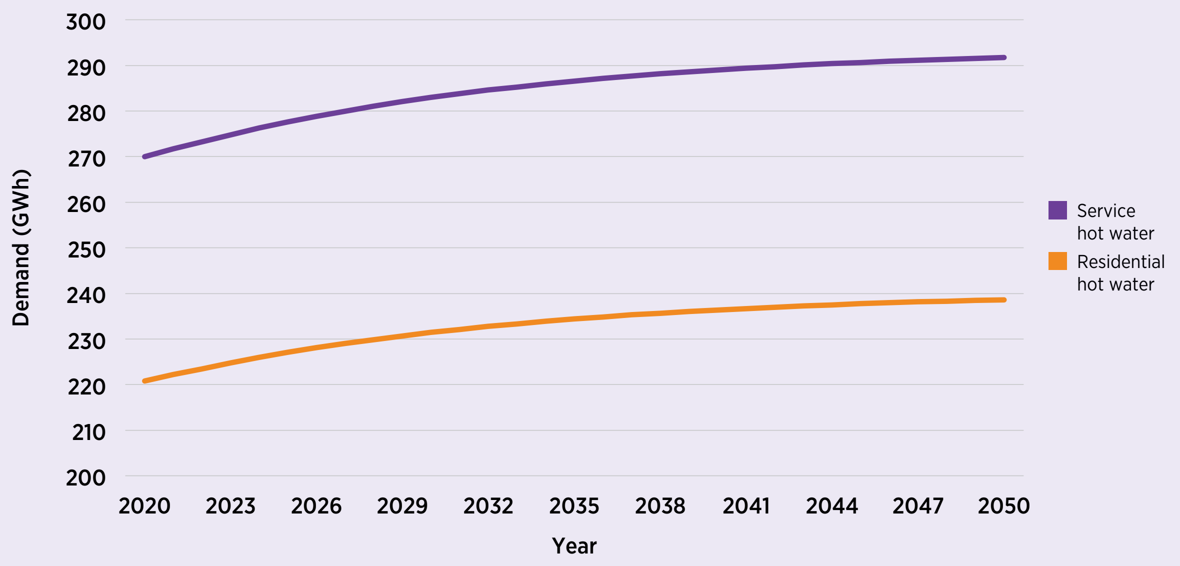
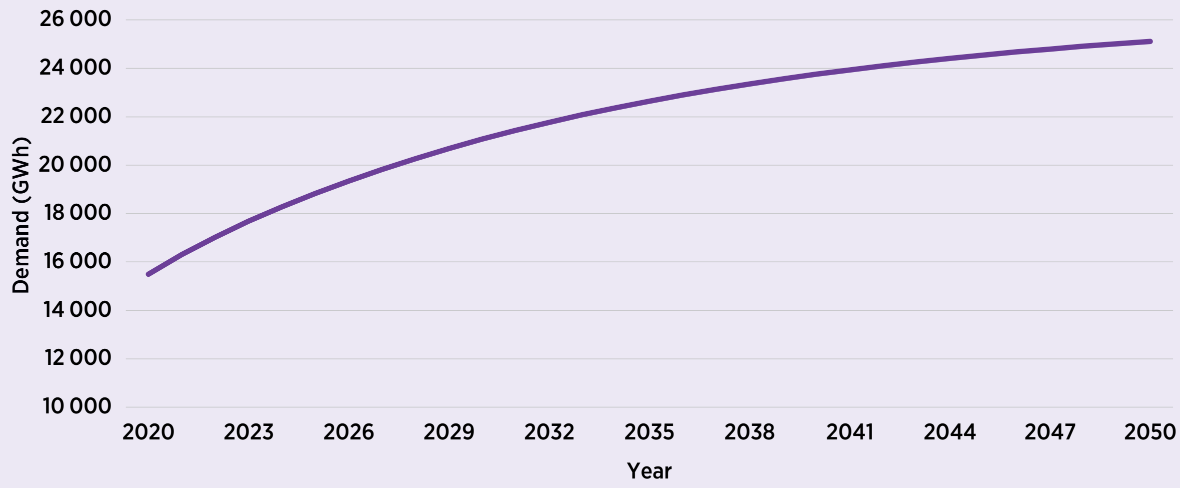


FIGURE 22: Total demand for all energy services in the Wuzhong District



Assumptions made on technology specifications in the model

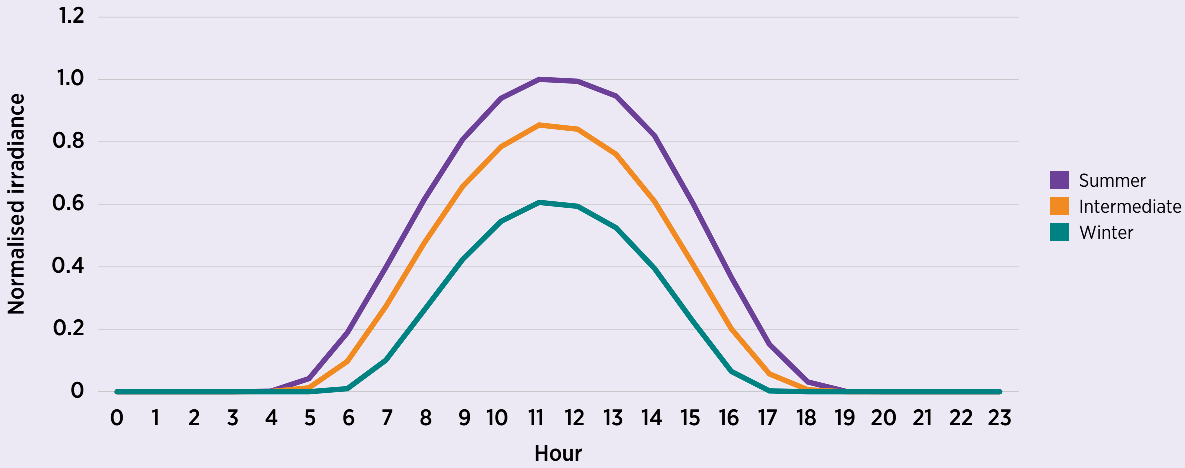
The key technology specifications and assumptions are described in the following subsections.

Solar energy resource potential

Estimations of solar irradiance profiles are based on a five-year average (2015-2019) in Wuzhong (Solcast, n.d.). Normalised seasonal solar profiles are given in Figure 23.

SGCERI estimates that approximately 1 860 megawatts (MW) of PV potential is available for Wuzhong in the medium term. A total potential of 2 000 MW is assumed until 2050 in the model. For solar thermal energy applications, given the available land area for centralised installations, the solar thermal potential is estimated to be 975 MW.

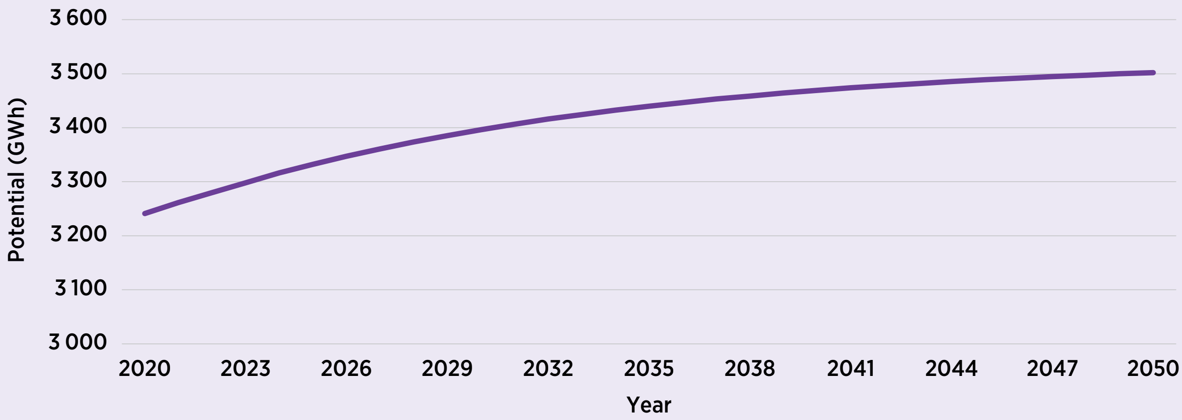
FIGURE 23: Normalised seasonal solar irradiance profiles



Biomass

Biomass is sourced primarily from municipal waste in Wuzhong. Therefore, we assume that the total waste potential scales with population growth in general. The resulting biomass waste potential is shown in Figure 24.

FIGURE 24: Biomass waste potential projection



Transportation

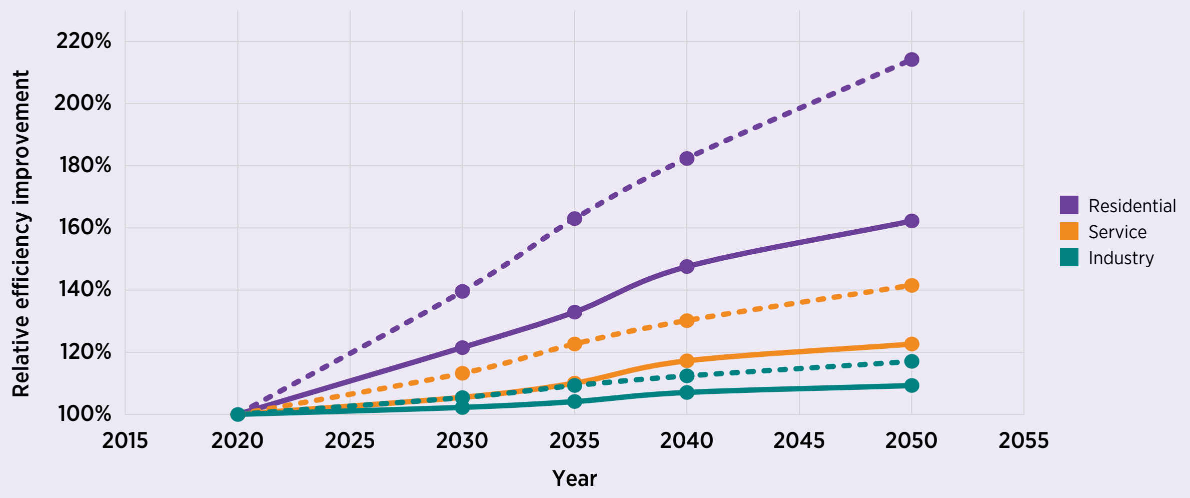
Three transportation modes are considered: internal combustion engine vehicles, battery-electric vehicles and fuel cell vehicles. Vehicle costs and drivetrain energy consumption rates are considered for battery-electric and fuel cell vehicles relative to internal combustion engine vehicles, based on performance data from Yazdanie *et al.* (2016).

