Energy transition
in the Yangtze River Delta Region of China

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I dedicate this thesis to

my parents, my husband

for their constant support and unconditional love!

Abstract

Electricity systems around the world are undergoing a sustainable energy transition, and in this process, traditional thermal power plants play a role in maintaining the stability of the electricity supply. The term "thermal power plants" refers to the fossil fuels combustion electricity generation technologies, such as coal-fired, oil-fired, and gas-fired power plants. Fossil-fuel resources are dominated by a limited number of countries; for example, Russia is the world's largest exporter of natural gas. The outbreak of the Russian-Ukrainian war caused natural gas supply scarcity, which led to a large amount of rebooting of coal-combustion power plants in many countries to alleviate the electricity supply difficulties. The carbon emissions were largely increased in a short term. The unstable global situation has also accelerated the transformation of national power systems worldwide. All EU member states have chosen renewable or nuclear energy as an alternative to address the energy security problem. France plans to increase the installed capacity of solar power to 100 Gigawatt (GW), offshore wind power to 40 GW, and nuclear power to 25 GW by 2050. The United States plans to reach 80% clean power by 2030, by which time the cumulative installed renewable energy capacity in the United States will have risen to 885 GW.

In 2021, China, as the world's largest energy consumer, producer, and importer, faced the security problem of high dependence on energy imports. China's power generation structure is still overwhelmingly dominated by coal-fired power. The installed power generation capacity and power generation volume show a trend of increasing the share of renewable energy. In 2019, fossil power accounted for 68.9%, and nonfossil energy generation accounted for 31.1% of China's power generation. The share of thermal power in power generation has shown a decreasing trend since 2011, while the share of nuclear power, hydropower, wind power, and solar photovoltaic power generation has steadily increased. With the rising share of renewable power, its intrinsic intermittence and fluctuation supply characteristics, the power system is bound to have a high demand for flexible power-dispatching systems or storage systems. On the one hand, in China, the mismatch between power development and grid planning has led to a situation where a large amount of renewable power is lost. On the other hand, the current high cost of electrochemical energy storage limits its market penetration, which leads to a massive waste of renewable power. Establishing a safe and stable low-carbon system has become a crucial issue.

To avoid power withdrawal and secure a low-carbon electricity supply, an important way is to appropriately integrate the newly added power generation system based on the existing spatial conditions, the impact of adding new power generation technologies, and the development goals of institutional decision-makers, market investors and the public. This thesis is divided into four studies, in which a multitude of research methods and empirical data are used.

Chapter 2 proposes a suitability index scheme of evaluation criteria and compares the spatial site potential of seven low-carbon energy power plants by ranking their suitability with the analytic hierarchy process (AHP) based on geographic information systems (GIS). According to the findings, over 78% of the region is suitable for the installation of power plants. More than 30% of the eligible land is regarded as having a high potential for natural gas (NG), solar, biomass, and waste-to-energy (WtE) electricity. Over 70% of the suitable area is regarded as having medium potential for wind power. Moreover, the suitability maps of the evaluation criteria and the integrated site potential maps are presented in this chapter.

Chapter 3 summarizes the socioeconomic and environmental impacts of mainstream energy technologies populated in the study area and assesses subjective technological sustainability based on stakeholder perceptions by applying the AHP and weighted sum method. The findings show that no technology is absolutely the most sustainable. For instance, nuclear power has the most sophisticated technical features for securing a constant supply of power; natural gas power has the lowest economic cost; pumped-storage hydropower and onshore wind have the least negative effects on the environment and society. Moreover, based on the subjective consideration of stakeholders, pumped storage hydropower is determined to be the most sustainable energy source, followed by nuclear and onshore wind generation.

Afterward, the output spatial suitability maps in Chapter 2 and the sustainable criteria values in Chapter 3 are incorporated as data input in Chapter 4 to develop an agent-based, energy-planning model that explores customized low-carbon energy plans with different stakeholders making decisions unilaterally or in groups. The model determined that economic factors are always critical in energy planning and that group negotiation decision-making can better satisfy the interests of each stakeholder, allowing for the simulation of a realistic and feasible sustainable energy landscape. The Yangtze River Delta region is likely to continue the development of natural gas power in the short term to ensure sufficient electricity supply and shift toward mixed renewable energy generation systems, especially wind and hydropower, in the long term. Such a long- and short-term electricity plan will ensure a reduction in negative social and environmental impacts and increase the security of the energy supply without reducing economic efficiency.

Finally, in Chapter 5, several abstract scenarios are established to investigate the impact of socioeconomic development pathways on the future energy transition. This chapter introduces an interesting idea in which the fossil-energy development socioeconomic pathway may lead to a sustainable energy landscape with a high share of clean and low-carbon technologies.

Overall, the findings of this research aid in understanding the low-carbon sustainable energy system transition, which is the most efficient strategy to reduce anthropogenic carbon emissions. This study can help with decisions on achieving carbon neutrality.

Zusammenfassung

Elektrizitätssysteme auf der ganzen Welt befinden sich im Übergang zu einer nachhaltigen Energieversorgung. In diesem Prozess spielen traditionelle Wärmekraftwerke eine wichtige Rolle bei der Aufrechterhaltung der Stabilität der Elektrizitätsversorgung. Der Begriff "Wärmekraftwerke" bezieht sich auf Technologien zur Stromerzeugung durch Verbrennung fossiler Brennstoffe wie Kohle-, Öl- und Gaskraftwerke. Die Ressourcen an fossilen Brennstoffen werden von einigen wenigen Ländern beherrscht, so ist beispielsweise Russland der weltweit größte Exporteur von Erdgas. Der Ausbruch des russisch-ukrainischen Krieges verursachte eine Verknappung der Erdgasversorgung, was in vielen Ländern zu einem umfangreichen Neustart von Kohlekraftwerken führte, um die Stromversorgungsprobleme zu lindern. Die Kohlenstoffemissionen stiegen kurzfristig stark an. Die instabile globale Lage hat auch den Umbau der nationalen Energiesysteme weltweit beschleunigt. Alle EU-Mitgliedstaaten haben sich für erneuerbare Energien oder Kernenergie als Alternative zur Lösung des Problems der Energiesicherheit entschieden. Frankreich plant, bis 2050, die installierte Kapazität der Solarenergie auf 100 Gigawatt (GW), der Offshore-Windenergie auf 40 GW und der Kernenergie auf 25 GW zu erhöhen. Die Vereinigten Staaten wollen bis 2030 einen Anteil von 80 % sauberer Energie erreichen. Bis dahin wird die kumulierte installierte Kapazität an erneuerbaren Energien in den Vereinigten Staaten auf 885 GW gestiegen sein.

Im Jahr 2021 steht China als weltweit größter Energieverbraucher, -erzeuger und -importeur vor dem Sicherheitsproblem einer hohen Abhängigkeit von Energieimporten. Chinas Stromerzeugungsstruktur wird immer noch überwiegend von der Fossilekraft dominiert. Die installierte Stromerzeugungskapazität und das Stromerzeugungsvolumen zeigen den Trend auf, dass der Anteil an erneuerbaren Energien zunimmt. Im Jahr 2019 entfielen 68,9 % der chinesischen Stromerzeugung auf fossile Energie und 31,1 % auf nicht-fossile Energieerzeugung. Der Anteil der thermischen Energie an der Stromerzeugung ist seit 2011 rückläufig, während der Anteil der Kernenergie, der Wasserkraft, der Windenergie und der Solar-Photovoltaik-Stromerzeugung stetig gestiegen ist. Mit dem steigenden Anteil der erneuerbaren Energien, die inhärent intermittierend und fluktuierend sind, ist das Stromsystem an einen hohen Bedarf an flexiblen Stromverteilungs- oder Speichersystemen gebunden. Einerseits hat in China die Diskrepanz zwischen der Energieentwicklung und der Netzplanung dazu geführt, dass eine große Menge erneuerbarer Energie verschwendet wird. Andererseits begrenzen die derzeit hohen Kosten der elektrochemischen Energiespeicherung deren Marktdurchdringung, was zu einer massiven Verschwendung von Strom aus erneuerbaren Energiequellen führt. Die Frage, wie ein sicheres und stabiles kohlenstoffarmes System aufgebaut werden kann, ist zu einer entscheidenden Frage geworden.

Um Stromabschaltungen zu vermeiden und eine kohlenstoffarme Stromversorgung zu gewährleisten, besteht ein wichtiger Schritt darin, das neu hinzukommende Stromerzeugungssystem auf der Grundlage der bestehenden räumlichen Gegebenheiten, der Auswirkungen neuer Stromerzeugungstechnologien

und der Entwicklungsziele der institutionellen Entscheidungsträger, Marktinvestoren und der Öffentlichkeit angemessen zu integrieren. Diese Arbeit gliedert sich in vier Studien, in denen eine Vielzahl von Forschungsmethoden und empirischen Daten verwendet werden.

Chapter 2 proposes a suitability index scheme of evaluation criteria and compares the spatial site potential of seven low-carbon energy power plants by ranking their suitability with the analytic hierarchy process (AHP) based on geographic information systems (GIS).

In Kapitel 2 wurde ein Eignungsindex für die Bewertungskriterien vorgeschlagen und vergleicht das räumliche Standortpotenzial der sieben kohlenstoffarmen Kraftwerke durch eine Einstufung ihrer Eignung mithilfe einer Analytischer Hierarchieprozess (AHP) auf der Grundlage eines geografischen Informationssystems (GIS). Die Ergebnisse zeigen, dass über 78 % der Region für die Errichtung von Kraftwerken geeignet sind. Mehr als 30 % der infrage kommenden Flächen weisen ein hohes Potenzial für Erdgas, Solar, Biomasse und Abfallverstromung Strom auf. Über 70 % der Eignungsflächen besitzen mittleres Potenzial für die Gewinnung von Windenergie. Darüber hinaus werden in diesem Kapitel die Eignungskarten der Bewertungskriterien und die integrierten Standortpotenzialkarten ausgegeben.

Kapitel 3 fasst die sozioökonomischen und ökologischen Auswirkungen der im Untersuchungsgebiet verbreiteten Energietechnologien zusammen und bewertet die subjektive Nachhaltigkeit der Technologien auf der Grundlage der Wahrnehmung der Interessengruppen unter Anwendung des AHP und der Methode gewichteter Summen. Die Ergebnisse zeigen, dass keine Technologie absolut nachhaltiger ist. So verfügt beispielsweise die Kernkraft über die ausgefeiltesten technischen Merkmale zur Sicherstellung einer konstanten Stromversorgung; Erdgas hat die geringsten wirtschaftlichen Kosten; Pumpspeicherkraftwerke und Windkraftanlagen an Land haben die geringsten negativen Auswirkungen auf Umwelt und Gesellschaft. Auf der Grundlage der subjektiven Überlegungen der Beteiligten wurde die Pumpspeicherkraft als die nachhaltigste Energiequelle ermittelt, gefolgt von der Kernenergie und der Onshore-Windenergie.

Anschließend werden die in Kapitel 2 erstellten räumlichen Eignungskarten und die in Kapitel 3 ermittelten Werte für nachhaltige Kriterien als Dateninput in Kapitel 4 integriert, um ein agentenbasiertes Energieplanungsmodell zu entwickeln, das maßgeschneiderte kohlenstoffarme Energiepläne mit verschiedenen Interessengruppen untersucht, die einseitig oder in Gruppen Entscheidungen treffen. Das Modell hat gezeigt, dass wirtschaftliche Faktoren bei der Energieplanung immer von entscheidender Bedeutung sind und dass eine gruppenweise Entscheidungsfindung die Interessen der einzelnen Interessengruppen besser befriedigen kann, was die Simulation einer realistischen und machbaren nachhaltigen Energielandschaft ermöglicht. In der Region des Jangtse-Flussdeltas ist es wahrscheinlich, dass kurzfristig die Entwicklung von Erdgaskraftwerken fortgesetzt wird, um eine ausreichende Stromversorgung zu gewährleisten, und langfristig auf gemischte Systeme zur Erzeugung erneuerbarer Energien, insbesondere Wind- und Wasserkraft, umgestellt wird. Ein solcher lang- und kurzfristiger Elektrizitätsplan wird eine Verringerung der negativen sozialen und ökologischen Auswirkungen gewährleisten und die Sicherheit der Energieversorgung erhöhen, ohne die wirtschaftliche Effizienz zu beeinträchtigen.

Schließlich werden in Kapitel 5 mehrere abstrakte Szenarien erstellt, um die Auswirkungen der sozioökonomischen Entwicklungspfade auf die künftige Energiewende zu untersuchen. Dieses Kapitel brachte die interessante Idee, dass der sozioökonomische Entwicklungspfad für fossile Energien zu einer nachhaltigen Energielandschaft mit einem hohen Anteil an sauberen und kohlenstoffarmen Technologien führen kann.

Insgesamt tragen die Ergebnisse dieser Forschung dazu bei, den Übergang zu einem kohlenstoffarmen, nachhaltigen Energiesystem zu verstehen, der die effizienteste Strategie zur Reduzierung der anthropogenen Kohlenstoffemissionen darstellt. Sie können bei Entscheidungen zur Erreichung der Kohlenstoffneutralität helfen.

List of publications:

This list provides the published and submitted papers derived from Ph.D. research as the first author. Chapter 2 has been published in the journal *Energies* (1), Chapter 3 is currently under review in *Sustainable Energy Technologies and Assessments* (2), Chapter 4 has been submitted to *Energy Strategy Reviews* (3). In addition, the list also includes publications (4-6), in which the doctoral candidate also appears as the first author.

1. Peng, Y.; Azadi, H.; Yang, L.; Scheffran, J.; Jiang, P (2022). Assessing the Siting Potential of Low-Carbon Energy Power Plants in the Yangtze River Delta: A GIS-Based Approach. Energies 15, 2167. https://doi.org/10.3390/en15062167
2. Peng, Y., Yang, L. E., Azadi, H., Scheffran, J., Jiang, P. (2023). Assessing and enhancing the regional sustainability of electricity generation technologies in the Yangtze River Delta, China. Sustainable Energy Technologies and Assessments, under review.
3. Peng,Y., Yang, L. E., Scheffran, J., Schneider, U. (2023). An agent-based spatial energy planning model for a sustainable transformation of electricity generation: The case of the Yangtze River Delta region. Energy Strategy Reviews, in progress.
4. Peng, Y., Yang, L.E., Scheffran, J., Yan, J., Li, M., Jiang, P., Wang, Y., Cremades, R. (2021). Livelihood transitions transformed households' carbon footprint in the Three Gorges Reservoir area of China. J. Clean. Prod. 328, 129607. https://doi.org/10.1016/j.jclepro.2021.129607
5. Peng, Y., Yang, L.E., Scheffran, J. (2021). A life-cycle assessment framework for quantifying the carbon footprint of rural households based on survey data. MethodsX 8, 101411. https://doi.org/10.1016/j.mex.2021.101411
6. Peng, Y., Lopez, J. M. R., Santos, A. P., Mobeen, M., & Scheffran, J. (2022). Simulating exposure-related human mobility behavior at the neighborhood-level under COVID-19 in Porto Alegre, Brazil. Cities, 104161. https://doi.org/10.1016/J.CITIES.2022.104161

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Chapter 1: Introduction

1.1 Background

1.1.1 Energy structure in China

China is the world's major energy producer and largest consumer, accounting for 26.1% (BP, 2021) of global energy consumption in 2020. Coal is the dominant energy source, accounting for 67.6% of primary energy production and 56.8% of total energy consumption in 2020 (National Bureau of Statistics China, 2022). Oil and gas consumption continues to grow, accounting for 18.9% and 8.4% of the total energy consumption in 2020, respectively (National Bureau of Statistics China, 2022). In addition, electricity production has greatly increased to 7,521.4 TWh, which is 15.9% of the total national energy production (National Bureau of Statistics China, 2022). Since 2011, China has been the largest global electricity producer. At the end of 2017, China ranked first in the world for total installed power generating capacity (BP, 2019). These power generators consist of thermal power (fossil fuel power), hydropower, grid-connected wind power, grid-connected solar power, and nuclear power.

In addition, China figures large in renewable energy's future. In 2018, China's renewable energy installation capacity reached 728 GW, which includes 352 GW for hydropower, 184 GW for wind power, 174 GW for photovoltaic (PV), and 17.8 GW for biomass energy (IHA & Association, 2016; Y. Liu, 2019; Tsinghua University, 2020). In 2020, China was the largest contributor to global nuclear and renewable power consumption, accounting for 30.76% and 24.57%, respectively (BP, 2021). In China, solar power capacity has experienced the fastest growth over the past 5 years (Figure 1.1).

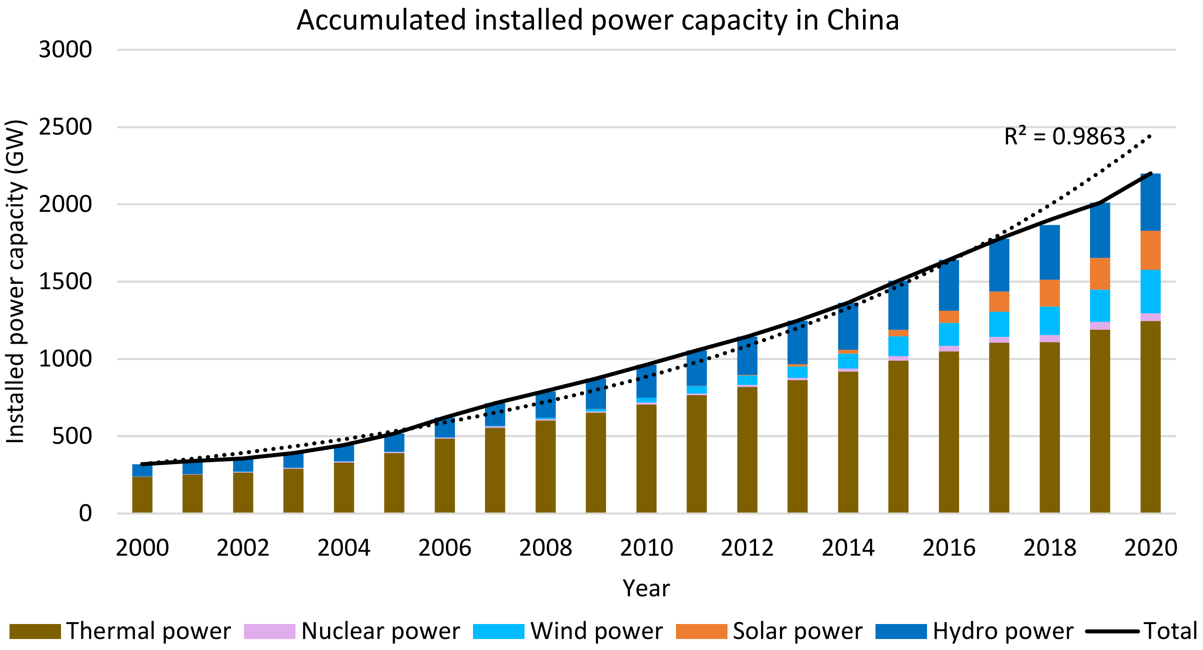


Figure 1.1 Installed power capacity in China

Figure 1.1 shows that thermal power is the predominant technology in China, and its capacity rapidly increased before 2015. Although the increasing rate of thermal power has decreased since 2015, the long lifetime of power plants (Davis et al., 2010), especially coal plants, limits the low-carbon transition of power generation systems. Switching to low-carbon energy sources would be a long-run challenge for China.

1.1.2 Carbon emissions of the energy system

In the past 50 years, China's economic growth and nonrenewable fuel consumption have had a great negative effect on the environment and have contributed greatly to global climate change. The study by Bélaïd & Youssef (2017) also indicates that "in a long term, economic growth and nonrenewable electricity consumption have a detrimental effect on the environment quality". Since 1949, the Establishment of the People's Republic, economic and energy consumption has experienced tremendous growth. By 2021, the per capita GDP reached 80,976 yuan, which is 210.33 times that of 1949 (385 yuan) (National Bureau of Statistics China, 2022). One of the consequences of rapid economy growth is the fast energy consumption increase (K. Dong et al., 2018a; Ozturk & Acaravci, 2010). Accordingly, the national energy consumption in 2019 ($4.875*10^9$ tons standard coal) was 205.34 times higher than that in 1949 ($23.74*10^6$ tons standard coal). The CO_2 emitted from energy consumption accounted for 9810.5 million tons in 2019 and reached 9899.3 million tons in 2020 (BP, 2021), which contributed to 30.7% of global CO_2 emissions.

In 2018, China's thermal power (approximately 90% of which is coal-based) contributed 43% of the national total CO2 emissions and was the largest source of CO2 emissions (F. Zhu & Wang, 2021). Reducing coal consumption in the power sector is indeed an effective means to reduce CO2 emissions. In 2020, the CO2 emissions of electricity production were approximately 832 g/kWh on average in China. The CO2 emissions declined by 20.6% from 2005 to 2020 (Hebei Provincial Department of Natural Resources, 2021). From 2006 to 2020, the power generation sector cumulatively reduced CO2 emissions by approximately 18.53 billion tons, which was contributed by the substitution with non-fossil energy (62%), the reduction of coal consumption (36%), and the lowering of the line loss rate (2%), which refers to the power lost in the power transmission network (Hebei Provincial Department of Natural Resources, 2021). To reach carbon neutrality by 2060, it is necessary to transition the electricity generation system from a thermal power dominated to a better mix system with a high proportion of renewables.

1.1.3 Government intervention for electricity generation system transition

In China, energy policy plays a crucial role in driving the energy transition, but the marketization reforms have also allowed the market to play a decisive role. The energy sector's government structure is shown in Figure 1.2.

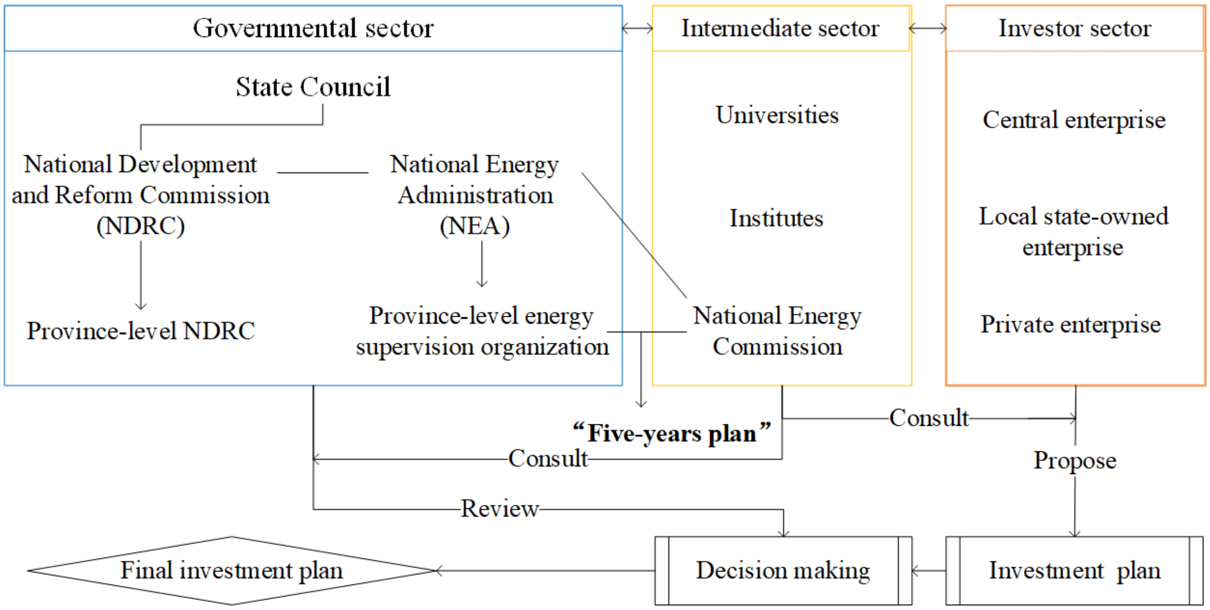


Figure 1.2 Energy sectors' governmental regulating structure

In Figure 1.2, the National Development and Reform Commission (NDRC) and National Energy Administration (NEA) are the departments leading the energy development strategy formulation (NDRC, n.d.). The main responsibilities of the National Energy Administration include participating in drafting laws, energy development plans, and policies (NEA, 2013); promoting research on energy development; and promoting international cooperation. The NDRC's main responsibility in energy development is reviewing the action plans or energy policies submitted by the NEA and ensuring the common development of energy and the national economy. The government regulating system is formed by the central government dominating instruction and provincial government agencies enforcing national laws and standards. State-owned enterprises (SoEs) are often large companies with monopoly or oligopoly positions in a heavily regulated market and can influence policy development and implementation. . In between these two stakeholders, there are many experts from universities and institutes consulting with their investment plans or developing plans. The National Energy Commission is an interagency energy development strategy body established in 2010. One of the most important functions of the National Energy Commission for the domestic energy structure is designing the Five-Year Plans for Energy Development together with NEA (General Office of the State Council of the People's Republic of China, 2010).

Table 1.1 shows the national "Five-year energy development plan", which sets investment and technology deployment targets for power supply and grid development in each province. Provincial government authorities are responsible for implementing the national-level plan and assessing and licensing project feasibility.

Table 1.1 The empirical data of the national energy sector in 2015, and the "five-years" development goals from 2015 to 2050.

Time span		The empirical data in 2015	Development plan from 2015-2020	Development plan from 2021-2030	Development plan from 2030-2050
Energy consumption structure (unit: percentage of total consumption; numbers without unit: hundred million kW)	Non-fossil	12%	15%; 7.7	20%	>50%
	Hydro	2.97	10%; 1.1	15%	
	Wind	1.31	2.1		
	Solar	0.42	1.1		
	Nuclear	0.27	0.58		
	Fossil		61%		
	Coal		55%;11		
	NG	0.66	>5%; 1.1		
	Energy/ GDP		15% lower than in 2015	decrease	
Energy security	Energy supply		80% self-sufficient	highly self-sufficient	
Environmental factors	CO2		18% lower than in 2015	60%-65% lower than in 2005	
	Waste		decrease	decrease	
Technology factor	Energy technology		improving	leading in the world	
References		(NEA, 2016b)	(NEA, 2016a, 2016b, 2016c)	(NEA, 2016a)	(NEA, 2016a)

The national plan has noted explicitly that only clean energy could be newly added to the whole energy system. As shown in Table 1.1, the energy transition is encouraged in three aspects, technology innovation, the growth share of renewables and clean energy consumption, and energy security improvement. In addition, environmental factors have become critical criteria for future energy system development. The national plan focuses on carbon emissions decrease and waste minimization.

1.1.4 Challenges of electricity generation system transition

China is currently undergoing a reform of the electricity generation system toward a low-carbon, clean, and highly efficient power production system. However, many challenges remain.

First, it is difficult to make the predominantly coal-combusted plants obsolete, while coal resources are the most abundant fossil fuel in China. However, the average age of China's coal-fired power generation facilities is only 12 years (K. Wang et al., 2022), which makes it difficult to phase out coal-fired power generation technology in the short term. Currently, two-thirds of the globally installed coal-fired power generation facilities with an operating age of less than 20 years are located in China. In addition, the average age of 20-30 MW plants was 21 years old, whereas the average age of plants with above 1 GW capacity was only 6 years. As the average lifetime of coal-fired power generation facilities is approximately 40 years, it is necessary to transition the electricity generation system from a coal-dominated to a low-carbon system.

Second, the expansion of natural gas power plants is limited in China. Insufficient domestic natural gas derives from the high reliance on imports. In 2020, China's total consumption of energy from imports accounted for 15.8% of total energy consumption and is split as follows: 58.14% crude oil, 34.44% coal, and others (National Bureau of Statistics China, 2022). By 2020, China's dependence on natural gas imports exceeded 43.54%, which brought much concern about energy security. The high reliance on import gas could be influenced by many uncertainties, including price fluctuations, supply chain stability, and transportation conditions. China is vulnerable to the external natural gas supply chain. The domestic energy structure should be improved by developing renewables.

Third, renewable power plants should be better integrated into the spatial environment. Historical electricity curtailments and power shortages result from unsuitable geographic conditions, insufficient transmission grids, and localized socioeconomic conditions. In the early 2000s, the economically developed provinces suffered from the most serious power shortage. Zhejiang, Jiangsu, and Shanghai experienced the highest percentages of power shortages, which were 19.0%, 18.8%, and 8.7%, respectively (Yu et al., 2013). The power shortage is a consequence of the incompatibility between power supply capacity and rapid economic development (Yu et al., 2013). Since 2015, a large amount of wind and solar power has been installed in the northeast region with the support of governmental subsidies (NEA, 2017). The northwest is rich in renewable resources, resulting in substantial electricity production that far exceeds the consumption capacity of the local market. The unsynchronized power generation and grid system result in renewable curtailment during cross-regional transportation from the northwest to the east region.

Fourth, the transition of the electricity system also needs to consider the interventions arising from different stakeholders. Since 2006, renewable power development in China were highly dependent on policy support and governmental subsidy. In more detail, China cut its renewable power subsidy to 5.67 billion yuan ($806.50 million) in 2020 from 8.1 billion yuan in 2019 (Reuters, 2019). At the start of 2021, China ended the subsidies for new onshore wind power projects and solar power projects. In addition, the liberalized pricing market brings more challenges to the development of renewable power (Guosen Securities, 2021). As section 1.1.3 described, the investors' actions, government intervention, expert and public opinion play a virtual role in the current electricity generation system market. The energy transition plan should consider the stakeholders' involvement.

1.2 Problem definition

Since we moved into the industrial era, electricity has become irreplaceable and important for our lives. Renewable energy has become a great substitute for conventional energy due to its inexhaustible and nonpolluting characteristics. The current national and regional energy development plants are focused on resulting in a renewable electricity production target or installation capacity target (Liang et al., 2019; Martinsen & Krey, 2008; Theodosiou et al., 2015), and there are no clear instructions guiding the deployment of power generation technologies to achieve these plans. A typical example in China is the "Five-years plan" (NDRC & NEA, 2016; NDRC Zhejiang & NEA Zhejiang, 2021; NEA Shanghai, 2020; Xinhua News Agency, 2021), which is a medium-term development announced by the central and local government. It only proposed the renewable power development target as a five-year increment target, such that the installation of solar power should increase by 1.23 GW from 2020 to 2025 in Zhejiang (NDRC Zhejiang & NEA Zhejiang, 2021). A spatially sustainable yearly energy development plan is needed.

There are three shortcomings of the current research on energy system development. First, the spatial condition is not widely included in the research on electricity planning. Only a few of them focus on spatial conditions, which consider biomass power development as the research object (Blaschke et al., 2013; Shu, 2014; Schardinger et al., 2012). However, spatial factors, including geographical conditions, local socioeconomic backgrounds, infrastructure construction, and spatial renewable resource potential, are confirmed to be essential in the site selection of renewable powers (Prasad et al., 2013; Spyridonidou et al., 2021; Tercan et al., 2020; Yousefi et al., 2018). The spatial siting potential is a prerequisite for spatial energy planning. Therefore, future energy planning should incorporate the existing electricity system and spatial environment. In this project, a method was sought to integrate spatial siting potential evaluation into the energy landscape simulation.

Second, the socioeconomic and environmental impacts accompanying energy plans should also be considered in energy planning. Much previous research has assessed the financial, environmental, and social influences of electricity generation technology (Atwa et al., 2010; Blaschke et al., 2013; Curto et al., 2019; Ivanova et al., 2005; Shu, 2014; Schardinger et al., 2012; Shaaban et al., 2019a; Theodosiou et al., 2015) but has not coupled them into an energy planning model. The feedback impact of installed electricity generation technologies could largely influence the future transition plan. For example, the significant carbon emission impact of coal-fired power plants reduces their chance of being further implemented in the current existing Chinese electricity generation system (NEA, 2016b). Therefore, in this research, the impact of electricity generation technologies was considered.

Additionally, the engagement of stakeholders is important for future energy plans (M. Chang et al., 2021; McGookin et al., 2021), but most energy system models incorporate only stakeholder inputs through scenarios (Bale et al., 2015; Ge & Kremers, 2016; McGookin et al., 2021), which cannot reflect the dynamic changes in stakeholders' perceptions and the interplay between different stakeholders. Most recent research is focused on the complexity of the energy system and only includes one executive stakeholder (Alfaro et al., 2016; Shu et al., 2015, 2017). The adaptive interplay between stakeholders has not been sufficiently explained by previous research. The current study will also address this shortage in the mixed-methods approach.