Efficiency measures

Building efficiency standards are considered for new buildings in Wuzhong according to national green energy building standards (Code of China, 2019). Energy savings are expected to be in the range of 20-30% and 30-40% for two- and three-star buildings, respectively, compared with non-energy efficient buildings. The corresponding incremental costs for new two-star buildings are 87.3 CNY per square metre (m^2) (13.6 USD/m^2) and 70.9 CNY/m^2 (11.11 USD/m^2) for public and residential buildings, respectively. Analogously, incremental costs for three-star buildings are 216.4 CNY/m^2 (33.91 USD/m^2) and 131.8 CNY/m^2 (20.65 USD/m^2) for public and residential buildings, respectively (Chai, 2018).

Efficiency improvements are also considered for electrical appliances based on projected improvements until 2050 in European studies (Kirchner *et al.*, 2012). Improvements in lighting, refrigeration, washer-dryers, TVs and other appliances are applied to Chinese electricity usage statistics to determine net efficiency improvements over time (Guo, Khanna and Zheng, 2016). The resulting efficiency improvement rates relative to 2020 over time are illustrated in Figure 25 for residential, service and industrial sectors for average and high efficiency cases. Service and industrial sector improvements appear relatively limited because only lighting efficiency gains are considered in these sectors (due to limited data availability for other end-use converters).

FIGURE 25: Relative efficiency improvements for electrical appliances across sectors



Thermal and gas networks
The district heating network in Wuzhong primarily serves industry and is, therefore, considered for the industrial sector only. Heat imports from the surrounding areas are considered only in the base year.

Data on maximum annual natural gas imports based on existing and future infrastructure were not available. Therefore, the model imposes an upper limit of 10 terawatt hours (or 36 petajoules) of gas imports in the base year; this limit scales with increasing total energy demand until 2050.

Carbon capture and storage
Three power plant technologies with carbon capture and storage (CCS) capabilities are considered in the net-zero emissions scenario: waste combined heat and power plant (CHP), gas combined cycle power plant (CCP), and coal integrated gasification combined cycle (IGCC) power plant. It is assumed that carbon storage is possible either through the construction of a geological storage facility locally or through transport to a subterranean storage facility outside of Suzhou city.

We model the waste CHP CCS after a bio-energy CCS demonstration plant in Oslo, Norway (Klemetsrud waste-to-energy plant, operated by Fortum Oslo Varme). There are currently only a handful of such operational plants in the world; this plant was selected as a basis for modelling because it is one of the newest and most advanced demonstration projects of this type for which data are available. The CHP incinerates municipal and industrial residual waste from both national and international customers. It consists of three incineration lines that produce flue gas, from which CO_2 is captured using an absorption technology with an Aker Solution Advanced Amine solvent. It is also equipped with two steam turbines. The plant aims to capture approximately 200 000 tonnes of CO_2 each year. Captured CO_2 is transported to an onshore facility on Norway's west coast for temporary storage, followed by pipeline transport to a subsea reservoir in the North Sea for permanent storage (Fortum, n.d.; Project CCS, 2019).

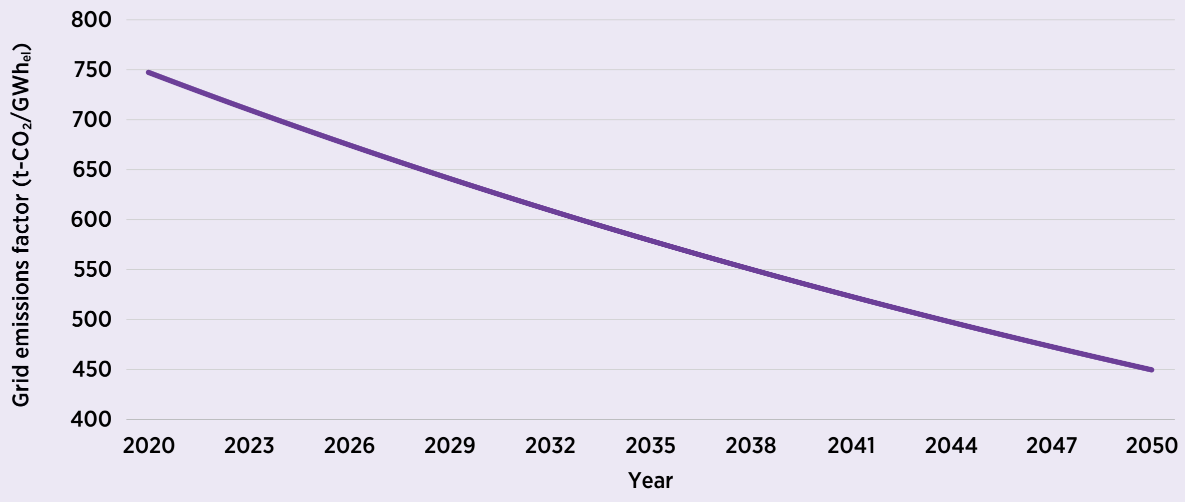
The IGCC CCS plant uses a thermo-chemical reaction with oxygen and steam to convert coal into a gas mixture of mainly carbon monoxide, hydrogen and CO_2. This mixture is cleaned, and pre-combustion CO_2 capture is usually performed using physical solvents. The cleaned gas mix is then used in gas and steam turbines for electricity generation in a combined cycle. In gas CCP CCS, post-combustion CO_2 capture is usually undertaken using solvents. Captured CO_2 can be stored locally or transported for storage elsewhere.

Emission data

Emissions are assumed for the combustion of fossil fuels (*i.e.* coal, natural gas and oil) based on standard combustion emission data; namely, the carbon content per unit of energy the fuel contains for combustion. These data do not take into account the heat loss that occurs during the combustion of fossil fuels for electricity generation (Engineering ToolBox, 2009). To demonstrate the difference among different fossil fuels in terms of carbon content, combustion emission values of 0.28 kilogrammes (kg) of CO_2 per kilowatt hour (kWh), 0.18 kg-CO_2/kWh and 0.26 kg-CO_2/kWh are assumed for coal, natural gas and gasoline, respectively.

Electricity imported to Wuzhong from the regional grid is projected on the basis of long-term regional electricity planning. We assume 50% of the electricity generation mix in 2050 is emissions-free (compared to a 20% share in Jiangsu province in 2020). The resulting emission factor projection is illustrated in Figure 26.

FIGURE 26: Carbon emission factor for grid electricity



2.3 Limitations

The model in this study aims to provide a macro-level, long-term analysis for the Wuzhong District using a linear, cost[3] and carbon optimisation model. It provides a strong basis for developing a sustainable energy strategy for Wuzhong as part of an iterative design process. Additional inputs would enable further refinement and expansion of the current model and scenarios, which would then serve as inputs for refining the energy strategy. The limitations can be summarised as follows:

- The observed outcomes in a linear optimisation model are dictated by data assumptions and assumed boundary conditions. Improved data inputs and assumptions will yield more accurate results. Additional data parameters that would improve analysis include future cost estimates for energy carriers and detailed infrastructure data for power grid and district energy networks (*e.g.* capacities, expansion potential, costs), as the current model does not consider infrastructure details, limitations and expansions. Should network data become available, a higher resolution model could be developed as part of a future study to investigate the optimal design and implementation of these networks.

- With further district heating data and modelling, the scope of technology options could also be expanded. For instance, the role of solar thermal and heat storage at a district level for low-temperature heating could be added (in the current model, heat storage is only considered at a decentralised level). Should the maximum PV potential be expanded or other intermittent renewable energy technologies prove feasible, battery technologies may also come to play an important role in Wuzhong, as storage would improve demand-side flexibility.

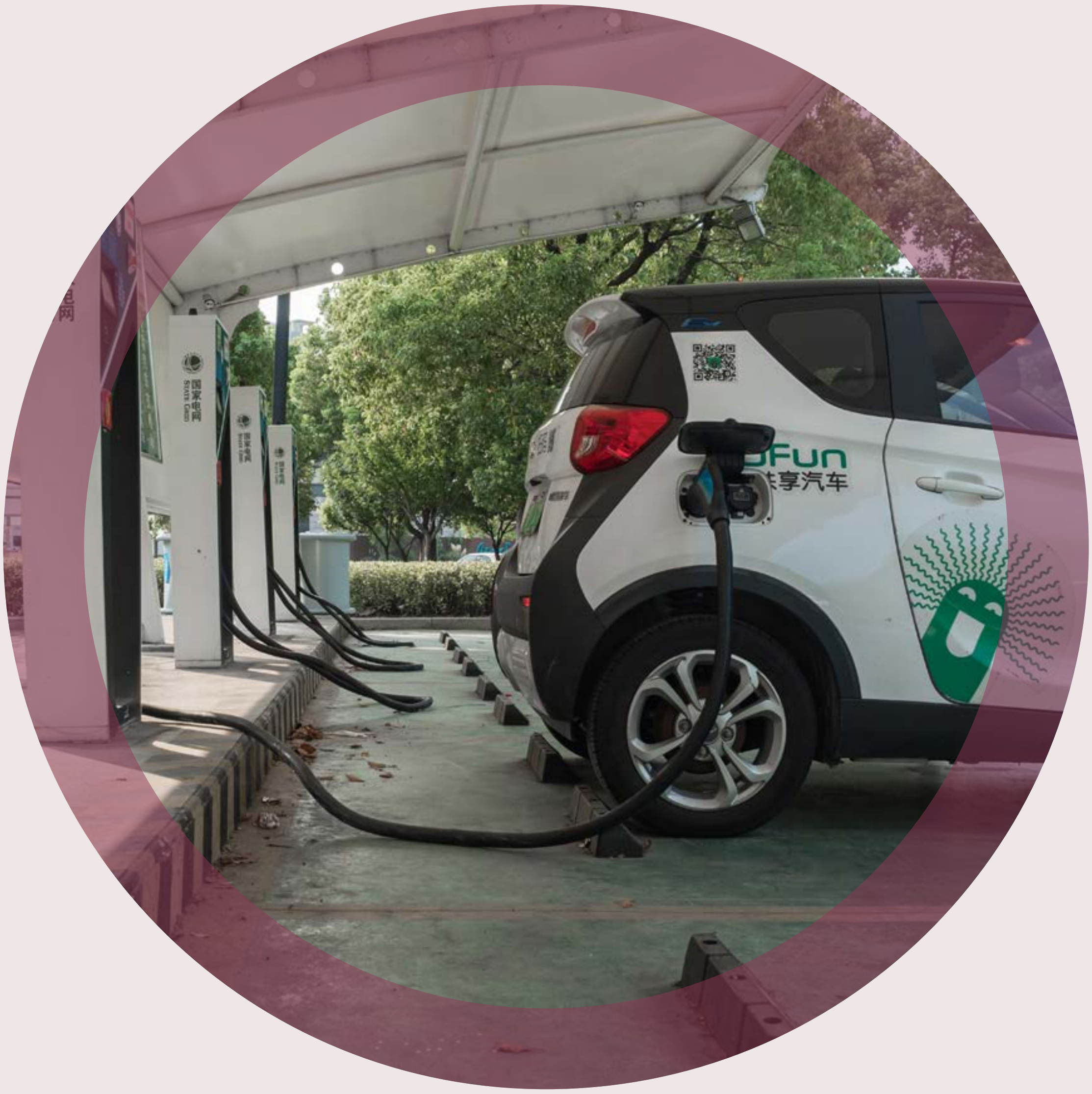
- Further data on the transportation sector and infrastructure would also allow for the development of a more detailed transport model. This opens up opportunities for sector coupling between transportation and electricity demand, for example by considering battery-electric vehicles as a potential storage source (*i.e.* operating as a virtual power plant, which also increases demand-side flexibility) or considering gas-to-power opportunities for fuel cell vehicles should regional low-carbon hydrogen or syngas generation become available in the future.

- The addition of data regarding the potential of efficiency measures in the Wuzhong District is another area for expansion. As efficiency measures demonstrate significant potential to reduce local energy demand and carbon emissions in Wuzhong, further studies are needed to identify areas for efficiency improvement, energy saving potential, and implementation costs. This is especially applicable to the industrial sector and existing building stock renovations, where feasible.

- Limited data on CCS applicability in Wuzhong are available. Further study on its feasibility would be necessary to justify it as a feasible option for the district.

3. The cost data applied in this study can be found in Annex C.

3



MODELLING SCENARIOS AND RESULTS

This chapter presents the four scenarios that were constructed for the study: a baseline case (BC) scenario for comparative purposes and three low-carbon scenarios. The main differences between the scenarios lie in emission reduction targets and technology scope.

3.1 Baseline case

The BC represents a scenario without an emission or renewable energy development target. Therefore, the optimisation in the BC uses only one modelling objective: minimising the total system cost to meet the given energy demand. It includes all the generation technology options in the technology scope when performing the optimisation, except for CCS. The key current decision on fuel switching, which essentially aims to phase out coal power in the district, has also been factored in. On the energy efficiency side, the BC scenario adopts average improvement measures, which are assumed to meet the two-star green building standard for new residential buildings and the three-star standard for commercial and service buildings. In the transport sector, given the overall rapid pace of vehicle electrification in China, this scenario assumes 20% and 50% of the transportation fleet in Wuzhong District is electrified by 2035 and 2050, respectively.

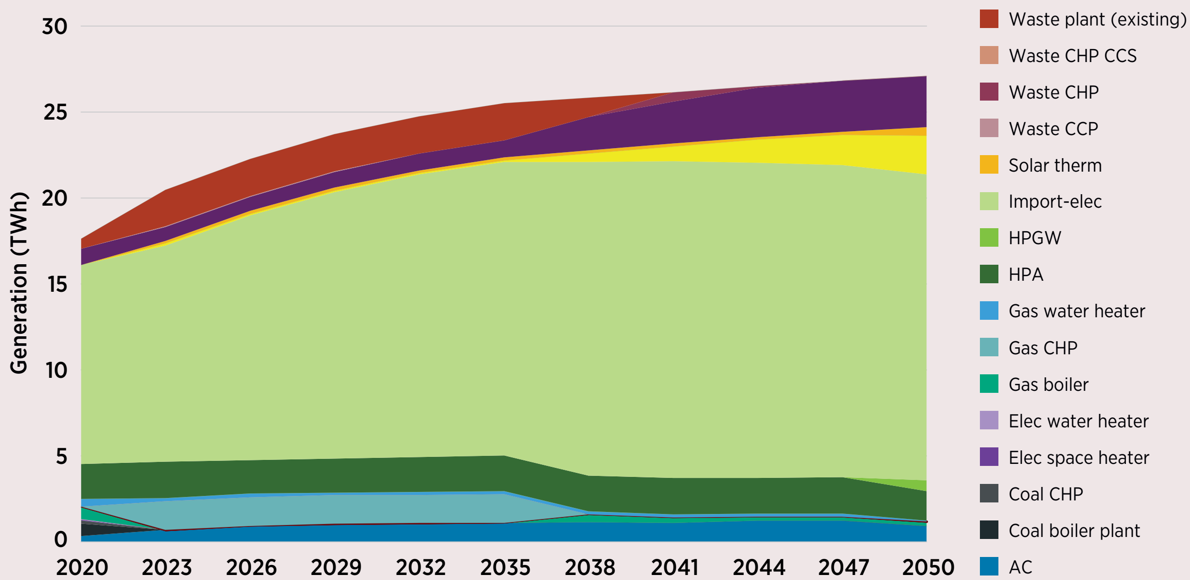
The aim for developing such a BC is to provide a benchmark for comparison of modelling results, particularly of the potential impact of carbon constraints and targets on the generation profile for the district.

The only coal-fired power plant in Wuzhong District will be replaced by a new gas-fired power plant, which has been already indicated by the local authority. Thus, the district will be coal-free from as early as 2022. This also makes economic sense, given that the plant is small (30 MW in capacity). This is the cut-off size for the closure of inefficient coal power plants as part of the national clean energy policy. Small coal plants can hardly compete economically with national grid electricity. Phasing out coal power can also eliminate the logistical need for coal transportation by waterway and railway, as well as storage – another saving to be gained to justify the closure of this plant.

Figure 27 illustrates the modelling results for the BC scenario. As shown, electricity from the regional and national grids will be expected to increase by about 50% over the projected period, providing the most cost-effective electricity to meet growing electricity demand in Wuzhong. For the first half of the studied period, electricity from the local gas-fired power plants is expected to scale up to meet the demand growth, except for the initial transition phase from coal to gas in power generation in 2021-2022. This also fits the overall national strategy to use natural gas to replace coal as a transitional step towards renewables. For the second half of the projected period (*i.e.* 2036-2050), renewable electricity will be expected to take off and replace gas due to its strong cost competitiveness. Therefore, the combined share of gas-fired electricity and renewable electricity over the next three decades would make up the remaining quarter of the supply for Wuzhong in the BC.

In the area of renewables, solar PV will grow dramatically to over 85% of its full resource potential, even in the BC, thanks largely to the cost decline. This makes it a very cost-competitive source of electricity generation at the local level, indicating associated benefits, such as the creation of local economic activities and job opportunities. PV is projected to provide 11% of the electricity supply by 2050. Solar thermal energy in the service sector will also grow, but its contribution to the overall renewable portfolio will be rather modest. Another sizeable contribution, as far as renewable applications are concerned, will be from waste-to-energy systems, accounting for nearly 10% of energy generation. This option addresses two challenges – waste management and clean energy generation – in one go. Nevertheless, a potential barrier to this option is the constraint on land availability and limited options for siting. Therefore, careful urban planning would be of critical importance in this regard. In addition, the waste heat from gas-fired CHPs has a role to play until at least 2035, when the lower cost of imported electricity, renewable electricity and decentralised heat generation will gradually replace gas-based operation (although the facilities might be kept for emergencies and for regulating power generation). Overall, by 2035 and 2050, the shares of renewables would reach 13% and 21%, respectively, in the BC.

FIGURE 27: Baseline scenario – electricity and heat production



AC = air conditioner; CCP = combined cycle power plant; CCS = carbon capture and storage; CHP = combined heat and power plant; HPA = air-source heat pump; HPGW = ground- or water-source heat pump.

In this scenario, the energy performance requirements for residential and commercial buildings are implemented at the minimum required rate in the model. Yet we would see a rise in the use of heat pumps in residential and commercial or service buildings. Heat pumps will take off, regardless of emission constraints, thanks to the economic benefits they can bring through improved efficiency of energy use and the growing demand to regulate room temperature for comfort under future climate change conditions, where extreme weather patterns would occur more frequently and more severely than before. For Wuzhong, both individual units and the centralised application of heat pumps would be adopted subject to the demand density in a given area within Wuzhong.