To better incorporate newly added clean power into the existing environment and ensure sustainable system development, in this research, I am designing a mixed method to simulate a spatially sustainable energy plan based on the existing energy system and the perception of stakeholders.

1.3 Objective and research questions

In general, this research addressed the question of **how to deliver a sustainable energy-mix plan to secure electricity supply in the Yangtze River Delta region in 2060**. To address electricity security problems and respond to the human-environmental system, this research will be cross-disciplinary. To develop a future sustainable energy mix plan, it is necessary to illustrate the spatial environment through the integration of qualitative and quantitative analysis. Second, based on the current renewable industries in China, this study will demonstrate the impact of electricity generation technologies by a review of relevant life-cycle analyses. Additionally, this study proposes an agent-based model to simulate future development strategies for the synchronous development of electricity generation systems, which could meet the requirements of environmental sustainability, economic viability, social stability, and technology innovation.

In doing so, the following sub-questions should be investigated:

1. How to efficiently allocate spatial potential in energy planning?
2. What are the socioeconomic and environmental impacts of electricity generation technologies, and which is the most sustainable technology?
3. Which potential future electricity-mix landscape would better secure a sustainable electricity supply in China?
4. How could future socioeconomic conditions influence the future energy mix plan?

The listed questions are all related to each other and are revealed in the following chapters. The complex research questions are revealed by cross-disciplinary mixed methods.

1.4 Method and data

The dissertation adopted mixed methods to investigate sustainable energy planning. To answer the above research questions, several methods were applied: literature review, field investigation, analytic hierarchy process, geographic information system, and agent-based model. Figure 1.3 shows the complex research framework and multiple research methods for different chapters to address different research questions.

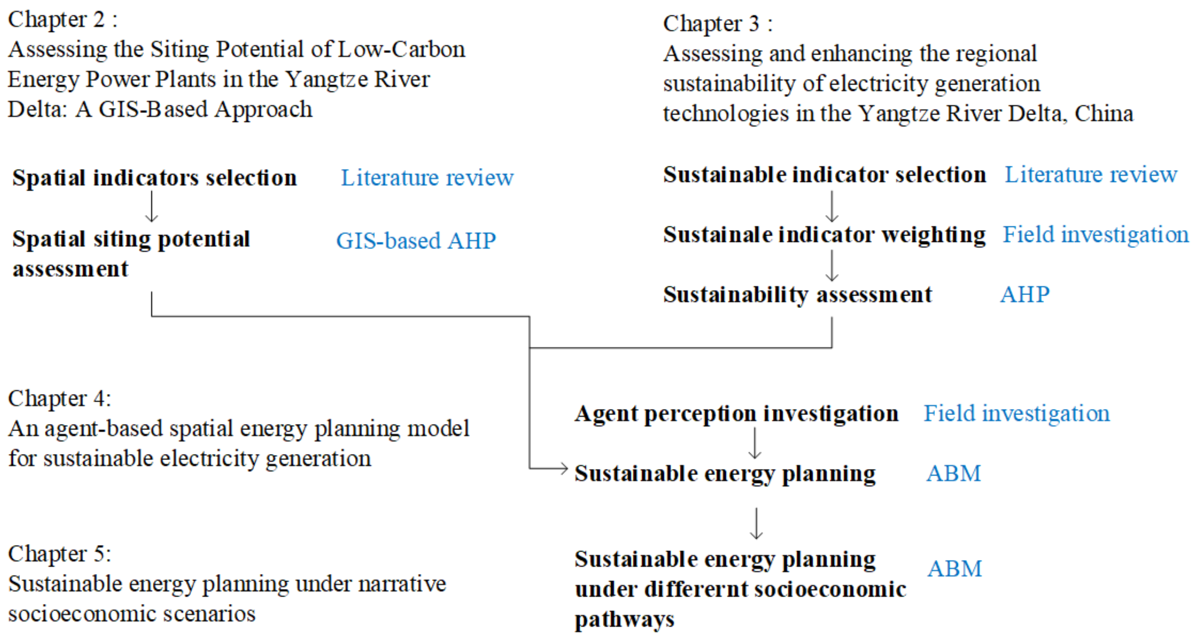


Figure 1.3 Research framework and methods

In Chapter 2, the GIS-based AHP is implemented into the spatial siting potential assessment. A geographic information system (GIS) is a tool for gathering, managing, and analyzing geographic data [38,39]. It is possible to illustrate various data in map layers and reveal deeper cognition of the spatial data. In the circumstance of geospatial information as a decision criterion, the assembly of GIS and the analytic hierarchy process are mutually complementary [40]. The AHP arranges a number of criteria from different dimensions (social, environmental, and economic), which are essential for spatial power plant site selection, in a hierarchic structure descending from the overall goal to the criteria [41]. Based on the well-presented decision criteria maps by ArcGIS, the AHP function could result in spatial power plant siting potential maps for alternative low-carbon energies, which could support energy planners in better interpreting the complex problem of energy planning [42]. The data used for this chapter are based on open data resources.

In Chapter 3, data were gathered from the literature review and field investigation. First, sustainable indicators are reviewed and selected from the literature research according to the technology background of alternative powers in China. The results can be found in Appendix 8.1. Second, the field investigation conducted in January 2021 collected stakeholder weights of these indicators through interviews, questionnaires, and online surveys (Appendix 4 and 5). Therefore, the AHP and WSM were used to integrate these resulting values and assess the sustainability of alternative electricity generation technologies.

Chapter 4 designs an agent-based model to simulate the future energy landscape. The agent-based model (ABM) is built on agents that have their own goals and are capable of adapting their behaviors autonomously in response to the changing environment, according to their memory and their decision rules (Epstein, 2008). To achieve socioeconomically and environmentally sustainable development, this agent-based model is based on stakeholders who are involved in energy planning. Additionally, the interplay between the stakeholders delivers different group-decided energy landscapes. Due to the complexity of the energy system, it was necessary to consider the spatial conditions, technology impacts, stakeholder perceptions, etc. Therefore, the model uses stakeholder perceptions and results from Chapters 2 and 3 as the input data to deliver different future energy landscapes and find more sustainable cases.

Chapter 5 applied different socioeconomic development pathways to the agent-based energy planning model. Different socioeconomic pathways (SSPs) (Wenying Chen et al., 2017) were downscaled to the regional level and presented by the temporal change in model parameters, including technology innovation, electricity demand rate, and fossil fuel pricing. Energy landscapes based on the narrative socioeconomic scenarios were generated.

1.5 Research area

The Yangtze River Delta region (YRDR) was considered as the study region (Figure 1.4) because of its geographic importance, economic importance, high electricity demand, and high risk of climate change. It is meaningful to conduct future energy planning research in this region.

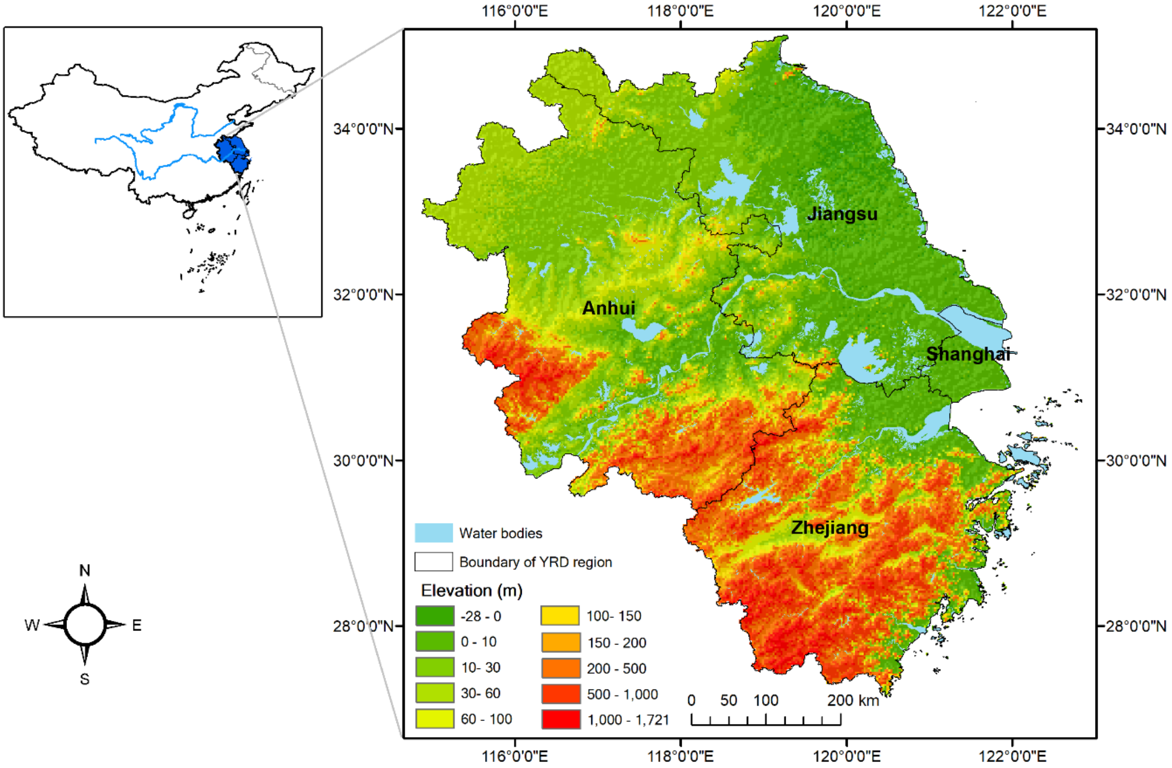


Figure 1.4 Map of the Yangtze River Delta Region (YRDR), the research area

The Yangtze River Delta covers 358,000 square kilometers, including Shanghai, Jiangsu Province (13 prefecture-level cities), Zhejiang Province (11 prefecture-level cities), and Anhui Province (16 prefecture-level cities). The region is located in the lower reaches of the Yangtze River, which has been historically known as the "Silk of the House, the land of plenty" due to the deposit of large flat and fertile land surrounding the mouth. The area is the confluent area of rivers and sea, which is a natural trade hub for import and export trade. With its superior geographical conditions, advanced transport infrastructure, excellent natural endowments, and heavily industrialized economic foundation, it has become one of the regions with the strongest competitiveness worldwide.

In 2021, the GDP of this region reached ¥27.6 trillion (approximately $4.6 trillion), accounting for approximately 24.14% of the national GDP (calculated from the national open data (National Bureau of Statistics China, 2022)). The population size reaches 236.5 million (National Bureau of Statistics China, 2022), which is far larger than some of the world's largest urban agglomerations, such as the New York metropolitan area (18.4 million), the San Francisco Bay Area (7.8 million), and the Tokyo Bay Area (40 million) (CEIC, 2022). The YRD region is also responsible for one-third of China's imports and exports. In addition, in December 2019, the State Council issued the Outline of the Yangtze River Delta Regional Integrated Development Plan, which proposes to achieve the integration of the social and economic development of the region by 2025 (General Office of the State Council of the People's Republic of China, 2019a). The integrated development within the YRD region makes it more meaningful to conduct research. The energy planning simulation in this region can be a good example for other similar integrated economic advanced regions.

Economic development drives a considerable amount of electricity consumption. The whole region consumed 1708 TWh of electricity, which is 22.8% of the national electricity consumption in 2019 (National Bureau of Statistics China, 2022). The total power generation of the Yangtze River Delta region is 1141.3 TWh, which accounts for 66.82% of the total electricity consumption (calculated from the provincial level electricity production and consumption data (National Bureau of Statistics China, 2022)). The rest of the consumed electricity is imported from other regions. As a large electricity consumer and importer, the YRD region faces the risk of electricity supply security. A total of 91.41% of locally produced electricity was generated from thermal power in 2019. The great potential of renewable power has not been well developed in the Yangtze River Delta region.

The YRD region has a high potential to develop renewable power plants to reduce supply risk. First, many industrial parks create technically suitable conditions for installing distributed solar power (Taminiau et al., 2021). Second, since biomass energy and waste-to-energy technology are well developed, the construction of biomass and waste-to-energy power plants could generate available heat and electricity (Al Garni et al., 2016; D. Zhang et al., 2015). It also solved the environmental problem of field straw burning and waste landfill. Additionally, the coastal geographical advantage benefits wind power development (World Resources Institute, 2021b). Jiangsu's wind power and solar power technology are in the national leading position, which can drive the development of renewable powers in the Yangtze River Delta. It would be essential to incorporate renewable powers into future sustainable energy plans.

A large amount of electricity consumption contributes to atmospheric carbon emissions and pollution, which would accelerate global climate change and reduce local environmental conditions. Long-term climate change and local geographic conditions would result in many extreme weather events, including heat waves, locally heavy rainfall, thunderstorms, heavy fog, and strong winds (Sun et al., 2019), in the YRDR. Highly industrialized urban agglomeration regions, with high electricity consumption, resulting in urban heat islands (Huang & Lu, 2015) and high pollutant concentrations. Conversely, electricity consumption is also an incentive for climate change and global warming. Li's study shows that temperature changes on cold days (<7 °C) and warm days (>28 °C) will lead to a great increase in electricity consumption in the YRDR (Y. Li et al., 2019). Therefore, it is meaningful to look for sustainable energy planning for such urbanized, economically advanced, and high electricity consumption regions.

In the study region, the provincial governments have derived their own goals from achieving sustainable electricity system development. The Yangtze River Delta is aiming to develop non-fossil powers, including wind power, hydro power, solar energy, bioenergy, and nuclear energy. And the provincial government set more environmental criteria for energy development, including PM2.5, weather quality, water quality, ozone depletion, and waste discharge.

Table 1. 2 Regional energy sector development goal and priorities in the Yangtze River Delta.

Time span		2020-2025
Energy development factor	Energy consumption/GDP	10% lower than in 2017
	Energy development focus	Wind; Hydro; Solar; Nuclear; Bio
Economic factors	Urban-rural developing gap	gap shrinking and being more balanced
Environmental factors	PM2.5	reaching the standard
	Weather quality	good weather > 80%
	Water quality	>80%
	Ozone	decrease
	Waste	decrease
References		(General Office of the State Council of the People's Republic of China, 2019b; Government office of Jiangsu Province, 2017; Government office of Shanghai, 2017; Government office of Zhejiang province, 2017)

1.6 Structure of the thesis

The thesis includes one published, two submitted, and one likely to-be-submitted journal article. In all papers, the author of this thesis is the first and corresponding author. The thesis presents an interdisciplinary study involving various approaches. Chapters 2 to 5 contribute to answering the research questions associated with the overall study. Finally, Chapter 6 concludes the findings from the previous chapters and draws future research directions.

Chapter 2: Assessing the Siting Potential of Low-Carbon Energy Power Plants in the Yangtze River Delta: A GIS-Based Approach

Abstract: China announced a target of achieving carbon neutrality by 2060. As one of the most promising pathways to minimize carbon emissions, the low-carbon electricity supply is of high consideration in China's future energy planning. The main purpose of this study is to provide a comparative overview of the regional siting potential of various low-carbon power plants in the Yangtze River Delta of China. First, unsuitable zones for power plants are identified and excluded based on national regulations and landscape constraints. Second, I evaluate the spatial siting potential of the seven low-carbon energy power plants by ranking their suitability with geographic information system (GIS)-based hierarchical analysis (AHP). The results revealed that around 78% of the area is suitable for power plant siting. In summary, biomass power plants have high siting potential in over half of the spatial areas. Solar photovoltaic and waste-to-electricity are encouraged to establish in the long-term future. The maps visualize micro-scale spatial siting potential and can be coupled with the sustainability assessments of power plants to design an explicit guiding plan for future power plant allocation.