3.2 Carbon policy

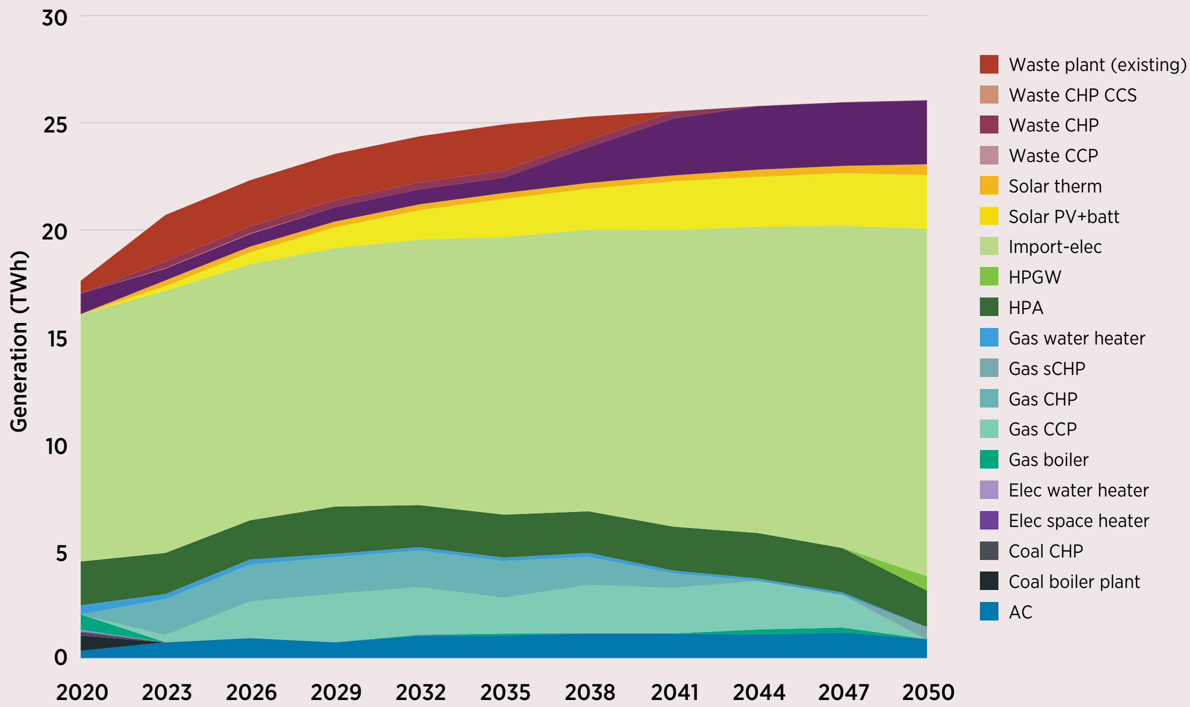
The carbon policy (CP) scenario describes a case in which the Wuzhong energy system is driven by an objective to reduce carbon emissions by 15% by 2040 compared with 2020 levels – a target recommended in carbon peak guidelines for Shanghai and Suzhou by the Chinese National Center for Climate Change Strategy and International Cooperation (Cao *et al.*, 2019). This scenario is not intended to achieve net-zero emission by 2050 but rather to present a portfolio of energy technologies for achieving gradual emission reductions under a suggested CP while keeping cost minimisation as an optimisation objective. This scenario includes improved energy efficiency measures for end-use appliances and three-star building energy performance standards for new residential and service or commercial buildings. It also includes a high transportation electrification rate of 40% by 2035 and 70% by 2050.

Wuzhong has a less carbon-intensive economic structure than the Suzhou average and does not have many carbon-intensive industries, including fossil fuel-based energy generation facilities, in its territory. The recommended carbon target applied in the analysis (a 15% reduction over 2020-2040) is considered modest and reasonable in comparison with the historical and projected trajectories of Suzhou city's carbon emissions: (a) over 2006-2017, the annual growth rate of emissions had declined from +20% to -7%, while the total emissions became relatively stable, in the range of 160 million tonnes CO_2 since 2013, with a slight downward trend in 2017; (b) over 2020-2050, the emissions will be reduced by 26% under the prescribed policy objective to realise a smooth trajectory for emission reductions after peaking in 2020 (WRI, 2020).

As with the BC scenario, coal-fired power generation has no role to play in this scenario after its phase out in the early 2020s. In terms of generation from solar PV by 2050, the difference between the BC and CP scenarios is rather small, given the limited total resource potential available in Wuzhong, as indicated in Figure 28. The important advancement in the CP scenario is that the solar PV generation will scale up significantly earlier than in the BC scenario and will reach its full potential in about 2040. Only mainstream technologies such as rooftop PV are modelled, which suggests potential room for growth of solar PV by applying advanced and innovative technologies such as building-integrated PV (BIPV) on building envelopes and other city-integrated solar solutions (to be discussed in the next chapter).

As in the BC scenario, municipal and industrial waste-to-energy facilities, as well as heat pumps, continue to supply the majority of heat demand in Wuzhong. Solar thermal energy for both residential and commercial or service buildings will also make a contribution to meeting the heat demand, but at a scale as small as one-sixth of that from the other heat sources.

FIGURE 28: CP scenario – electricity and heat production



CCP = combined cycle power plant; CCS = carbon capture and storage; CHP = combined heat and power plant; HPA = air-source heat pump; HPGW = ground- or water-source heat pump; PV = photovolatic.

In the CP scenario, imported electricity from the grid will account for a significant share of the electricity mix in the second half of the projected period in view of the overall decarbonisation of the grid electricity mix in China. In the medium term, however, gas-fired power plants through CCP and CHP will have an important role to play in achieving the CP objective, under the assumption that the carbon intensity of grid electricity[4] will not dramatically decline until 2035, after which low-carbon energy generation is planned to significantly accelerate towards achieving net-zero goals by 2060.

Overall, since the carbon emission target is set rather modestly in this scenario, there is insignificant difference in terms of the generation profile from that in the BC, except that the role of natural gas alters around 2035, as discussed before. However, the local environmental benefits from carbon emission reductions driven by the CP, which have long been recognised at both international and local levels (Karim *et al.*, 2017; UNECE, 2016), should not be overlooked. A study on the Shanghai area – a megacity adjacent to Suzhou city, where Wuzhong is located – has also suggested that shifting from carbon-intensive energy generation technologies to low-carbon solutions offers a cost-effective way to improve the local environmental quality (Gielen and Chen, 2001). Therefore, it is important for Wuzhong – a district with a mandate to preserve its ecological and environmental quality – to give serious consideration to setting carbon emission reduction targets in its energy policy and plans.

4. Currently, coal-fired power generation still accounts for nearly 60% of the national total electricity; its emission factor is much higher than that of the electricity from gas-fired generators.

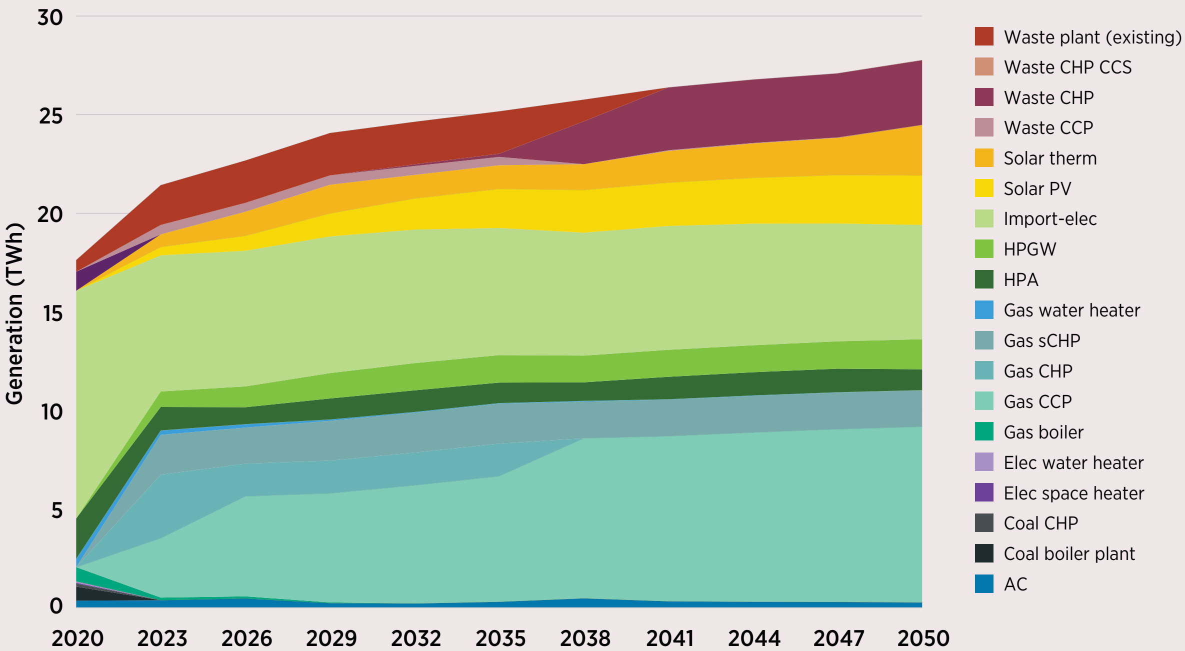
3.3 Sustainable development scenarios

The sustainable development (SD) scenarios examine optimal planning pathways for a range of CO_2 emission reduction objectives over the modelling horizon. The objectives range from cost-optimal CO_2 emission minimisation at one end to cost-only minimisation at the other, with varying CO_2 target cases in between. A Pareto efficiency curve is developed for the SD scenario to demonstrate the plausible solution space for achieving the dual objectives.

First, we present a scenario for minimising carbon emissions without CCS (the SD-CO_2Min scenario), as illustrated in Figure 29. For now and the foreseeable future, electricity is expected to remain the largest share of the final energy consumption in Wuzhong. The optimal option for minimising emissions will be maximising the use of local renewables and substituting grid electricity with local gas-fired power generation (Figure 29). For renewables, the maximal levels, in terms of resource potential and the efficiencies of conversion technologies, will be reached. For instance, in contrast with the CP scenario, waste is optimally used to generate both electricity and heat using CHPs in the long term (compared with heat-only generation using industrial boilers in the CP scenario).

In this scenario, the electricity imported from the grid to Wuzhong will be reduced by approximately two-thirds compared with the BC and CP scenarios in 2050. The supply gap will be filled by a substantial increase in gas-fired power generation, stretching the natural gas import potential to the limit, and by a 70% and 40% increase in renewable electricity in comparison to the CP and BC scenarios, respectively. Other measures, particularly scaling up the use of heat pumps coupled with renewable thermal energy sources for residential and service end-users, will also contribute to carbon emission minimisation.