Keywords: low-carbon energy; power plant; spatial suitability; energy planning; analytic hierarchy process; carbon neutrality

2.1 Introduction

In 2020, the low-carbon energy power development was promoted by the "Net-Zero" emission target, which was set by Europeans and three major Asian economies, including China, Japan, and Korea (European Commission, 2019). China has set a target to increase the share of non-fossil fuels and reach "carbon neutral" by the end of 2060 (Draworld, 2020; McGrath, 2020). Since 1980, the Chinese economy has grown rapidly for over forty years (S. Liu, 2017). One of the consequences of rapid economic growth is the immediate increase in energy consumption (K. Dong et al., 2018b; Y. Peng, Yang, & Scheffran, 2021; Y. Peng, Yang, Scheffran, et al., 2021). In China, the abundant coal resources and limited oil and natural gas have resulted in a coal-dominated (installed capacity of 1007 GW in 2018) energy structure, quadrupling since 2000 (IEC, 2018). It contributed, largely, to carbon emissions, and posed a significant challenge to the clean energy transition. In 2018, the carbon emissions resulting from the coal-fired power plants was 4.6 Gt (49.23% of China's total) (Zheng et al., 2022), which decreased to 1.4 Gt in 2020 (IEA, 2020). To wean from its heavy reliance on coal, China has been undergoing a reform of its power generation structure and seeking alternative clean energies (Paris Agreem., 2015). Low-carbon power plays a vital role in effectively controlling carbon emissions in the power generation system (NEA, 2016b, 2020).

For the low-carbon power plants' implementation, the spatial condition has been evidenced to be important by recent research and the energy transition history of China. The spatial availability of energy resources, especially renewable energy, determines the operating hours and generation capacity of the power plant (Voivontas et al., 1998). For instance, the geographic locations of crop residue supply areas are important for the bioenergy plant siting (Ali & Waewsak, 2019; Pergola et al., 2020; Soha et al., 2021), since the intermediate feedstock transportation influences the supply security of bioenergy resources (J. Zhu et al., 2020). Second, to avoid electric curtailment, the siting location of power plants should also consider the local electricity supply–demand market or the accessibility of high voltage power transmission grid (Solangi, Shah, et al., 2019; Yilan et al., 2020). In the early stages of China's energy transition, renewable energy plants with significant capacity were installed in the western and northern resource-rich regions (Van Holsbeeck & Srivastava, 2020). However, large amounts of electricity can neither be consumed by the local market nor efficiently transmitted to the economically developed eastern coastal regions due to the poorly constructed transmission grid. Until 2019, the power curtailment was reduced to 4% for wind power and 2% for solar power (NEA, 2020). Third, the ecological and social environment around the power plant site also needs to be considered since the pollution and noise generated by the power plant can affect the surrounding environment (Wenjun Chen et al., 2017; Feyzi et al., 2019; Rios & Duarte, 2021). Furthermore, specific political criteria should be, also, considered in some countries based on the localized political conditions, such as political stability are important for the case studies in Egypt (Shaaban et al., 2018).

Based on these spatial conditions, previous research evaluated the spatial energy resource potential (Ali & Waewsak, 2019; Feyzi et al., 2019) or identified preferable sites of power plants (Pergola et al., 2020; Solangi, Tan, et al., 2019) by implementing the GIS-based AHP. The assembly of GIS and the analytic hierarchy process are mutually complementary to reveal deeper cognition of aggregated spatial data (Ali & Waewsak, 2019). For instance, Derdouri et al. (Derdouri & Murayama, 2018) considered the environmental, social, and economic conditions to evaluate the wind farm suitability in Japan using the GIS-based AHP weighted linear combination and ELECTRE-TRI. The methodology has been widely used in practice and gained significance for different electricity generation technologies, including bioenergy (Pergola et al., 2020; C. N. Wang et al., 2019), municipal solid waste power (Feyzi et al., 2019), wind (Cunden et al., 2020; Jamshed et al., 2018; Xing & Wang, 2021; Y. Xu et al., 2020), solar (Solangi, Shah, et al., 2019; Tercan et al., 2021; Yousefi et al., 2018), and hydro (C.-N. Wang et al., 2019; X. Yan et al., 2019). Although, these independent studies can demonstrate the optimal site or suitable sites for their particularly focused type of power plant over a spatial extent. They cannot rank the spatial suitability of various power plants within the same spatial cell and didn't consider different land-carrying capacities (L. Yang et al., 2010). Clear instructions for comparing the spatial siting potential of low-carbon power plants are missing but needed to optimize spatial energy planning.

Therefore, I develop a mapping tool to illustrate a potential power plant landscape across alternative low-carbon powers in high-resolution spatial cells in the Yangtze River Delta region. I first define suitable areas in the study region for power plant installation. Second, I evaluate the spatial suitability of the implementation for alternative low-carbon power plants through GIS-based AHP. To enable a comparison of the spatial suitability of different power plants, I propose a suitability index scheme for the selected siting evaluation criteria. Data from the selected theoretical, environmental, economic, and social criteria have been collected, scaled, and processed as the criteria maps calculated by the ArcGIS AHP function (Taminiau et al., 2021). As a result, I obtain spatial siting potential maps of alternative power plants, which support decision-makers in better interpreting the complex problem of energy planning. This study represents a replicable example, which could be applied in other regions or in energy planning models, which contribute to future sustainable energy planning. The mapping tool can be valuable for energy planners and energy managers in the government or private sectors.

This chapter is organized as follows: Section 2.2 introduces the overall research process and the relevant methodological details. Section 2.3, firstly, illustrates the suitable area for sting power plants, and second presents the scaled suitability indices of different criteria. Finally, the results of the spatial siting potential of alternative low-carbon powers and the comparison of these spatial siting potentials are demonstrated. Section 2.4 discusses the research results by comparing them with previous literature. Finally, Section 2.5 concludes the remakes of this research and research outlook.

2.2 Materials and Methods

2.2.1 Study Area

In Figure 2.1, the Yangtze River Delta region (YRD) encompasses Shanghai, Jiangsu, Zhejiang, and Anhui (between 115–122° E and 27–35° N) and covers approximately 358×103 km^2 (Shanghai statistical bureau, 2020). In the YRD region, 16.65% of the national population contributed to 23.94% of China's national gross domestic product (GDP) in 2019 (calculated from the GDP statistical data sources: (Anhui statistical bureau, 2020; Jiangsu statistical bureau, 2020; Shanghai statistical bureau, 2020; Zhejiang statistical bureau, 2020)) in 3.69% of the national land area. YRD region consumed 20.53% of China's total electricity production in 2019 (calculated from the electricity consumption statistical data sources: (Anhui statistical bureau, 2020; Jiangsu statistical bureau, 2020; Shanghai statistical bureau, 2020; Zhejiang statistical bureau, 2020)), mainly supplied by local thermal power plants and electricity imported from the other regions. Furthermore, fossil fuel resources are also mostly imported into the YRD region. As the largest electricity consumer and importer, the YRD region faces the risk of electricity supply security. In 2020, the total power generation of the Yangtze River Delta region is 1226.8 GW, which accounts for 80.67% of the total electricity consumption. Of the total electricity generation, only 20.38% (250.06 GW) of electricity is generated from non-fossil sources (Tsinghua University, 2020). Under such a circumstance, renewable and nuclear power, which are not limited by regional resources, become a potential solution for improving the power generation capacity in the region to ensure energy supply security. The state council has developed integrated development goals of flexible power dispatching and low-carbon energy resource exploration for the overall region to promote electricity security in the medium or long term (General Office of the State Council, 2019). However, adequate feasibility visualized studies of spatial low-carbon energy are still necessary and scarce for energy planners.

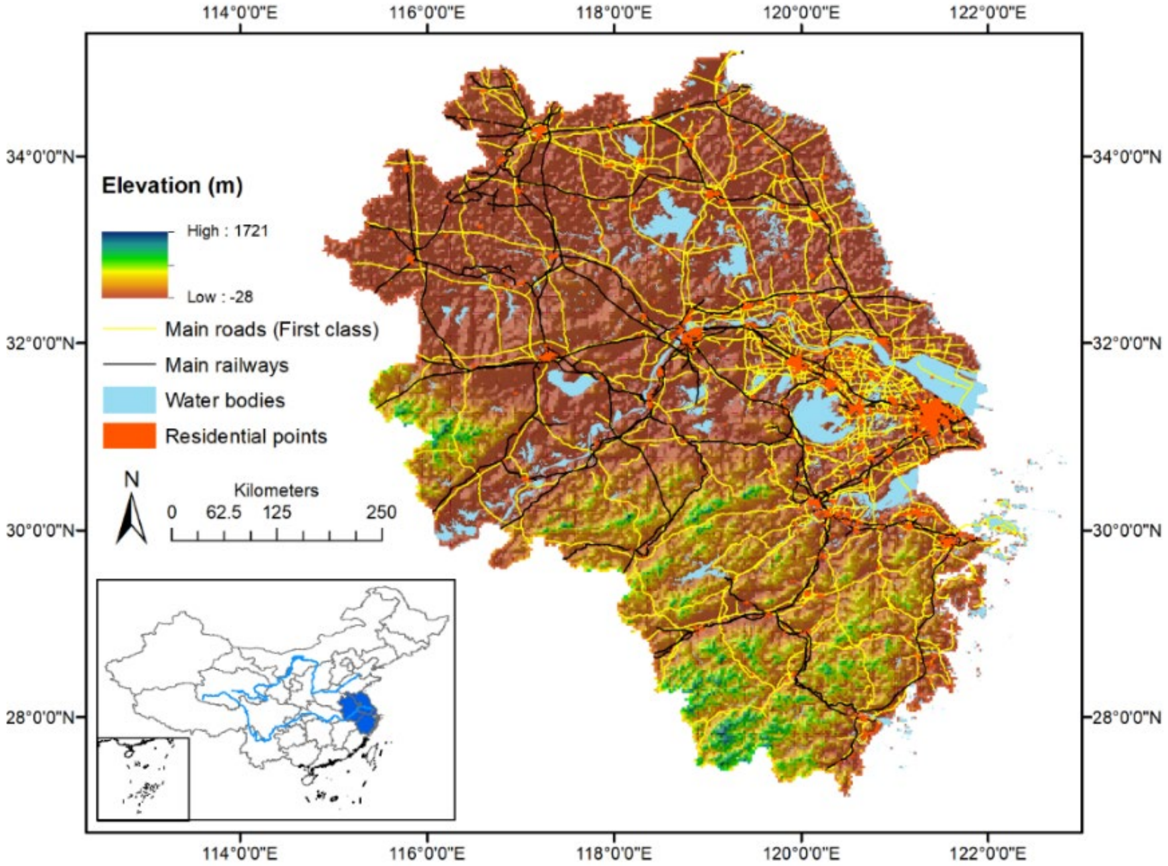


Figure 2.1 Study area—the Yangtze River Delta region.

2.2.2. Methodology

2.2.2.1. Methodology Framework

This paper selects seven types of low-carbon power plants as the research objects based on their developing potential in the Yangtze River Delta Region, including natural gas (NG) power, nuclear power, on-shore wind power, solar PV, pump-storage hydropower, biomass power, and waste-to-energy. I extend the approach of power plant suitable site selection for one specific power generation technology to a comparable spatial siting potential evaluation across alternative low-carbon power plants.

As shown in Figure 2.2, the study methodology is divided into two phases:

1. The first phase identifies the unsuitable zones through constraining rules formed by legal system provisions, technical difficulties, etc. derive the suitable zones by eliminating these unsuitable areas.
2. The second phase evaluates the spatial siting potential of alternative power plants in the suitable zones proposed by the first phase. It applies the GIS-combined AHP method to determine the value

and weight for evaluation criteria. The weighted sum value of the evaluation criteria is calculated to rank the spatial siting potential of alternative energy technologies.

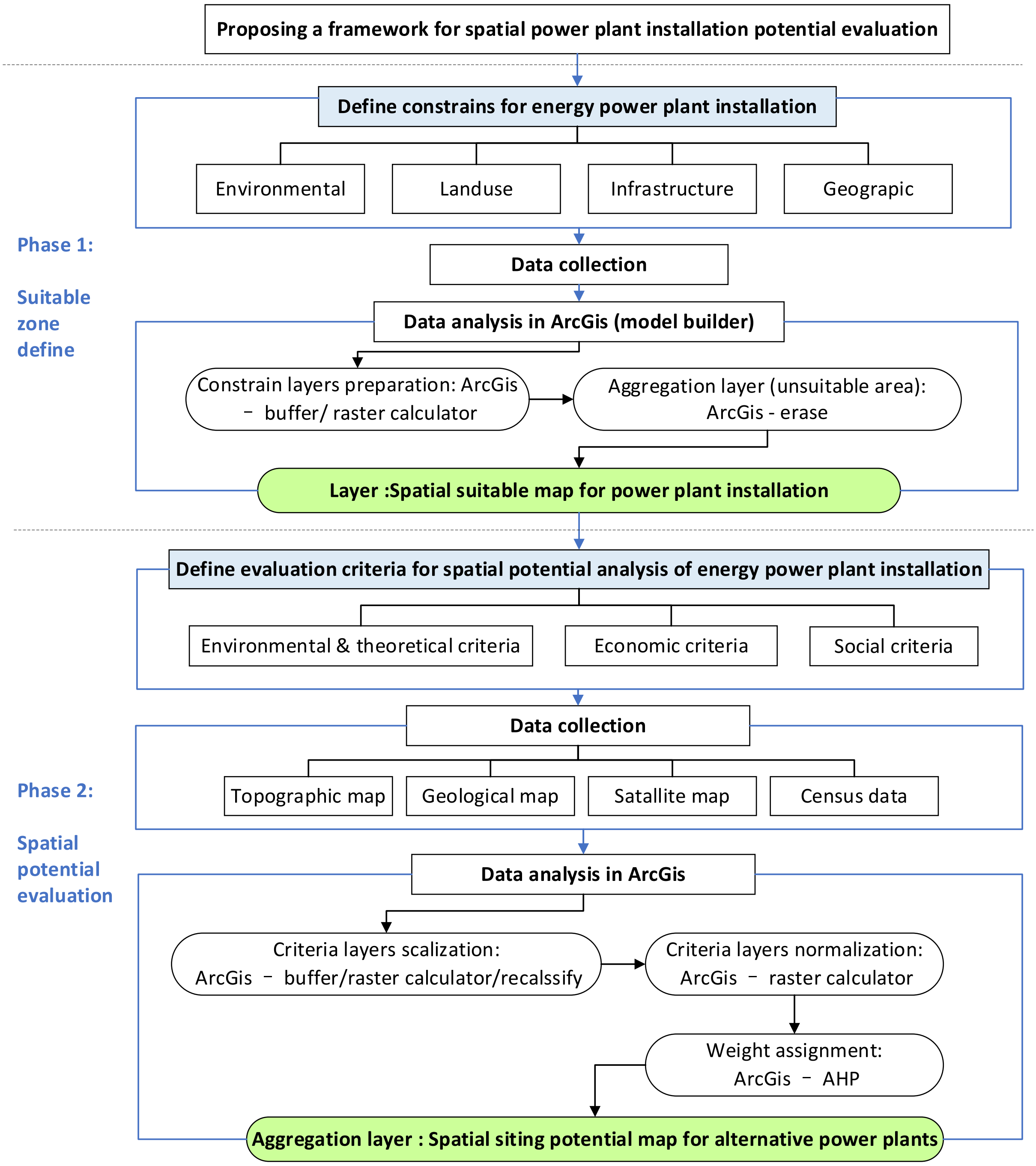


Figure 2.2 Flowchart of the methodology (adapted from Siefi et al. (2017)).

Phase 1 is used to exclude unsuitable areas. However, suitable areas do not refer to the high potential areas of the power plant installation, but only the areas where implementation is allowed from a technical and legislative perspective. In comparison, even if the power plant siting potential is highly ranked by Phase 2 in the spatial cells, the insurmountable impediments created by the constraints (Phase 1) shut down the possibility to install power plants. Therefore, the combination of Phases 1 and 2 is necessary. Suitable areas from Phase 1 would join the spatial siting potential evaluation in Phase 2. The whole process would eventually lead to an overall siting potential evaluation for each type of low-carbon power plant in each spatial cell.

2.2.2.2. Identification of Suitable Zones

This phase identifies the suitable zone for energy power plant siting by eliminating unsuitable zones resulting from several constraining factors. The constraining factors shown in Table 2.1 derive from the existing legal and institutional regulations and the literature review concerning the impact of power plants on the natural and human environment and the technical difficulties in power plant siting. According to the listed constraints, each restrictive layer is generated by the "buffer" analyzing tool. The constraints could be illustrated through individual GIS map layers, and an aggregated suitable zone map is generated by "erasing" the unsuitable zone from the original study area.

Table 2.1 Constraining factors of the unsuitable zones.

Constraining factor	**Constraining parameter**	**Constraining map layer**	**Buffer zone (Unsuitable area)**	**Ref**
Environmental reason	Distance to water and rivers	Constraining map to distance to permanent rivers and lakes	$D < 500$ m	(General Office of the State Council, 2019)
	Distance to protected areas	Constraining map to distance to national and regional natural ecosystem reserves, wildlife refuges, and nature reserves	$D < 300$ m	(General Office of the State Council of the People's Republic of China, 2011)
Land use reason	Distance to the residential area	Constraining map to distance to residential areas Area > 1000 km^2 (megacity)	$D < 5$ km	(Sliz-Szkliniarz & Vogt, 2011)
		Constraining map to distance to residential areas 400 km^2 ≥ Area >100 km^2 (large and median cities)	$D < 2$ km	(Yousefi et al., 2018)
		Constraining map to distance to residential areas Area ≤ 100 km^2 (small towns and rural areas)	$D < 500$ m	(Sliz-Szkliniarz & Vogt, 2011)
Infrastructure reason	Distance to roads	Constraining map to distance to motorways, firs-class roads, secondary roads, and tertiary roads	$D < 50$ m	(Panagiotidou et al., 2016)
	Distance to railways	Constraining map to distance to major railways	$D < 50$ m	(Panagiotidou et al., 2016)
	Distance to grid	Constraining map to distance to high-voltage electricity grids (Voltage > 100,000 Volt)	$D < 50$ m	(Panagiotidou et al., 2016)
Geographic reason	Slope	Constraining map to slope percentage	>30%	(Derdouri & Murayama, 2018)
	Elevation	Constraining map to the altitude	>2000 m	(Yousefi et al., 2018)

The first constraining factor resulted from the impact of power plants on the environment during the construction and operation period. In the parameter of distance to protected areas, the constraint comes down to national legislation. Production and operation activities are prohibited in protected areas and limited in the peripheral area (300 m) of the protection zone (General Office of the State Council of the People's Republic of China, 2011). Second, unsuitable zones are determined by land-use conflict. Most research excludes the urban area and its buffer zones between 1.5 km to 2 km (Panagiotidou et al., 2016; Sliz-Szkliniarz & Vogt, 2011; Yousefi et al., 2018). In the study area, the city scale varied from smaller than 100 km^2 to over 1000 km^2 (Shanghai). The urbanization speed of these cities with different scales significantly correlated to per capita GDP and industrial level (Lin et al., 2018). Cities with larger sizes and higher per capita GDP, thus, have the potential to expand more speedily than small cities. Thus, the constraining parameters of distance to the residential areas are differentiated with the city size from 500 m for small towns and rural areas (smaller than 100 km^2) to 5 km for Shanghai megacity (over 1000 km^2). Third, the potential visual and sound impacts of power plants could influence the surrounding infrastructures. Thus, it is necessary to consider such neighboring areas (< 50 m) as limiting. In addition, the difficult access areas, including steep slopes larger than 30% and high elevations larger than 2000 m, are not suitable to install power plants from the technical and economic perspectives (Derdouri & Murayama, 2018; Yousefi et al., 2018).

2.2.2.3. Evaluation Criteria and AHP

In the second phase, the power plant siting potential is evaluated by the most important criteria that affect power plant siting. Figure 2.3 presents the analytic hierarchy process of power plant siting potential evaluation in spatial cells. The nine sub-criteria are energy potential, slope, elevation, proximity to the road, proximity to high voltage grid, proximity to surface water, energy demand, population density, and ecological and environmental impact. In this research, a cell size of 0.025 × 0.025 degrees is used in the study area. Each spatial cell is evaluated by the selected criteria. An integrated grade, which represents the potential to accommodate alternative energy power plants, would be generated through an analytical hierarchy process.

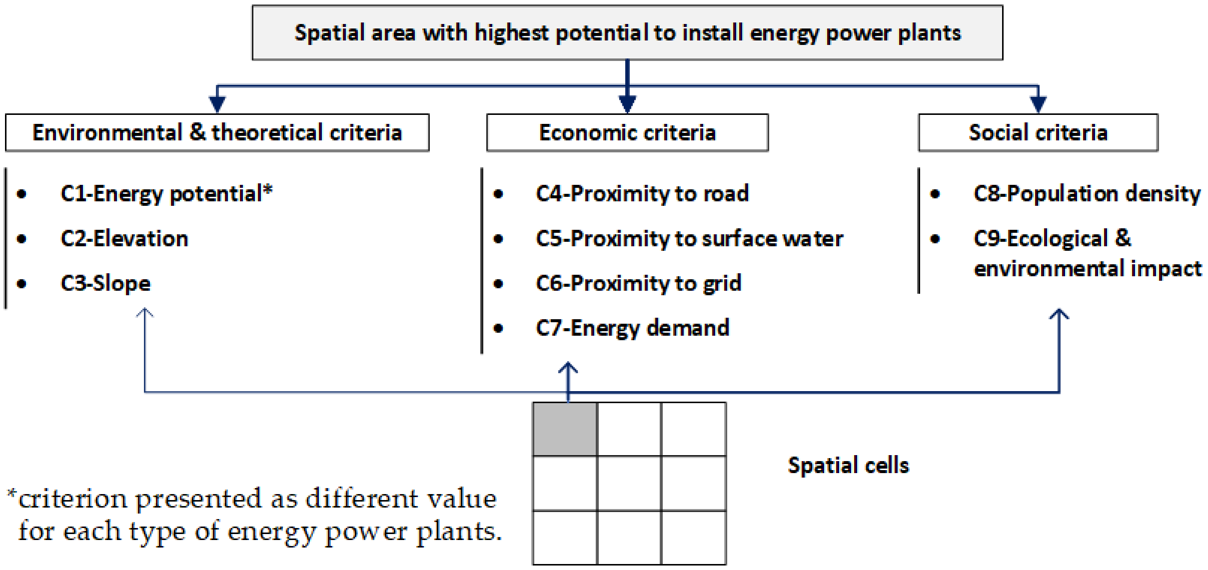


Figure 2.3 The analytic hierarchy of spatial siting potential evaluation.

Since the evaluation criteria are measured by different units or scales, it is necessary to transform these layers into comparable units. In this research, I propose a suitability index scheme (Table 2) to score the spatial area from 1 (low) to 10 (high) based on each evaluation criterion. This suitability degree index scheme is established through literature reviews by comparing the suitability of evaluation criteria from previous research. Table 2 shows the detailed scoring of each criterion.

C1-energy potential * presents the energy potential of each type of power plant. The scoring method differentiates between renewable and non-renewable energy. In particular, the environmental and theoretical criterion of energy potential is essential for renewable power plants. The suitable areas are graded based on renewable resources potentials, such as Global horizontal irradiance (GHI) for solar

PV power plants and wind power density for wind power plants (Baseer et al., 2017; Wenjun Chen et al., 2017; Xing & Wang, 2021). In addition, there are minimum thresholds (an index of zero) to establish renewable power plants. Previous literature stated that spatial areas with wind power density of less than 150 W/m^2, technically, have no potential (score 0) to install a wind power plant (Junfeng Li et al., 2007; J. Yang et al., 2017). For solar PV, the minimal requirement is 1000 kWh/m^2. Unlike renewables, the energy potential (C1) is rather complex depending on the aggregated influences of accessibility to fuel (Nuclear Energy Agency; International Atomic Energy Agency, 2016), the spatial location of previous power plants, and others. The installed power plants have the highest potential to be extended. As an example, I defined the spatial areas within 5 km around the previous nuclear power plants as the most suitable areas with a suitability index of 10. In addition, nuclear power plants are necessary to be considered implemented in the 10 km buffer inland area of coastal, resulting from its requirement of the high cooling efficiency of seawater (Gao et al., 2018).

C2–elevation and C3–slope impact the spatial suitability of low-carbon power plants from both economic and technical aspects (Odhiambo et al., 2020; Taminiau et al., 2021). High latitudes and steep slopes lead to high transportation costs and create technical challenges for power plants' installation (Soha et al., 2021; Van Holsbeeck & Srivastava, 2020). Many reviewed scientific studies have identified different ranges of suitable elevation and slope values for different power plants (Derdouri & Murayama, 2018; Ferretti & Pomarico, 2012; Odhiambo et al., 2020; Rojanamon et al., 2009; Siefi et al., 2017). In particular, Yousefi et al. (Yousefi et al., 2018) proposed a slope threshold value of 10° for solar power, and Ali et al. (Ali & Waewsak, 2019) proposed 15° for biomass power plants. This research uses the most applied ranges of suitable elevation and slope as a common standard. The lowest score of slopes is assigned to the area steeper than 17% (10°). Suitability scores increase with the stepwise decreased value of C2 and C3.

The proximity to roads (C4), surface water (C5), and ultra-high voltage grids (C6) are closely related to the costs of the construction and operating stage. Proximity to the transporting and transmission infrastructure could reduce costs and avoid electricity loss (Jamshed et al., 2018; Solangi, Tan, et al., 2019; Wu et al., 2018). Therefore, the whole region is classified along with the distance to the road connections, ultra-high voltage grid (voltage >= 1000 kV), and surface water resources. The maximum threshold has been set for C4 (proximity to roads) by Yousefi et al. (Yousefi et al., 2018) and Ali et al. (Ali & Waewsak, 2019). They considered the area without road connections in the 10 km surrounding area as the lowest suitable area. I applied this threshold in this research and assigned the area with an index of 1. Similar thresholds "10 km" were also applied for criterion C6 (proximity to ultra-high voltage grids) in many previous studies (Jamshed et al., 2018; Yousefi et al., 2018). Therefore, the areas beyond 10 km from the ultra-high voltage grids were assigned with the lowest index of 1.

In addition, the other economic criterion is energy demand (C7). Panagiotidou et al. (Panagiotidou et al., 2016) state that "the proximity of production and consumption could reduce energy losses caused by the electricity distribution". Thus, it is valuable to consider the electricity demand of local markets (Chien et al., 2020; Jeong & Ramírez-Gómez, 2018). Power plants are suggested to be located as closely as possible in areas with high energy demand to minimize electricity losses during transmission (Derdouri & Murayama, 2018). The highest score of C7 is assigned to the triangle-shaped megalopolis led by Shanghai, with an annual energy demand value larger than 7500 MWh/km^2.

Unlike the economic criteria, social criteria (C8—population density and C9—ecological and environmental impact), negatively affect spatial subtility (Wenjun Chen et al., 2017; Heng ming et al., 2020; Panagiotidou et al., 2016; Solangi, Tan, et al., 2019; Wu et al., 2018). Power plant siting will cause pertinent inferences (emissions, pollutions, and visual and sound impacts) on nearby areas during the construction and operation stages (X. Li et al., 2019; Ramos et al., 2018). Derdouri and Murayama (Derdouri & Murayama, 2018) suggested establishing new power plants away from the populated and natural protected area to avoid conflict with residents and guarantee natural conservation (Solangi, Tan, et al., 2019). The most populated areas with a population density larger than 3000/km^2, such as Shanghai, are probably unsuitable for power plants (Score 1). The area around the protected area with a distance greater than 5 km has a high score of 9.

Table 2.2 Scoring scheme of criteria map layers.

Criterion	**Map Layer**				**Low**			**Medium**			**High**	
Index		0	1	2	3	4	5	6	7	8	9	10
C1—NG potential	NG plant and Distance to NG pipeline (km)	-	>40	-	30–40	-	20–30	-	10–20	-	<10	NG plant and 5 km buffer area
C1—Nuclear potential	Nuclear plant and Distance to uranium ore (km)	-	-	-	>400		200–400	-	<200	-	-	Nuclear plant and 5 km buffer area
	Coastal buffer (km)	Coastal areas and 10 km buffer areas										
C1—Wind potential	Wind power density in 100 m (W/m^2)	<150	150–200	200–250	250–300	300–350	350–400	400–450	450–500	500–550	550–600	>600
C1—Solar potential	Annual GHI (kWh/m^2)	<1000	1000–1050	1050–1100	1100–1150	1150–1200	1200–1250	1250–1300	1300–1350	1350–1400	>1400	-
C1—Hydro potential	Contour (5 m) density	100	100–300	-	300–500	-	500–700	-	700–900	-	>900	power plant and 10 km buffer
	River buffer	River and 10 km buffer area										
C1—Biomass potential	Agricultural and forest land kernel density	-	<100	100–300	300–500	500–700	700–900	900–1100	1100–1300	1300–1500	>1500	-
C1—WTE potential	Annual house refuse density (tons/km^2)	-	<150	-	150–300	-	300–450	-	450–600	-	>600	-
C2	Elevation (m)	-	1700–2000	1500–1700	1300–1500	1100–1300	900–1100	700–900	500–700	300–500	100–300	0–100
C3	Slope (%)	-	17–30	15–17	13–15	11–13	9–11	7–9	5–7	3–5	1–3	<1
C4	Proximity to road: motorway, 1st, 2nd, 3rd (m)	-	>	-	7500–1000	-	5000–7500	-	2500–5000	-	<2500	-
C5	Proximity to waterbody(m)	-	>	-	7500–1000	-	5000–7500	-	2500–5000	-	<2500	-
C6	Proximity to powerline with voltage> 1000 v (m)	-	>	-	7500–1000	-	5000–7500	-	2500–5000	-	<2500	-
C7	Energy demand (MWh/km^2)	-	<900	-	900–1600	-	1600–3000	-	3000–7500	-	>7500	-

C8	Population density (pop/km^2)	-	≥3000	-	1500–3000	-	1000–1500	-	500–1000	-	<500	-
C9	Protected zone buffer (m)	-	-	-	-	-	<5000	-	-	-	≥5000	-

The relative importance of criteria is determined through literature reviews. Then, according to the pairwise relative importance of criteria for each type of power plant, the comparison matrixes are generated for each type of clean power plant. The resulting weights of criteria for each type of power plant are shown in Table 2.3.

Table 2.3 Weight of criteria for energy power plants.

	NG	**Nuclear**	**Wind**	**PV**	**Hydro**	**Biomass**	**WTE**
$\boldsymbol{W_{C_1}}$	0.1005	0.2811	0.2734	0.2470	0.2552	0.2787	0.2367
$\boldsymbol{W_{C_2}}$	0.0438	0.0644	0.0788	0.0811	0.0215	0.0306	0.0891
$\boldsymbol{W_{C_3}}$	0.0671	0.0343	0.1882	0.1207	0.0492	0.0572	0.2398
$\boldsymbol{W_{C_4}}$	0.0575	0.0644	0.1039	0.0664	0.1455	0.0306	0.1040
$\boldsymbol{W_{C_5}}$	0.0327	0.0644	0.0259	0.0253	0.0656	0.2787	0.0615
$\boldsymbol{W_{C_6}}$	0.0232	0.0601	0.0579	0.2118	0.2134	0.0513	0.0234
$\boldsymbol{W_{C_7}}$	0.2251	0.0245	0.1386	0.0471	0.1304	0.1441	0.0238
$\boldsymbol{W_{C_8}}$	0.2251	0.2351	0.0306	0.0335	0.0327	0.0980	0.1453
$\boldsymbol{W_{C_9}}$	0.2251	0.1717	0.1026	0.1672	0.0865	0.0306	0.0764

Table 2.3 shows that C1 is more important for renewable and nuclear power plants. This is due to the heavy reliance on spatial energy resources of renewable powers. For nuclear power, I include the distance to costal as an important indicator of energy potential. Thus, the nuclear power siting is also highly reliant on C1—energy potential. Unlike renewable power plants, which are more sustainable and play an important role in the future energy transition, the NG power plant is less sustainable but more secure in electricity supply. Therefore, the weights of energy demand (C7) and social indicators (C8 and C9) of NG power plant are higher than other indicators.

2.2.2.4. GIS Dataset Acquisition and Processing

According to the AHP framework, I present the evaluation criteria as GIS maps. The initial data sources for map layer preparation include the 1:1,000,000 scale geographic information map, remote sensing land use map, topographic radar map, renewable energy resources map, location map of existing power plants, open street map, and annual statistical data (Table 2.4). To be more specific, the initial data resources are projected, re-sampled, and spatially analyzed to be in the same format with the same extent and cell sizes to present the criteria.