FIGURE 29: SD-CO_2Min – electricity and heat production

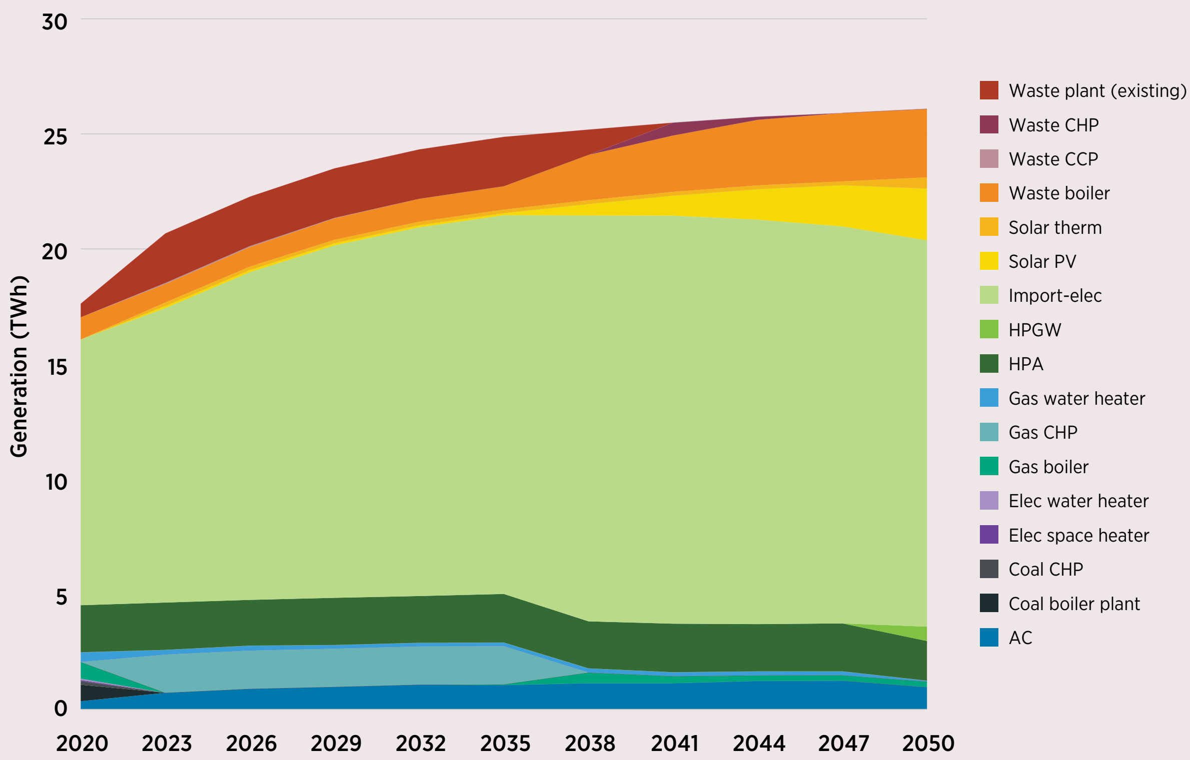


AC = air conditioner; CCP = combined cycle power plant; CCS = carbon capture and storage; CHP = combined heat and power plant; HPA = air-source heat pump; HPGW = ground- or water-source heat pump; PV = photovoltaic.

However, the plausibility of this scenario can easily be challenged due largely to constraints such as the lack of available land for installing such a large number of gas power fleets, the gas supply and volatility over time, and the high cost per tonne of CO_2 avoided. Nevertheless, the SD-CO_2Min scenario does suggest that there is a need for the other SD scenarios, with a balanced trade-off between emission reductions and costs – two key elements to be considered.

The generation mix for the SD-CostMin scenario, illustrated in Figure 30, presents a suite of technology options to deliver a cost-optimal solution under minimal CO_2 reduction constraints. It bears close resemblance to the BC scenario (Figure 27) with only 6 million tonnes less in total CO_2 emissions, largely due to stronger efficiency measures and a larger renewable energy target share than the BC. The CO_2 emissions in the SD-CostMin scenario are nearly 40% higher than in SD-CO_2Min.

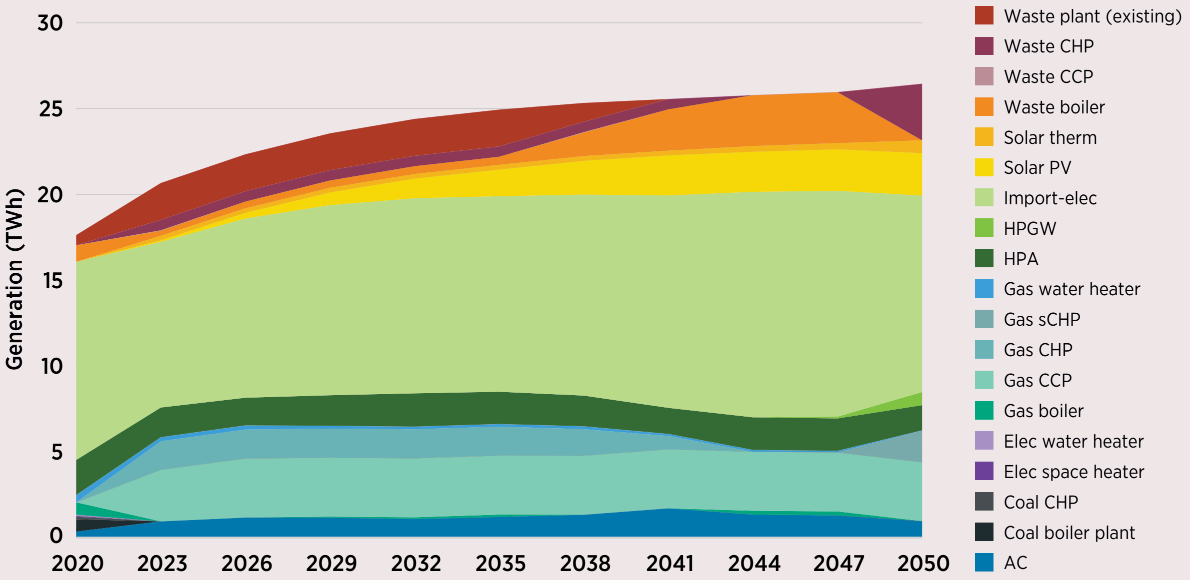
FIGURE 30: SD-CostMin – electricity and heat production



AC = air conditioner; CCP = combined cycle power plant; CHP = combined heat and power plant; HPA = air-source heat pump; HPGW = ground- or water-source heat pump.

SD-CO_2Mid, presented in Figure 31, aims to balance the trade-offs between electricity imports (*i.e.* higher imports for cost optimality) and gas technologies (*i.e.* higher gas generation for low CO_2) to meet a mid-range CO_2 reduction target (halfway between the CO_2 emissions level of the SD-CO_2Min and SD-CostMin scenarios). In some ways, this scenario appears similar to the CP scenario, except for a slightly greater use of grid electricity towards 2050 than in the CP scenario, in view of the carbon and cost targets.

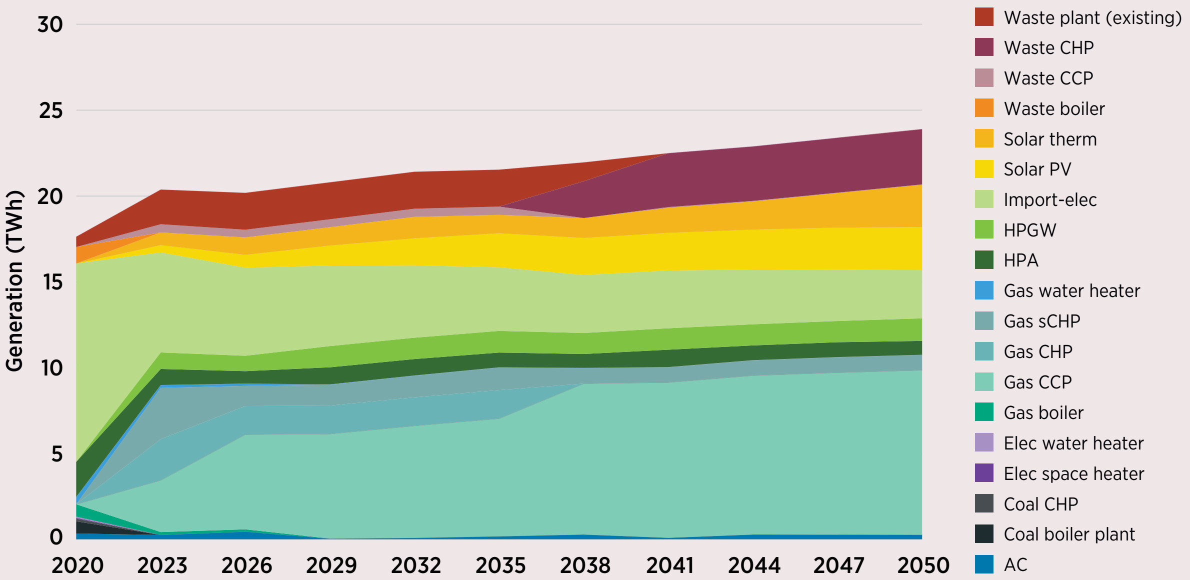
FIGURE 31: SD-CO_2Mid – electricity and heat production



AC = air conditioner; CCP = combined cycle power plant; CHP = combined heat and power plant; HPA = air-source heat pump; HPGW = ground- or water-source heat pump; PV = photovoltaic.

Figure 32 presents the generation mix for the SD-CO_2Min-LD scenario, which is similar to the SD-CO_2Min scenario, but with reduced (high CO_2) grid imports under the assumption of greater energy efficiency improvements leading to reduced overall demand.