I further scale the criteria map layers with continuous or discontinuous data based on the suitability degree index. Based on the proposed suitability degree index scheme, each criterion's values are classified into several ranges by using a "multi-buffer" or "reclassify" function of ArcGIS. For instance, I use the multi-buffer function to grade the spatial potential according to the radial distances from the main roads, surface water, and high-voltage electricity grids (C4–C6).

By adding up these graded multiple evaluation map layers according to their weight through the AHP function of ArcGIS, I obtain the spatial siting potential of different low-carbon powers.

Table 2.4 GIS data sources for criteria map layers.

Criteria	Map Source	Map Layer	References
C1—NG potential	Location of power plants; Spatial allocation of natural gas pipeline	Natural gas power plants and their buffer area; Distance to pipeline	(Google Global Energy Observatory & KTE Royal Institute of Technology in Stockholm World Resources Institute Enipedia, 2018; NDRC & NEA, 2017)
C1—Nuclear potential	Location of power plants; The map of mineral resource distribution; Boundary map	Nuclear power plants and their buffer area; Distance to uranium ore; Distance to coastal areas	(Google Global Energy Observatory & KTE Royal Institute of Technology in Stockholm World Resources Institute Enipedia, 2018; Ministry of natural resources of the People's Republic of China, 2020)
C1—Wind potential	Mean wind power density at an altitude of 100 m	Mean wind power density	(World bank & Technical University of Denmark, 2019)
C1—Solar potential	Annual global horizontal irradiance	Global horizontal irradiance (GHI)	(Solargis & World Bank, 2019)
C1—Hydro potential	SRTM 90 m Digital Elevation Database	Streams; Elevation drop	(Geospatial Data Cloud site et al., 2018)
C1—Biomass potential	Global land 30	Agricultural and biomass density	(Ministry of natural resources of the People's Republic of China et al., 2020)
C1—WTE potential	Statistical yearbooks of county-level administrative regions	Annual house refuse density	(Anhui statistical bureau, 2020; Jiangsu statistical bureau, 2020; Shanghai statistical bureau, 2020; Zhejiang statistical bureau, 2020) *
C2—Elevation	SRTM 90 m	Elevation	(Geospatial Data Cloud site et al., 2018)
C3—Slope	SRTM 90 m	Slope	(Geospatial Data Cloud site et al., 2018)
C4—Proximity to roads	Road map	Distance to motorways, first-class roads, secondary roads, and tertiary roads	(National Catalogue Service For Geographic Infomation, 2015)
C5—Proximity to surface water	River map Waterbody map	Distance to rivers and water bodies	(National Catalogue Service For Geographic Infomation, 2015)
C6—Proximity to grids	Electricity grid map	Distance to high-voltage electricity grids	(OSM, 2019)
C7—Energy demand	Statistical yearbooks of the county and city-level administrative regions	Annual electricity demand density at city and county levels	(Anhui statistical bureau, 2020; Jiangsu statistical bureau, 2020; Shanghai statistical bureau, 2020; Zhejiang statistical bureau, 2020)*
C8—Population density	Spatial population distribution of China in 1 km	Spatial population distribution of resampled grid	(Xingliang, 2017)
C9—Ecological/ environmental impact	Protected zone map	Protected zone buffer	(National Catalogue Service For Geographic Infomation, 2015)

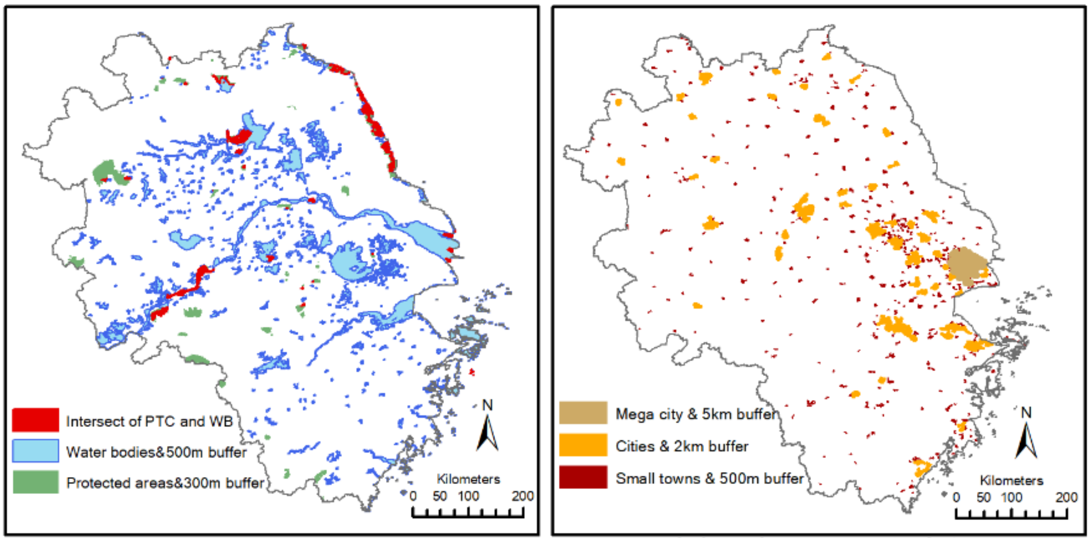
* More data from 2019 statistical year books at the city or county level have been included.

2.3 Results

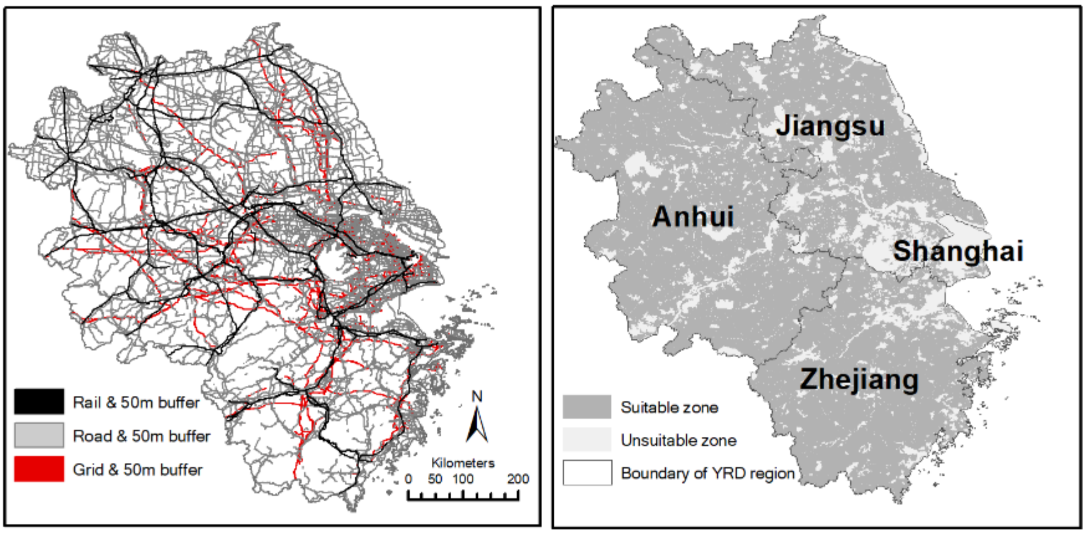
2.3.1. Map of Suitable Zone

As Section 2.2.2.1 described, the unsuitable zone for power plant siting should be excluded in phase 1. Figure 2.4 shows the unsuitable area due to each constraint and the rest areas, which are suitable for the establishment of power plants.

Only three constraints (environmental, land use, and infrastructure constraints) have resulted in unsuitable areas in the study area. The Yangtze River Delta region, located in the middle and lower Yangtze Valley Plain, has the highest spatial cell of 1721 m and the steepest cell of 17.93%. Thus, no area is excluded due to geographical constraints. The other three constraining maps (Figure 2.4a–c) define the areas where power plant siting is legally, technically, or environmentally prohibited. The unsuitable areas result from environmental constraints (Figure 2.4a), land use constraints (Figure 2.4b), and infrastructure constraints (Figure 2.4c). By eliminating the three overlying unsuitable zone in the study region, Figure 2.4d results from the rest unsuitable zones. The unsuitable area for power plants siting is calculated through the “zonal geometry” function of GIS. As a result, 21.78% of the whole region is defined as unsuitable areas, and the rest 78.22% areas are suitable. A large area of Shanghai is excluded because it is a mixed area of the mouth of the Yangtze River and the highly populated megacity of Shanghai.



a.Environmental constraints b.Land use constraints



c.Infrastructure constraints d.Integrated unsuitable and suitable area

Figure 2.4 Suitable zones.

2.3.2. Map of AHP Evaluation Criteria

To obtain the normalized AHP spatial siting potential map of alternative power plants, I first create spatial theoretical energy potential (C1) maps (Figure 2.5) for alternative power plants. Second, the spatial suitability maps for the other evaluation criteria (C2–C9) (Figure 2.6) are created according to the suitability index in Table 2.3.

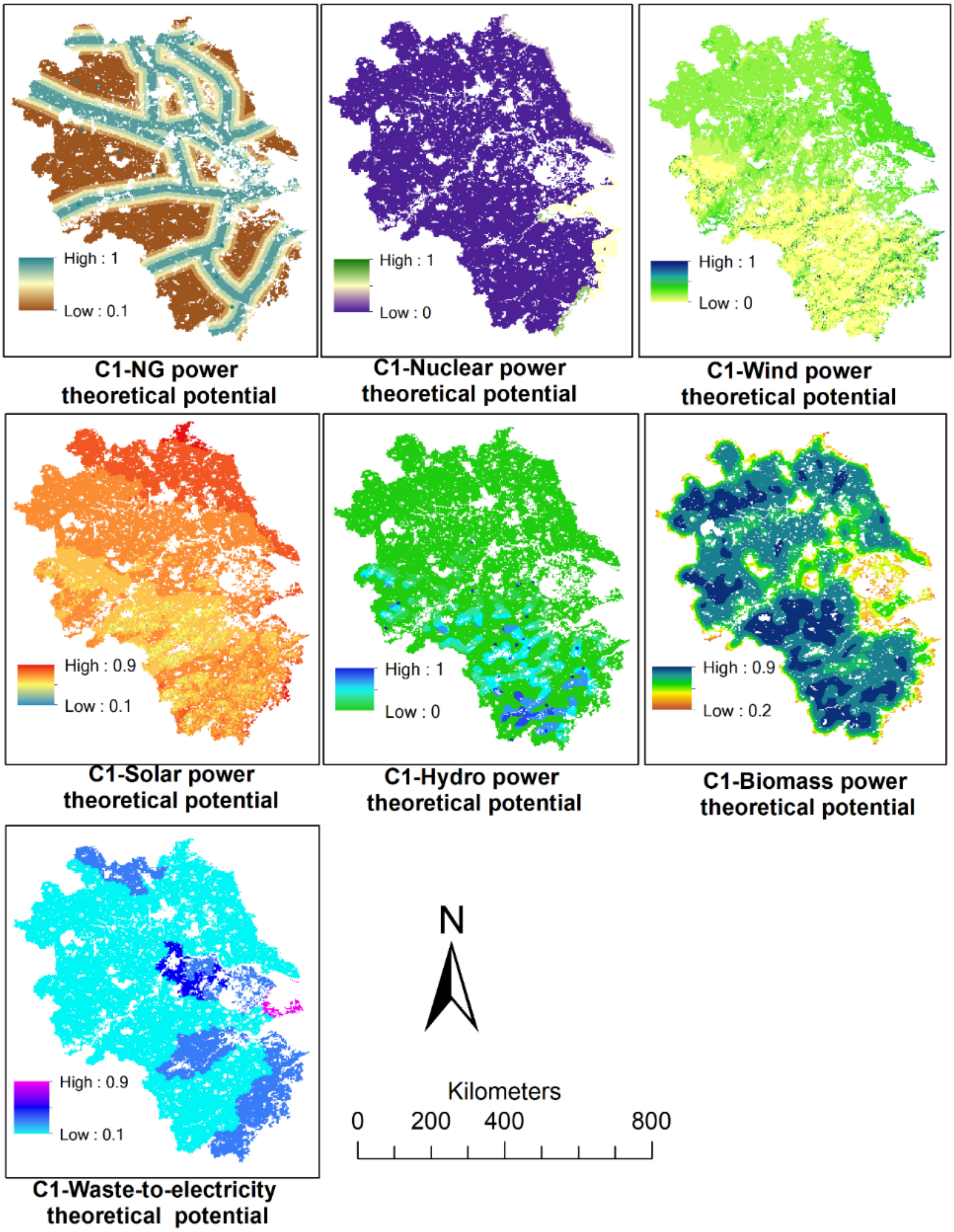
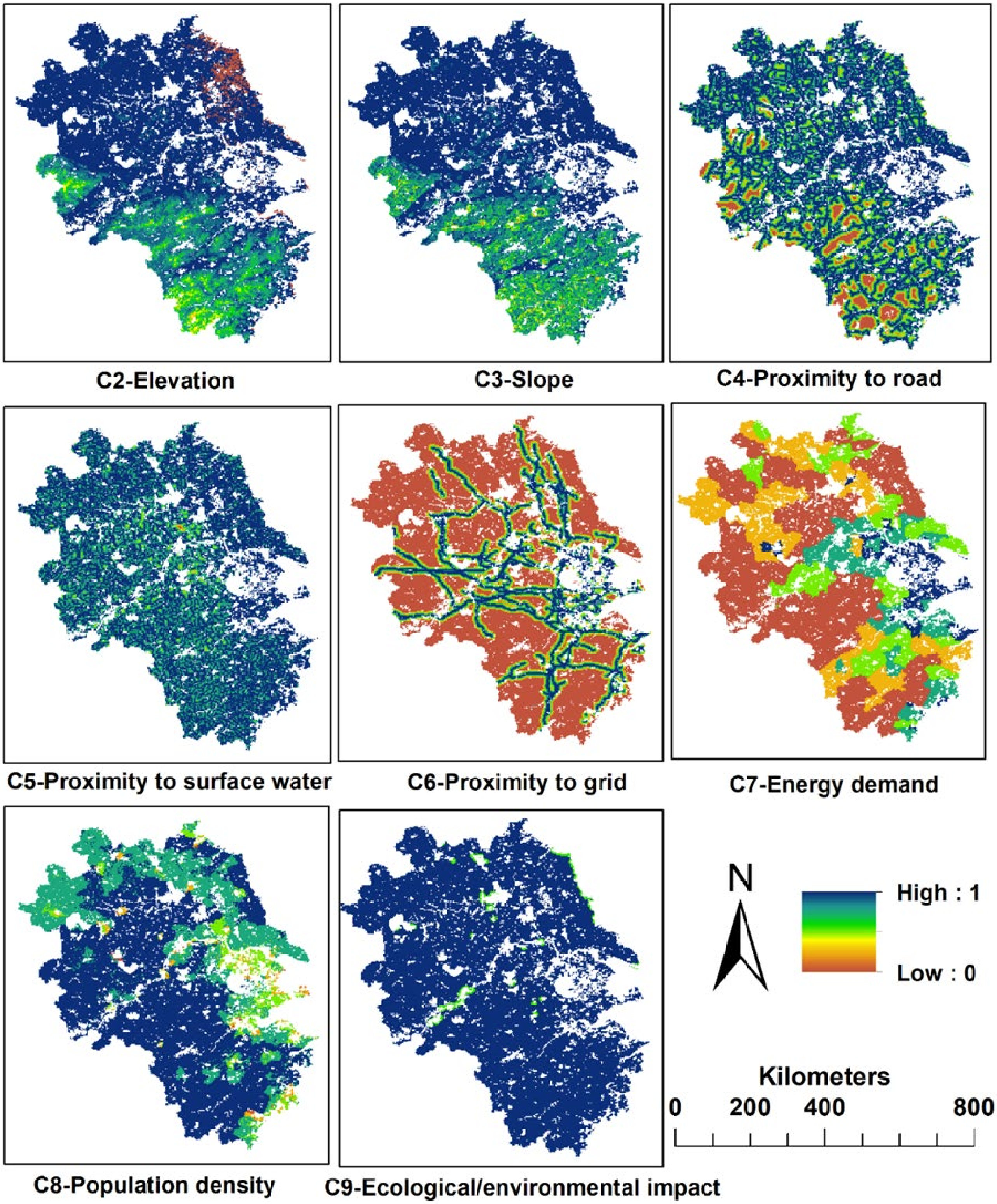


Figure 2.5 Spatial theoretical energy potential (C1) maps of alternative power plants.


C2-Elevation

C3-Slope

C4-Proximity to road

C5-Proximity to surface water

C6-Proximity to grid

C7-Energy demand

C8-Population density

C9-Ecological/environmental impact

Figure 2.6 Spatial suitability maps of evaluation criteria (C2–C9).

Figure 2.5 presents the result of spatial theoretical energy potential (C1) for each type of low-carbon energy power. The first map of NG power theoretical potential shows that areas with highly suitable indexes (> 0.8) are concentrated near the NG pipeline. This is due to the fact that this area could better assess the imported NG resources from other regions or other countries. In the second map, the theoretical energy potential of nuclear power highly depends on the distance from the sea. Only the coastal area has theoretical potential to establish nuclear power plants. The south coastal region has a higher potential than the north coastal region due to the higher accessibility to uranium resources, which is essential for nuclear power plants. The third map of wind power theoretical potential shows that the overall region has low wind power potential. Most of the areas are assigned with a suitable index lower than 0.4 (wind density < 300 W/m^2), and the suitability index decreases from northeastern to southwestern areas. The northeast coastal area of the YRD region has the highest wind power theoretical potential because it is close to the sea with high stable wind speed and regular wind direction changes (X. Wei et al., 2018). Similar to the wind power theoretical potential, the solar power theoretical potential also decreases from northeastern to southwestern areas. Nevertheless, solar energy resources are richer than wind power resources. Most areas in the solar energy potential map are assigned with a suitable index higher than 0.6, presenting the annual GHI larger than 1250 kWh/m^2. The fifth map of hydropower potential shows that only a small riverside area in the south with a significant elevation drop has a highly suitable index (>0.8). The sufficient river discharge from the perennial river and significant natural elevation drop in these areas provides geographical benefits for establishing hydropower plants (Bódis et al., 2014; Ingason et al., 2008). The remaining area with flat terrain has a very low theoretical potential for hydro powers. In the biomass power potential map, it is easy to find that biomass resources are abundant in the overall study area, which could easily satisfy the feed-in stock of biomass resources for biomass plants (Ali & Waewsak, 2019; Pergola et al., 2020). Most of the area has been ranked over 0.8, which is highly suitable for biomass plants. However, in China, the high crop demand has limited the development of biomass powers. In the last WtE theoretical potential map, results rely highly on the spatial distribution of house refuse density. Although the metropolitan and large cities, such as Shanghai and Hangzhou, have been eliminated as unsuitable areas, the areas surrounding these cities have a higher potential for establishing WtE sites. This is due to the high population density and the high production of domestic waste in the areas surrounding large cities. Conversely, in counties and small cities, the population density is much lower, and the generated domestic waste is only sufficient for a few WtE plants. Therefore, the theoretical potential of waste-to-energy plants is very low in these areas.

Unlike C1, determined mainly by different conjunct factors, criteria C2 to C9 only depend on the individual criterion as it is named. Figure 2.6 shows the resulting map of C2 to C9. From the map, I can easily find that the high suitability indexes of C2 and C3 exist in the flat area in the northeast of the YRD region. It results from the geographic characteristic of the northeast of the YRD region, which locates in the middle and lower Yangtze natural alluvial plain. The region is low and flat, so the values of elevation and slope are low, indicating high suitability for power plant siting (Feyzi et al., 2019; Odhiambo et al., 2020). However, the southwest of the YRD region is covered by hilly areas, which is less suitable for power plant implementation. Except for the geographic advantage, the east region is also highly urbanized (W. Zhao et al., 2020), including Shanghai, Suzhou, and Hangzhou, and has a well-developed transportation system and power transmission grids. Therefore, in the map of C4 and

C6, the east areas are most suitable to implement power plants. To be more specific, most areas of the YRD region are close to the roads, except for some hilly areas in the south. By the same token, the north and west are more urbanized and more economically developed with higher population and energy demand (Yan Wang et al., 2018). For criteria, C7 and C8, the north and east areas have a higher suitability index than the south and west areas. In the map of C5 and C9, most of the areas are assigned with high suitability indexes. The research area with the Yangtze River and Tai Lake is rich in water resources (Bu & Luo, 2014; Yan Wang et al., 2018). There are also high-density tributaries, which distribute water to the whole region. Thus, it is easy to access surface water in the overall region. As for C9, only the impacts on the nearby areas of protected regions are considered, so that most of the areas in the region have a high value.

2.3.3. Map of Spatial Power Plant Siting Potential

The aggregated spatial siting potential maps from evaluation criteria C1–C9 of alternative power plants are shown in Figure 2.7. The map shows that areas with higher siting potential of different low-carbon powers are distributed very differently in the study area. This is due to the different spatial theoretical energy potential and different weight matrices of evaluation criteria for each type of power plant. Regarding the different weighting matric of alternative power plants, the spatial siting potential of power plants is rated differently from low to high (0–1). The areas with high siting potential of NG power plants are concentrated in the east because of the well-developed pipeline (C1) and high electricity demand (C7). The theoretical energy potential (C1) is also crucial for renewable and nuclear power plants. Therefore, the highest potential siting value for nuclear power is seen in the southern coastal area; the high potential value of wind power plant siting is seen in the northeastern area with rich wind resources; the high potential value of WtE power plant siting is seen in the nearby area of urban agglomeration. In addition, renewable power plants have higher siting potential in areas with a high suitability index of proximity to grids (C6), especially solar and hydropower plants. It is because renewable energy requires a transmission grid to minimize the financial cost of electricity storage devices.

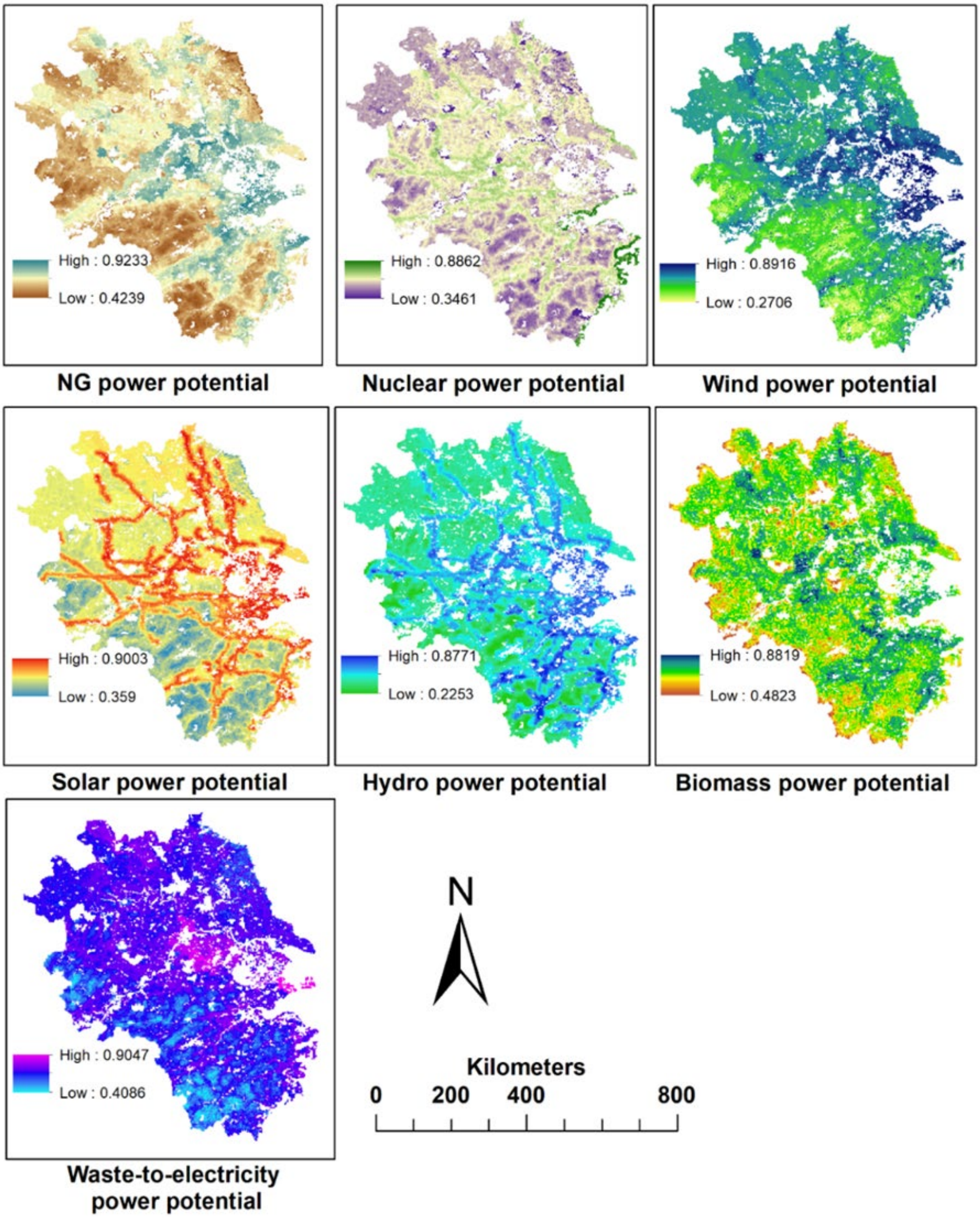


Figure 2.7 Spatial siting potential maps of alternative power plants.

The resulting spatial siting potential map shows the rated spatial siting potential scores of alternative power plants in each cell. The siting potentials of different low-carbon power plants can be compared in each spatial cell. Since the number of cells is very large, I select one random cell as an example in Figure 2.8, which shows the varied siting suitability of alternative power plants in one cell. The same cell is highly suitable for NG and WtE power plants but less suitable for pumped-storage hydropower and nuclear power plants. It could explicitly guide the decision makers' choice of power plants in each spatial cell.

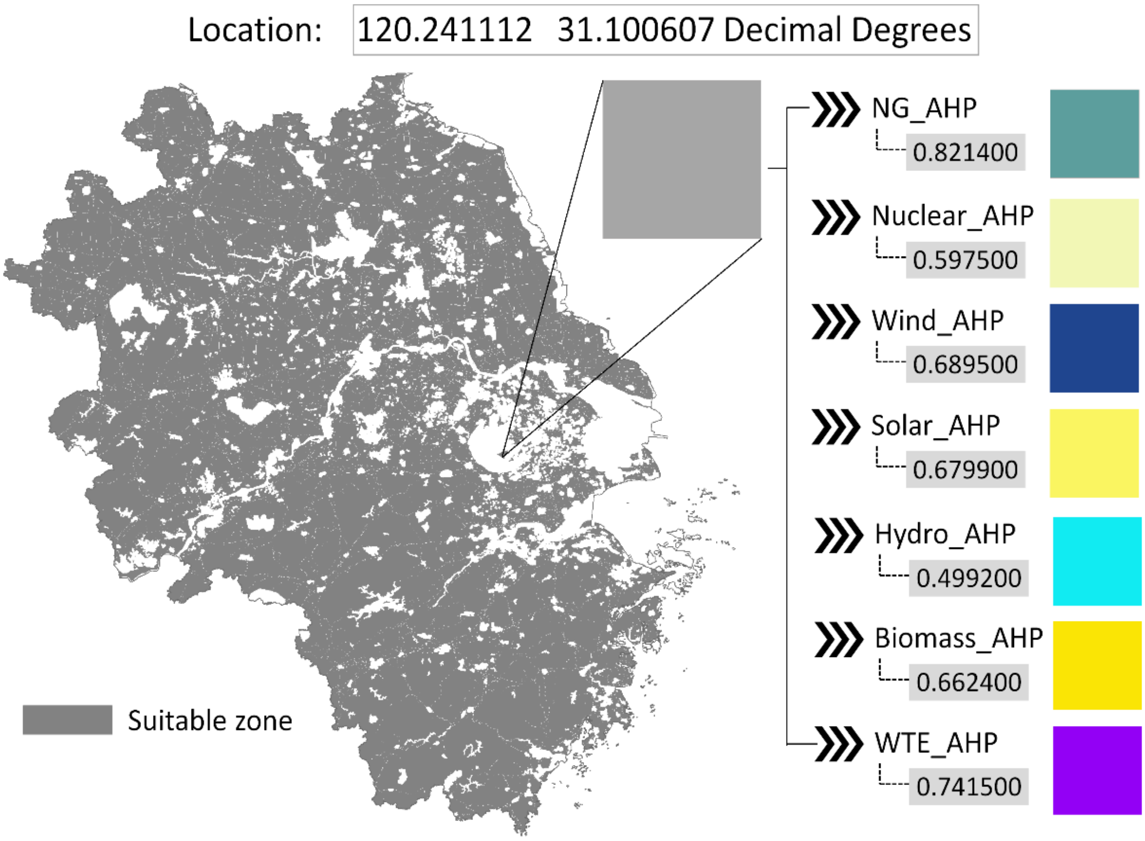


Figure 2.8 Spatial siting potentials of alternative power plants in one cell.

2.3.4. Comparison of Spatial Siting Potential of Alternative Power Plants

To compare the spatial siting potential of different power plants, the "zonal geometry" function of ArcGIS has been used to calculate the spatial area of different potential scales for each type of power plant. Table 2.5 shows the percentage of the area in each potential scale out of the suitable area for alternative power plants.

For hydro, nuclear, and wind power plants, more than 90% of the suitable area is assigned with low to medium potential, resulting from the low theoretical potential. The low theoretical potential of hydropower results from the non-significant elevation drops. Without significant elevation drops, the gravitational potential energy of the water discharge is less, which cannot be adequately converted into electrical energy (Bódis et al., 2014). The nuclear and theoretical wind potentials are, respectively, limited by the seawater accessibility and the annual wind power density in 100 m above the ground. In contrast, for NG, solar, biomass, and WtE powers, more than 30% of the suitable area is considered as high potential areas. For solar, biomass, and WtE powers, there is a stretch of areas with high theoretical energy potential in addition to high spatial siting potential. However, NG and biomass are not encouraged in the long-term future due to the characteristics of their fuel resources. In particular, 62.476% of the suitable areas are considered as high potential areas for biomass power plants. However, the conflicts between the food supply and biomass resources of power plants could limit the developing potential of biomass power plants (Shu et al., 2017). To achieve “carbon neutrality” by the end of 2060, the NG power can only serve as a short-term electricity transition path to secure electricity supply, but not in the long-term because the NG power is not a “zero-carbon” choice.

In summary, the NG, solar, biomass power, and WtE power plants are ranked with high potential to be populated and installed in a large area of the study region by only considering the spatial theoretical potential and suitability. From the long-term perspective, solar and WtE power plants are more encouraged to be established for future energy planning.

Table 2.5 Percentage of areas in each potential scale out of the suitable area for alternative power plants.

	Low			**Medium**			**High**		
Potential Scale	**0.1–0.2**	**0.2–0.3**	**0.3–0.4**	**0.4–0.5**	**0.5–0.6**	**0.6–0.7**	**0.7–0.8**	**0.8–0.9**	**0.9–1**
NG	0%	0%	0%	0.163%	13.986%	47.320%	32.557%	5.957%	0.017%
Nuclear	0%	0%	0.097%	5.220%	76.179%	17.200%	1.288%	0.017%	0%
Onshore Wind	0%	0.052%	3.736%	17.271%	45.690%	28.381%	4.797%	0.073%	0%
Solar PV	0%	0%	0.002%	1.148%	14.887%	49.301%	20.666%	13.993%	0.002%
Hydro	0%	3.899%	27.798%	33.426%	22.748%	10.957%	1.141%	0.031%	0%
Biomass	0%	0%	0%	0.002%	1.600%	35.922%	59.641%	2.836%	0%
WTE	0%	0%	0%	0.903%	11.212%	56.538%	30.194%	1.148%	0.005%

2.4 Discussion

China is currently facing the challenge of achieving carbon neutrality by the end of 2060 (McGrath, 2020). The country has managed to disengage itself from the coal-reliant electricity generation system (NDRC & NEA, 2016). However, with the rapid increase of renewable power capacity, the country has experienced many problems associated with transmissions and electricity supply. The YRD region is an economically advanced region of China (W. Zhao et al., 2020), which has high energy intensity and historically relies on input electricity from other areas of China (World Resources Institute, 2021b). To satisfy the energy demand, flexibly modulate peak loads of the electricity supply, and minimize the electricity loss during the transmission, complementary electricity generation mixed plans should be developed in the YRD region. To that end, comparing the spatial siting potential of alternative low-carbon power plants is essential in energy planning (Shu et al., 2017).