FIGURE 32: SD-CO_2Min-LD – electricity and heat production



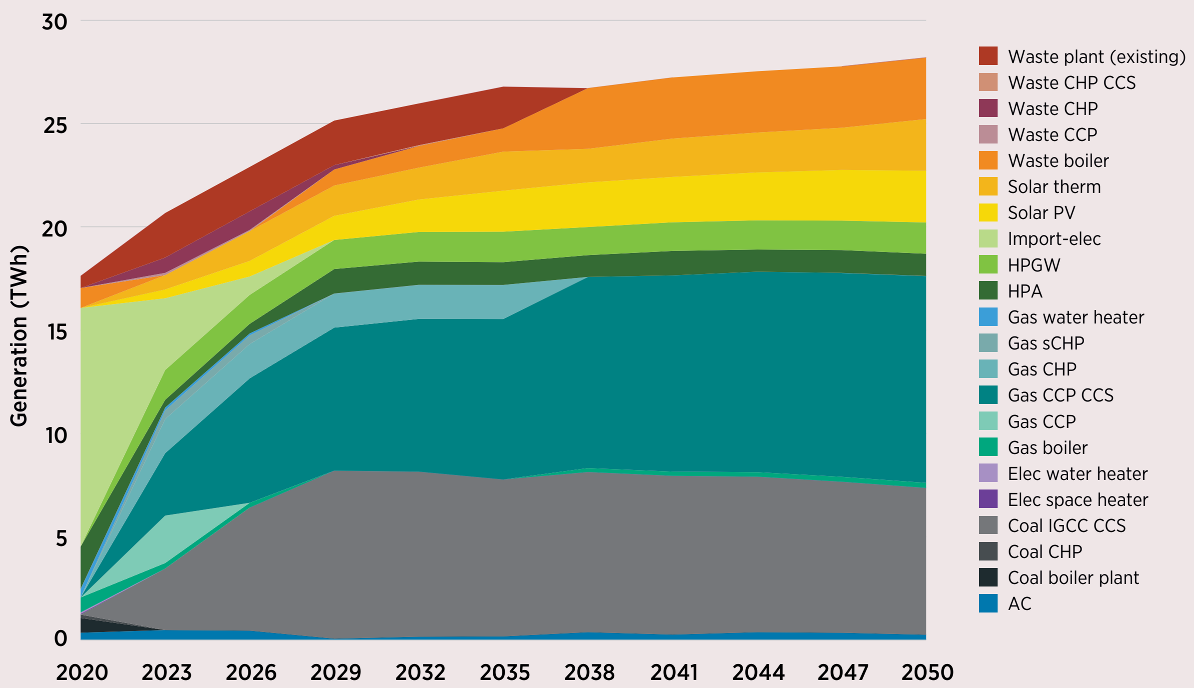
AC = air conditioner; CCP = combined cycle power plant; CHP = combined heat and power plant; HPA = air-source heat pump; HPGW = ground- or water-source heat pump; PV = photovoltaic.

3.4 Net-zero CO_2 scenario

A highly hypothetical scenario aimed at achieving near net-zero carbon emissions with locally self-sufficient energy generation was also developed; this is known as the net-zero CO_2 emissions (NZC) scenario in this study. Despite it being unlikely to occur, given the energy governance and great degree of integration of physical power systems at various levels throughout the entire country, it is interesting to examine the plausible options that the current technologies could provide if emissions had to be cut to near net-zero through local generation and resources.

As illustrated in Figure 33, in the NZC scenario, the modelling results indicate that CCS technologies would have a major role to play in mitigating CO_2 emissions. A distinct shift is observed from grid imports towards locally generated electricity and carbon capture using gas CCPs and coal IGCC power plants that would have CCS installations. Grid imports are entirely replaced on a net annual basis by these technologies by 2030, accompanied by maximal deployment of PV, waste-to-energy, ground- or water-source heat pumps, and solar thermal technologies until 2050 (as observed in the SD-CO_2Min scenario). Also as in the SD-CO_2Min scenario, gas imports are maximally utilised, indicating that gas CCP CCS is preferred (*i.e.* is more cost-effective) over coal IGCC CCS. Once the gas CCP CCS is fully utilised, IGCC CCS is installed to decarbonise the electricity mix. Gas CCP and waste CHP facilities would be equipped with CCS to reduce carbon emissions, under the assumption that sequestration does not present an issue, which will be discussed further in the next chapter.

FIGURE 33: Net-zero CO_2 emissions scenario – electricity and heat production

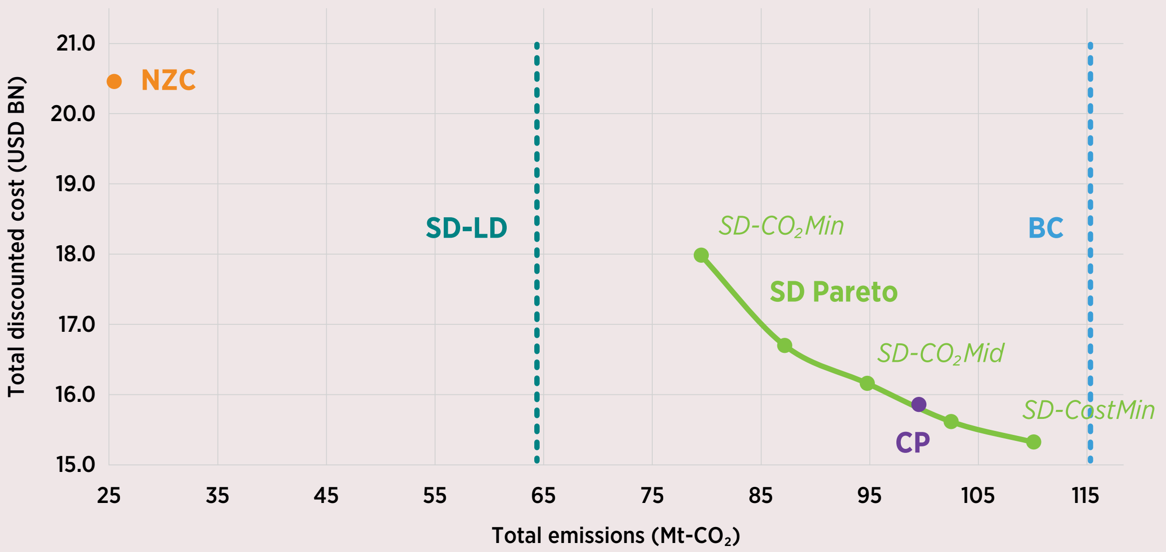


AC = air conditioner; CCP = combined cycle power plant; CCS = carbon capture and storage; CHP = combined heat and power plant; HPA = air-source heat pump; HPGW = ground- or water-source heat pump; I = industrial; IGCC = integrated gasification combined cycle; PV = photovoltaic.

3.5 Pareto efficiency

Costs and net CO_2 emissions are summarised in Figure 34 across the various scenarios. A Pareto efficiency curve is also plotted for the SD scenarios. This curve illustrates the boundary of cost-optimal solutions that satisfy different total CO_2 targets, from the CO_2 minimisation oriented scenario (SD-CO_2Min) to the cost optimisation scenario without a CO_2 target (SD-CostMin). Carbon dioxide emissions for the SD-CO_2Min-LD scenario, which has a 15% lower energy demand than SD-CO_2Min, and the NZC scenario are also presented in the chart for comparison.

FIGURE 34: Costs versus CO_2 emissions across scenarios and Pareto efficiency curve



BC = baseline case; CP = carbon policy; NZC = net-zero CO_2 emissions; SD = sustainable development.

The SD-CO_2Min scenario yields emissions that are 28% lower than the SD-CostMin scenario, with total costs that are 17% greater. The CP scenario lies almost directly on the Pareto front, close to the SD-CO_2Mid scenario; however, it lies closer to the cost-minimised SD-CostMin scenario than the carbon minimised SD-CO_2Min scenario, indicating that the CP appears to be reasonably designed in terms of practical achievability, providing a strong balance between cost and carbon minimisation objectives. Emission reductions due to the shift from imported grid electricity to local generation using gas-based technologies play a significant role in the CP and SD-CO_2Min scenarios, which demonstrate approximately 15% and 30% lower net CO_2 emissions, respectively, compared with the BC scenario. Emissions reduction in the SD-CostMin scenario compared with the BC scenario is only about 5%, which is almost entirely due to the energy efficiency improvement measures considered in the model. This indicates that further investigation is required into more advanced and innovative demand-side technologies.

The SD-CO_2Min-LD scenario indicates a similar trend, whereby emissions are 18% lower for SD-CO_2Min-LD than for SD-CO_2Min. This reduction is achieved through reduced energy demand, which is assumed to be implemented exogenously through demand-side management, below average growth trends, or other measures resulting in reduced long-term energy demand.

The NZC scenario presents a special case, with 70% lower emissions than SD-CO_2Min for a comparative 14% increase in total system costs. However, as mentioned in the previous section, this scenario is less likely to occur and bears high uncertainties in terms of CCS technology applicability and the associated costs for the district. However, given that CCS or carbon capture, utilisation and storage can be effective approaches under certain circumstances (Box 2), there is still a need for more diligence on this front for Wuzhong to better understand the viability of this option from a long-term perspective. Lastly, in the NZC scenario, for the transport sector the use of oil will be replaced by full electrification of the sector.

BOX 2: Role of carbon capture (utilisation) and storage

Carbon capture and storage (CCS) or carbon capture, utilisation and storage (CCUS – when utilisation of captured CO_2 is involved as part of the carbon management process) can be an effective approach for addressing carbon emissions from the use of fossil fuels in the absence of feasible abatement technology solutions. This typically happens in industrial sectors where fossil fuels cannot be substituted without technological breakthroughs as the specific requirements for the industrial processes cannot be met by the current options. For instance, in the cement industry, process emissions from cement clinker production form the majority of emissions, and it is difficult to decarbonise the emissions using only renewable energy sources due largely to the high temperature requirements of the process (IRENA, 2020b). On this front, China produced 60% of the world's cement in 2019 (Wang, 2021). While energy intensity measured by kilogrammes coal equivalent per tonne (kgce/tonne) of cement in China can be expected to improve by at least 26% compared with international best practices, this would not necessarily translate to emission reductions since reduced energy inputs are mainly from alternative fuels using recycled petroleum-based products like plastics and tires. Reducing emissions further would require end-of-pipe technologies such as CCS or CCUS in sectors such as cement, iron and steel to achieve carbon neutrality goals.

As of 2020, there are 40 CCUS projects in China, including both operational and under-construction facilities, capturing 3 million tonnes of CO_2 per annum. By 2060, China estimates that CCUS could potentially reduce carbon emissions in the range of 0.6-2.1 billion tonnes, subject to the need to meet the carbon neutrality goal, according to the *China CCUS Annual Report: Roadmap 2021* (Cai, Li and Zhang, X., 2021). However, most carbon storage capacities are located in the north, east and northwest of the country. For the southern and coastal regions of China, the storage capacities are moderate due to poor geological conditions as far as carbon storage is concerned.

It is widely acknowledged that CCUS will play a role in China's roadmap towards carbon neutrality by 2060, despite there being a high degree of uncertainty for a given location.

Source: IRENA, 2021; Lyons, Durrant and Kochhar, 2021.

4

DISCUSSION

Moving towards net-zero emissions can be achieved for Wuzhong District through a combination of local and regional measures if Wuzhong steps up its efforts in the following interrelated strategic areas. These areas will enable expansion of the decarbonisation options presented in the modelling results. This chapter discusses a suite of emerging innovative solutions that Wuzhong should consider, given the limitations of conventional abatement measures, as presented in the previous chapters. The discussion in this chapter also has strong relevance to Chinese cities and districts with a similar profile to Wuzhong and, thus, can be used as a starting point for them to discuss their pathways towards a net-zero carbon future. For this reason, the national energy transition and international examples are discussed.

4.1 Integrated solar PV holds untapped potential for cities

In China, the installation of distributed solar PV systems has been accelerating in recent years. Their share has reached 32.2% of the national total PV installed capacity, yet this is still much lower than the target of 55% set in the 13th Five-Year Energy Development Plan (2015-2020) (NEA, 2017)

Recently, the Chinese National Energy Administration issued a policy to encourage the installation of on-site distributed energy generation by requiring pilot cities and towns to allocate at least 50% of public building rooftop areas, and at least 40% of industrial and commercial building rooftop areas, to solar PV (China5e.com, 2021). For the first half of 2021, distributed solar PV installations (7.65 gigawatts [GW]) accounted for close to 60% of the solar PV addition, according to the National Energy Administration (NEA, 2021a). This trend is expected to continue thanks to the multiple benefits of on-site renewable energy generation, including improved electricity quality, less energy loss in long-haul transmission networks, avoided investment in transmission network expansion, improved local environmental quality, job creation, and economic opportunities benefiting local communities.

For the Wuzhong District, the limited local renewable energy resources and the constraints on land use impede greater use of local renewables beyond the renewable energy technologies considered in the model. Of the locally available renewable energy sources in the district, integrated solar PV in buildings and urban infrastructure appears to hold the greatest potential.

BIPV can significantly expand available surface area for solar PV electricity generation. This is particularly true for an area with high-rise buildings, where rooftop areas generally represent a small portion of the building envelope. With façade-integrated PV, the building can generate not only more electricity but much smoother daily generation output than rooftop PV systems alone, as the PV panels on the façades can continue to generate electricity at smaller solar altitude angles, from which the panels on the rooftops generate less electricity. This, in effect, widens the range of solar altitude angles for electricity generation compared with the use of installed rooftop PV systems alone. Pilot projects across the globe have demonstrated significant reduction in electricity demand in buildings with BIPV installations.

Over the past decade, BIPVs have made substantial progress in technology development and deployment. Such progress has been demonstrated through a growing number of pilot and commercial projects across the globe, generating positive feedback from policy makers, urban planners, energy and construction sectors, and end-users (SolarPower Europe and ETIP PV, 2019). Some examples are:

- **Treurenberg office building, Brussels (Belgium):** This is the first net-zero energy building to be certified BREEAM (Building Research Establishment Environmental Assessment Methodology) “Excellent”. Through the retrofitting process, 1960s building façades were covered with BIPV, accounting for 61 kilowatts peak (kWp) of installed power generation capacity. Another 61 kWp was installed on the rooftops. Altogether, the BIPVs generate enough electricity to meet the demand of the building.

- **The Solar Emerald commercial building, Drammen (Norway):** This building was renovated to achieve higher building energy performance by installing BIPV on all façades, with a total generation capacity of 115 kWp, and PV panels on the roof with a capacity of 68 kWp. Annually, the panels can generate 106 megawatt hours (MWh) of electricity (55.5 MWh from BIPV and 50.5 MWh from rooftop solar PV). This is sufficient to provide 23% of the total building electrical consumption (BIPVNO, n.d.).

- **Enzian office building, Bolzano (Italy):** This building’s façades were covered as much as possible by insulating glass (filled with argon gas) with amorphous silicon modules or opaque laminated glass. Solar PV modules were also installed on the roof. Annually, the system can produce 113 MWh of electricity from solar energy (EURAC, 2013).

In Wuzhong, electricity typically accounts for two-thirds of the total energy consumption of buildings. Therefore, BIPVs can play a very important role in decarbonising the building sector, as they could substantially contribute to the reduction of electricity demand from the grid, particularly in summer seasons when the electricity consumption for air conditioners (on average, accounting for half of annual household electricity consumption) is typically soaring (Wang, 2021).

Nevertheless, BIPV is still a niche market, largely because of its higher costs due to fewer automated manufacturing processes and fewer options on the market, although progress is rapidly evolving (Kuhn *et al.*, 2021).

In terms of cost outlooks, teaming up the PV and construction industries helps reduce costs while improving overall performance from both energy and construction perspectives. BIPVs also offer more than just electricity generation, including thermal and acoustic insulation, replacing conventional building components and providing an aesthetically pleasing appearance. Hence, there should be a fair way to compare their cost profiles with a conventional PV system performing a singular function.

More importantly, for a district or city with ambitions to achieve net-zero carbon emissions or positive energy, BIPV presents one of the few options to maximise the use of solar energy resources in cities when the available rooftop area is limited (Mose, Lovati and Maturi, 2018). This is particularly relevant to Chinese cities, where the population densities are generally much greater than those in Europe or North America. This suggests that the large market potential in China for BIPV would be able to bring down the cost and spur innovation for new designs to better meet the needs for energy and building materials.

In addition to buildings, urban infrastructure such as parking lot canopies and pavements can offer potential surface areas for integrated solar PV. For instance, in an effort to create a positive energy district, Groningen – the largest city in the northern Netherlands – will turn current bicycle lanes into a power plant by integrating solar PV panels into the surface, which will produce 60 MWh of electricity annually (Making City, 2019). Such integration would enhance public acceptance of solar PV solutions in the built environment, where the social dimension plays a critical role. The potential for applying integrated solar PV as part of the urban environment is therefore huge, yet it remains largely untapped. Wuzhong should explore opportunities to unlock such potential and showcase viable technological and business solutions for China.

4.2 Enhancing demand-side flexibility in support of grid integration of renewables

Grid flexibility is essential for scaling up the integration of variable renewable energy technologies into the power grid as part of the decarbonisation of the energy sector. The challenges typically grow with increasing shares of variable renewable energy sources.

In China, electricity from solar and wind energy is expected to supply 11% of the national electricity consumption by the end of 2021, an important milestone leading to the proposed target set for the 14th Five-Year Energy Plan (2021-2025): non-fossil fuel energy sources contributing to 20% of total primary energy consumption by 2025 (NEA, 2021b). It has been estimated that variable renewable electricity will account for 20% of the total electricity generation by 2030 (NDRC, 2021). Therefore, this decade (2020-2030) is a test period for China on the extent to which the country can rely on renewables to achieve its 2060 target. It depends on whether China can find a reliable, sustainable and affordable mechanism to provide the flexibility that the future energy system would need.

Currently, the majority of the responsibility depends on the two grid operators in China, the State Grid and the Southern Grid, to ensure grid integration of the planned quota of renewable-based power generation capacity. The present energy flexibility options from the supply-side in China primarily include pumped storage hydropower stations, natural gas-fired power plants and flexible coal-fired power plants serving as a regulating power instead of serving baseload demand. However, all of them are facing serious challenges in supporting grid operation under high shares of variable renewable energy sources. There are regulatory and technical barriers, for example a lack of market conditions for ancillary service provision. Yet, more importantly, the supply-side flexibility capacities would not be sufficient alone to meet the flexibility that would be needed, due to such constraints as insufficient availability of resources, environmental concerns, and lack of institutional and regulatory harmonisation. With the installed power generation capacity from variable renewables reaching about one-quarter of the national total, and being in relatively geographically distributed regions, the challenge will become greater if not dealt with in a systematic fashion.

Currently, renewable energy developers are encouraged to provide additional flexibility if they would like to install more than is permitted under the approved capacity addition plan. They can acquire such flexibility by building physical systems or purchasing such services on the marketplace. Over time, this option would be expected to become mainstream. In other words, a grid auxiliary service market would need to be established and flexibility would be an energy commodity that would be priced under a set of new rules as part of ongoing power market reform in China.

In this context, exploring the flexibility options that the demand-side can provide beyond conventional interruptible load management schemes is not only technically necessary but economically sensible. This is one of the critical roles that cities as load centres can play in the global energy transition, particularly those cities without excellent local renewable energy resources.

At present, such additional flexibility options are limited to power-to-heat and electromobility, given technological constraints and the system configuration (IRENA, 2019b). Looking forward, along with smart city development, a growing number of electrical appliances are being digitalised and connected to the Internet and would thus be theoretically controllable. According to the International Energy Agency, there will be 83 billion connected electric and electronic devices and sensors by 2024 (IEA, 2021). The energy consumption profiles of Internet-connected appliances could be altered to match generation curves from variable renewable energy electricity generation if digitalised intelligent energy demand-side management systems were put in place.

By harnessing potential flexibility through intelligent energy management systems, cities would be well positioned to provide technical support that the grid (both power and thermal) operators would need to support growing shares of variable renewables in systems as part of the decarbonisation strategy.

For Wuzhong, it would be advisable to focus on solving China's future problems while weaning off of today's fossil fuel-dominated energy systems – specifically, by building the flexible capacity that regional or national power grids would need. Practically speaking, electrification of transport and building sectors should be given priority in the immediate term, while in the medium to long term, flexibility can be provided through flexible or controllable home appliances that modify their consumption profiles (either by reducing or shifting their loads to different periods). For the latter, the aggregator[5] is a crucial player, offering the possibility for small consumers to participate in the flexibility management required by the distribution grids and, thus, supporting the accommodation of higher shares of variable renewables and reducing the carbon footprint of grid electricity.

4.3 Role of green hydrogen

Green hydrogen is produced via electrolysis powered by renewable electricity. Thanks to its flexible production using electrolysers, it can be used as an energy carrier that effectively stores electrical energy harnessed from variable renewable energy sources, such as solar

5. A new player in the energy market, the aggregator represents a cluster of smaller agents in an energy system. Benefiting from advanced information and communication technologies and energy management techniques, the aggregator functions as a united entity in transactions of grid services provided to the grid or other engagements in the energy market (IRENA, 2020c; MIT, 2016).

and wind energy. Its applications can also be extended to end-use sectors other than distributed stationary energy generation, such as the transportation sector through fuel cell automobile technologies, the chemical industry, and iron-making by replacing coke coal as a direct agent. It can also be used to decarbonise end-use sectors that are hard to decarbonise through an electrification approach. From this perspective, green hydrogen would play an important role in driving the global energy transition towards a carbon-neutral 2050 (IRENA, 2018).

In recent years, China has significantly elevated the strategic role that hydrogen will play in accelerating its national energy revolution. After the Chinese president announced in September 2019 that China would achieve carbon neutrality by 2060, hydrogen has swiftly been viewed as a plausible technological pathway to contribute to achieving this ambitious goal, despite some experts warning that China should take slow steps given the lack of clarity on how the hydrogen-for-decarbonisation strategy will unfold and the fact that China will likely rely on fossil fuel-based hydrogen at least for the short term.

The China Hydrogen Alliance projects that China will produce 37.15 million tonnes of hydrogen annually, contributing to 5% of the total final energy consumption in 2030, if carbon emissions peak in that year. However, only 13% of this will qualify as green hydrogen, according to the white paper on China's hydrogen energy and fuel cell industry (China Hydrogen Alliance, 2019), launched in April 2021. To achieve carbon neutrality by 2060, China would need 130 million tonnes of hydrogen, accounting for 20% of the total final energy consumption, of which 80% is expected to be green hydrogen to be produced from 500 GW of electrolysers, contributing to nearly 17% of China's current carbon emissions.

Suzhou city, to which Wuzhong District belongs, is part of the Yangtze River Delta region, regarded as one of the three hydrogen industry pioneers in China (Meng *et al.*, 2020). The city released a white paper on hydrogen industry development in early 2021 (Government of Suzhou, 2021). It not only presents the ecosystem for the hydrogen industry's development in Suzhou but, more importantly, sets the goals for 2035: creating 15 billion USD worth of businesses around hydrogen, promoting the use of hydrogen fuel cell vehicles and building 70 hydrogen refuelling stations, among others. At the current stage, the city has established designated industrial zones for companies to set up manufacturing capacities for hydrogen fuel cell vehicles (Government of Suzhou, 2021).

It would be sensible for Wuzhong to benefit from the local development of the hydrogen industry in Suzhou city by expanding its transport decarbonisation into heavy-duty and long-haul trucks, for which hydrogen fuel cell technologies hold substantial potential in the long run (IRENA, 2018). As importantly, Wuzhong should participate actively in hydrogen industry development in Suzhou, including encouraging investors and developers to build hydrogen production equipment manufacturing facilities and building hydrogen refilling stations, along with fuel cell electric vehicles, in the district.

4.4 Importance of sustainable urban energy planning

Overall, two key pathways are identified in this study through which the Wuzhong District could move towards net-zero emissions: through supply-side technology solutions and/or through demand-side management. Both are needed to scale up the use of renewables at the regional and national levels. However, how to strike a sound balance would depend on how soundly a sustainable energy plan can be developed and implemented. Sound planning is vitally important because, owing to the long lifespan of the physical energy infrastructure, the planning can either leapfrog a city over or lock it in to a certain energy development trajectory. On the global level, sound planning is even more important, particularly during the post-COVID period, when many municipal governments may fall short of financial resources as a consequence of overspending and lack of taxation revenues during the pandemic.

A growing number of organisations have developed instruments to assist local energy experts and authorities with urban energy planning (Hemis, 2017; Saheb *et al.*, 2014). Several resources provide detailed step-by-step guidelines on how to develop and implement a sustainable energy plan for cities. The key steps are described in the following text (EU, 2010; ICLEI, 2011; ICLEI, UN-Habitat and UNEP, 2009).

- Baseline review: This initial step, partially addressed by this study for Wuzhong, involves conducting a detailed CO_2 emissions inventory. The development of a track-and-trace carbon emissions management platform can help identify the highest polluting agents (*e.g.* specific enterprises or services) in a system. Sustainability projects (*e.g.* demand-side management or renewable energy projects) can then be targeted towards high-priority or high-impact sectors.

- Target setting: With a carbon management platform in place, the next key step is to establish targets. Studies, such as this one, should inform target setting. Targets may pertain to emission reductions, renewable energy shares, and efficiency measures, as well as other objectives, indicators and measurable targets. Local stakeholders should be engaged at all levels to define meaningful targets. For Wuzhong, this means targets should be set with reference to and in alignment with the emission reduction goals of Suzhou city.

- Political commitment and partnership: This step involves formalising the commitment to developing and supporting a sustainability plan by different agencies in cities. The local government should also involve and establish partnerships with key stakeholders; this is often identified as a factor that strongly influences the duration and the success or failure of the planning process.

- Implementation plan: A detailed plan should be developed and implemented in accordance with established targets and goals. Programme and project financing must also be defined with supporting partners.

- Monitoring and evaluation: In this stage, the progress, impacts, successes and failures of the implemented action plan are carefully monitored and evaluated. The carbon tracing platform established in the first stage will assist in this phase as well. Iterative adjustments to the implementation plan and supporting structures may be required.

The importance of integrating a city's sustainable energy plan into the overall urban planning at an early stage should be emphasised. Resource mapping, urban forms and functionalities, and coupling of different urban infrastructure and end-use sectors are all important variables for developing a solid and sustainable urban energy plan. More recently, it has become increasingly relevant and important for the climate resilience of urban energy systems to be factored into long-term planning, given the long lifespan of infrastructure and the increase in the severity and frequency of extreme weather patterns, which pose real and sustained threats to urban infrastructure and dwellers, economies, livelihoods and the continued urbanisation process.

5

CONCLUDING REMARKS

China has set clear targets to achieve its carbon peak by 2030 and carbon neutrality by 2060. The country will be less likely to deliver on its ambition if cities lag in taking action. Therefore, it is crucial for local authorities to make a long-term energy transition strategy towards carbon neutrality. Authorities must guide cities to implement adequate actions to decarbonise their economies. By doing so, they will also prevent themselves from being locked in to a portfolio of carbon-intensive stranded assets when carbon-intensive commodities become cost-prohibitive in future.

However, areas with modest renewable energy resources, like the Wuzhong District, need to give serious consideration to emerging and innovative renewable energy technologies to maximise the use of their limited resources. The conventional modelling approach could present a limitation, as carbon reduction by switching from high to lower carbon-intensive fossil fuels and through CCS is normally given priority in the optimisation process. For this study, four scenarios were built on the basis of the results from a district-wide, energy system optimisation model. In all scenarios, the renewable energy potentials are not fully unlocked at either the local or regional level.

Overall, the two main pathways for Wuzhong to achieve a low-carbon emissions future are through low-carbon generation technologies and demand-side management strategies, including efficiency measures. They are not mutually exclusive. The maximised use of local renewable energy resources requires enhanced demand-side management, which often has an important role to play in facilitating the integration of renewables at the regional level.

Renewable energy technologies – including PV, waste-based CHP and decentralised boilers – should be maximally deployed in Wuzhong and given priority in the planning process. Given the limited potential of these technologies, however, supplementary natural gas-based facilities would be needed to decarbonise the energy mix in the long term if the carbon intensity of regional grid electricity remains relatively high. The deployment rates and capacities of these technologies depend also on various factors, including expected energy demand growth rates, and how aggressively carbon emission targets are set. CCS technologies also demonstrate potential to reduce emissions drastically but may be better suited for implementation on a regional scale, which would yield benefits locally (*e.g.* through decarbonisation of the regional electricity grid). With the above, Wuzhong could substantially reduce its carbon emissions by 2050. However, the implementability of the carbon abatement options from the modelling results appear to be substantially dependent on key assumptions, which deserve further uncertainty studies.

Nonetheless, the modelling and scenario exercises are very helpful in terms of understanding the conventional decarbonisation approach. This, in turn, helps local authorities stretch the lines of thinking beyond conventional options.

The study has identified four strategic areas enabling expansion of the decarbonisation options presented in the modelling results: BIPV, demand-side flexibility, green hydrogen and urban energy planning. These areas are applicable not only for Wuzhong but for many districts and cities like Wuzhong, with modest local renewable energy resources and relatively high energy demand. The provision of demand-side flexibility at the distribution level could facilitate the integration of variable renewable energy sources at the regional level, thus significantly reducing the carbon intensity of the regional grid electricity. Therefore, the need for transmission capacity enhancement or expansion to transmit renewable electricity to the end users, in this case to Wuzhong District, should also be assessed and optimised in concert with the planned regional scale-up of variable renewable energy deployment.

Certainly, these strategic areas do not constitute an exhaustive list, but they do highlight the most relevant aspects that such cities or districts should look into and adjust to suit conditions in their localities.

The Chinese leadership has boosted its ambition and stepped up its efforts in addressing the climate challenges. Cities will take this as guidance and make corresponding strategies and actions plans to contribute as much as they can to achieving the national carbon peak by 2030 and carbon neutrality by 2060. However, the actions they take and the decisions they make should be based on their resources. For cities without sufficient local renewable energy resources, there are other options they could explore with the aim of achieving net-zero carbon emissions in a collective and collaborative fashion.

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