This research contributes to the comparison of spatial siting potential evaluation across different low-carbon powers by proposing a suitability index scheme for evaluation criteria based on the GIS-based analytic hierarchy process. This design complements previous research on power plant sites selection (Jamshed et al., 2018; Pergola et al., 2020; Xing & Wang, 2021; Y. Xu et al., 2020) by transforming incompatibility datasets into comparable scaled values according to the suitability index, which is gathered from a literature review. It allowed the spatial siting potential of different low-carbon power generation technologies to be comparable.

The case study in the Yangtze River Delta region shows that solar PV, biomass, WTE, and NG power are assigned with high siting potential (>0.8) in more spatial areas compared to other low-carbon power generation technologies. The great spatial siting potential of solar power in the YRD region has also been approved by Odhiambo et al. (Odhiambo et al., 2020). For biomass, WTE, and NG power, the theoretical energy potential is the most important criterion of siting potential. The geographical, climatic, and economic conditions support an adequate supply of fuel resources for these three energy technologies. However, the Chinese food shortage could limit the development of biomass power plants (Shu et al., 2017). Therefore, the spatial siting potential of low-carbon powers is not the only factor that should be considered in energy planning. Furthermore, in most areas of the Yangtze River Delta region, the siting potential for wind, nuclear, and hydro powers is in the medium range (0.4–0.7). Although wind resources are also plentiful in the YRD region (X. Wei et al., 2018), the theoretical potential of wind is relatively lower compared to solar resources, according to the suitability index proposed in Table 2.3. Nuclear and hydropower siting potentials are limited by geographic reasons (distance to coastal and elevation drops) in a vast area.

Results are promising, and the proposed suitability index scheme of siting potential evaluation criteria could be applied in the spatial siting comparison research in city-level or regional-level spatial areas. The ranked low-carbon power generation technologies in each spatial cell could sufficiently support decision-makers for energy planning.

2.5 Conclusions

This research develops a power plant siting potential mapping tool to compare the spatial siting potential of alternative low-carbon power plants in each spatial cell of the Yangtze River Delta region. The research supports us in taking steps further in the comparison of power plant spatial suitability and providing decision-makers with more applicable information for energy planning. Indeed, the previous research on individual energy technology is inadequate to show the suitability ranking of different technologies within a spatial cell. In this research, I first identified a suitable area of 381613.95 km^2 for power plant siting. Second, I ranked the suitability of different power plants in each spatial cell of the study region. Distributed solar PV and WtE plants should be encouraged to be established. This study represents a replicable example, which could be applied to regional-level or city-level spatial areas and contribute to future energy planning.

This research will be expanded into an energy landscape model to investigate the optimal spatial energy planning strategy for future sustainable energy development. Other factors should also be considered, including the environmental impact of power plants, the economic benefit of power plants, the conflict between renewable energy resources and regional demand, and the national developing inclination of specific electricity industries. Thus, instead of only considering the spatial potential, I recommend designing the future energy plan from more perspectives. Future research could be developed by considering the impact of power plants on the spatial environment and the decision-makers’ preferences for energy planning.

Chapter 3: Assessing and enhancing the regional sustainability of electricity generation technologies in the Yangtze River Delta, China

Abstract: Decision-makers are increasingly concerned about the sustainability of power generation technologies to achieve a secure and sustainable electricity supply in the future. This study aims to assess the sustainability of the seven most applied electricity generation technologies in the Yangtze River Delta region of China and further enhance the regional sustainability of the electricity generation mix. I applied the analytic hierarchy process to integrate 14 sustainability indicators and further employed the weighted sum method to rank the sustainability of the seven electricity generation alternatives. The results first revealed no technology is absolutely more sustainable. Second, according to the decision-makers' priorities, the pumped storage hydropower has been concluded as the most sustainable, followed by nuclear and on-shore wind power. Third, to adapt to the national promotion of distributed solar photovoltaic power, the technical innovation of silicon film manufacturing shall especially aim to minimize negative environmental impacts. I further argue that future sustainable energy planning should consider the geographic potential of renewable resources, supply-demand markets, and institutional promotion/regulation. Overall, this study suggests a priority of developing pumped storage hydropower and on-shore wind power to enable a low-carbon and sustainable electricity transition in the Yangtze River Delta region and beyond.

Keywords: Sustainability assessment; Electricity planning; Multi-criteria decision making; Analytic hierarchy process.

3.1 Introduction

3.1.1 Electricity generation and its sustainability

Electricity is the fundamental source of daily life and economic development. Electricity consumption will count about 50% of final energy consumption by 2050 under the IEA's renewable map (REmap) case, in terms of 54% in China, 42% in the European Union (EU), and 51% in the United States (USA) (IRENA, 2018). Besides, the electricity sector contributes a significant share of over 50% of total CO_2 emissions worldwide (IEA, 2021). Decision-makers are increasingly concerned about the sustainability of electricity generation technologies. EU has committed to a 32% renewable energy share of the energy system by 2030. Some states in the US have also made efforts towards a low-carbon energy transition. In China, the state government has set a target in its 13th five-year plan (FYP, 2016-2020) to achieve a non-fossil power of 50% by 2030 and promised to achieve "carbon neutral" by 2060 (Farand & Darby, 2020; NEA, 2016b).

The electricity generation technology of China is currently still dominated by coal-combusted power plants, which is the largest CO_2-emitting sector in China and poses a significant challenge to air pollution (L. E. Yang et al., 2017). Although it is hard to wean off from a coal-reliant electricity generation structure in a short time, China kept increasing its renewable energy power capacity, which reached 794.88 Gigawatt (GW) by 2019, accounting for 39.52% of the total power generation capacity (Draworld, 2020). Electricity transition from conventional fossil fuel to renewable is inevitable due to the disadvantages of fossil fuel resource conservation. However, simply expanding the renewable power plants would not be a feasible approach (Taminiau et al., 2021). There are many constraints on expanding renewable power plants, including the high investment cost, additional power storage equipment, inappropriate grid, uncontrollable daily or seasonal varied renewable resources, and restricted siting locations (Ploetz et al., 2016). A more flexible and diversified mixed electricity generation system, including renewable and non-renewable energies, needs to be established considering economic development, supply security, and ecological conservation(IEA, 2019a).

3.1.2 Multi-criteria decision-making in sustainability assessment

In order to design a reasonable and sustainable mixed electricity generation system, it is necessary to provide information to decision-makers about the sustainability of alternative electricity generation technologies. Different methods, such as life-cycle analysis and optimization, have been used to assess the sustainability of different perspectives on electricity generation technologies. There is no standard method to assess the sustainability of electricity generation technologies. To access comprehensive sustainability, a set of indicators/criteria from multiple dimensions (social, environmental, economic, and technical) should be considered to investigate the complex problem. Besides, there is no universally approved definition of sustainability (Moore et al., 2017). In this research, sustainability refers to the sustained ability of the electricity generation technologies based on the decision-makers' subjective perceptions. To demonstrate the subjective sustainability ranking of electricity generation technologies, the decision-makers' subjective preferences of development should be assigned to the weight of indicators.

The sustainable development of the electricity supply system requires rational decision-making on electricity generation technologies (J. J. Wang et al., 2009; Yilan et al., 2020). To comprehensively evaluate the sustainability of electricity generation technologies, many studies applied multi-criteria decision-making (MCDM) approaches to apply integrated indicators across the techno-economic, environmental and social dimensions on a life cycle basis (Bhandari et al., 2021; Evans et al., 2009; Maxim, 2014; Santoyo-Castelazo & Azapagic, 2014; Shaaban et al., 2018; J. J. Wang et al., 2009). Maxim (2014) applied the MCDM to rank the sustainability of 14 electricity generation technologies based on 10 indicators. Stamford and Azapagic (2011) also used this approach to assess the sustainability of nuclear power based on 43 indicators covering techno-economic, environmental, and social dimensions. Other studies applied life-cycle analysis (Backes et al., 2021; Teffera et al., 2020; L. Xu et al., 2018), logic models (Ribeiro et al., 2013) or SWOT (Strength, Weakness, Opportunity, Threats) analysis (Erdil & Erbıyık, 2015) to evaluate a specific dimension of sustainability of electricity generation. For example, many experts investigate the environmental impact of electricity generation technologies by applying life-cycle analysis (X. Cui et al., 2012; Felix & Gheewala, 2014; Quek et al., 2019); and some assess the integrated economic and environmental impacts of electricity generation (Ayodele et al., 2018; Varun et al., 2009). Kumar (2017) stated that the analytic hierarchy process (AHP) is the most suitable MCDM approach to assess the sustainability of energy systems because of its ability to qualitatively and quantitatively handle complex criteria. Sahabuddin' research (2021) also demonstrates the robustness of AHP in assessing the sustainability of the energy sector. The AHP is widely applied in the sustainable assessment to result in the most sustainable electricity generation technologies and rank the sustainability of other alternatives (Bhandari et al., 2021; Cajot, 2017; Kumar et al., 2017; Shaaban et al., 2018; Su et al., 2020).

Instead of finding the most sustainable electricity generation technology, experts stated that the MCDM approach serves as advice that could facilitate the decision-makers in identifying their subjective preferences for electricity generation technologies (Cajot, 2017; J. J. Wang et al., 2009). The weight ranking method of MCDM can be either subjective or objective. The objective weighting method is hardly applied to problems of sustainable energy decision-making and better suits the ecological system (Yilan et al., 2020). In contrast, the subjective weighting method is mainly applied in choosing the best option and ranking alternatives. Subjective weighting is applied in this research to determine the importance of each indicator based on decision-makers' subjective judgments.

In order to offer decision-makers' subjective sustainability assessment of alternative electricity generation technology, the sustainability indicators need to be customized according to study objects, scope, and study area (Maxim, 2014; Shaaban et al., 2018). Experts have mostly developed the research of sustainability assessment based on the specific study regions or nations. For instance, Shaaban (2019) reveals the sustainability of seven technologies in the energy system of Egypt; Ecer's (2021) research showed the sustainability of wind powers in Turkey. The indicator selection of this research links to the electricity sector of the study region (Atilgan & Azapagic, 2016; San Miguel & Cerrato, 2020; Shaaban & Scheffran, 2017). Besides, other research for specific study objects has been developed. For example, Gallego Carrera and Mack (2010) established a set of social indicators for sustainable assessment of electricity technologies to outline the social impacts; Mangla (2020) included the political indicators to emphasize the sustainability differences based on different countries' contexts. The current research targets to assess the sustainability of electricity generation technologies across economic, environmental, and social dimensions. There is also an increasing interest in the technical aspect of electricity generation technologies (Santoyo-Castelazo & Azapagic, 2014; Yazdani et al., 2018; Q. Yue et al., 2019).

3.1.3 The sustainability of electricity generation in China

As the largest electricity generation and consumption country, China is experiencing a fast energy transition (IEA, 2019a). On the one hand, electricity consumption has rapid increased in both city and rural areas (Y. Peng, Yang, & Scheffran, 2021; Y. Peng, Yang, Scheffran, et al., 2021). On the other hand, in the electricity generation system, the share of non-fossil fuels has increased to 45.2% of the national electricity generation capacity (CEC, 2020). Many previous studies focused on the sustainability of renewable electricity generation technologies at the provincial and national levels. Xu (2016) found that biomass-based electricity is not unconditionally cleaner than fossil fuel and the environmental impact of bio-electricity highly varied on the applied power plant technologies. Cudjoe's (2021) research reveals the environmental benefits and negative impacts of electricity generation from several solid wastes in China. The solid waste recycling of paper wastes, plastics, and steel increased the emissions of VOCs and PM (Cudjoe et al., 2021). At the provincial level, Yue (2019) stated that the installation of wind, nuclear, and biomass power should be encouraged in the Liaoning province under consideration of the environmental and economic impacts.

Currently, there are still three significant shortcomings in the sustainability research of electricity generation technologies in China. First, the social impacts of electricity generation technologies are still understudied. Social acceptance and employment opportunities created by power installation are often ignored in the electricity generation impact research in China (P. Li & Zhang, 2019; Q. Yue et al., 2019). The second shortcoming is that most sustainability assessment research of electricity generation technologies was conducted in China at the city, province, or national level (P. Li & Zhang, 2019; Lou et al., 2015; Q. Yue et al., 2019), but less at the regional level which is essential in China. The regionally distributed transmission grid system, energy resources, and electricity consumption form regional electricity markets, which promote the integrative development of the regional electricity generation system (Dan et al., 2021). The economic benefits of synchronously increasing regional electricity transmission and renewable power generation are verified by Abhyankar et al. (2020). In addition, China is spatially characterized by various energy resources: north China is enriched in coal resources and wind power; the southwest region has abundant hydropower resources; solar power is highly available in the north and east region (Dan et al., 2021). These two patterns formed a regionally specific electricity generation system in China. From the electricity consumption perspective, the uneven spatial economic conditions resulted in the regionally differentiated electricity consumption quantity (Bao, 2019). In response to these regional distribution patterns, it is necessary to assess the impacts of electricity generation alternatives at the regional level.

This paper aims to fulfill these gaps and assess the sustainability of electricity generation technologies at the regional level of China based on a localized dataset. An analytic hierarchy process is designed descending to different dimensions of sustainability and a set of sustainable indicators based on the national and regional developing scope. Moreover, the decision marker’s priority of electricity system development is considered in this research. With this approach, the paper provides a better understanding of the sustainability determinants of China’s electricity generation technologies. In addition, this research will be beneficial to propose some practical implications for regional energy planning to achieve a future transition to electricity sustainability.

This chapter is organized as follows: Section 3.2 introduces the overall research process and the relevant methodological details. Section 3.3 illustrates the results of the evaluation of the selected indicators across different dimensions. Section 3.4 provides the sustainability ranking of electricity generation technologies based on the developing preferences of decision-makers. In addition, the subjective sustainability ranking of different groups of decision-makers is compared. Section 3.5 views the current governmental development plan for the power generation system. Finally, detailed suggestions and priorities for the development of each electricity generation technology are proposed, based on the research outcomes.

3.2 Study area and methodology

3.2.1 Study area

The Yangtze River Delta (YRD) region is the most significant economic circle in China and one of the six giant urban circles globally, which encompasses Shanghai municipality, Jiangsu, Anhui, and Zhejiang provinces. In 2019, 16.65% of the national population ($235.21*10^6$ inhabitants) contributed to 23.94% of China's national Gross Domestic Product (GDP) (Calculated from the GDP statistical data sources: (Anhui statistical bureau, 2020; Jiangsu statistical bureau, 2020; Shanghai statistical bureau, 2020; Zhejiang statistical bureau, 2020)) and consumed in the YRD region ($358*10^3$ km^2, 3.69% of the national land area). The Yangtze River Delta region is also one of the largest electricity consumption regions (consumed 20.53% of China's total electricity consumption in 2019) with limited fossil fuel resources. It has been historically supplied by China's inter-provincial and inter-regional electricity transmission projects, such as "power transmission from west to east" (World Resources Institute, 2021b). In 2020, the Yangtze River Delta region's electricity self-sufficiency rate was 80.51% (Calculated from the electricity consumption statistical data sources: (Anhui statistical bureau, 2020; Jiangsu statistical bureau, 2020; Shanghai statistical bureau, 2020; Zhejiang statistical bureau, 2020)) (Figure 3.1). The Yangtze River Delta region is the primary place for China's energy transition. Therefore, the continuously reliable energy supply has been one of the most critical issues in the YRD region. One way to solve this challenge is to improve the supply ability of the local electricity generation mix system. In this regard, a comparative sustainability assessment of alternative electricity generation technologies, which could be applied to the region, is needed to guide future energy planning.

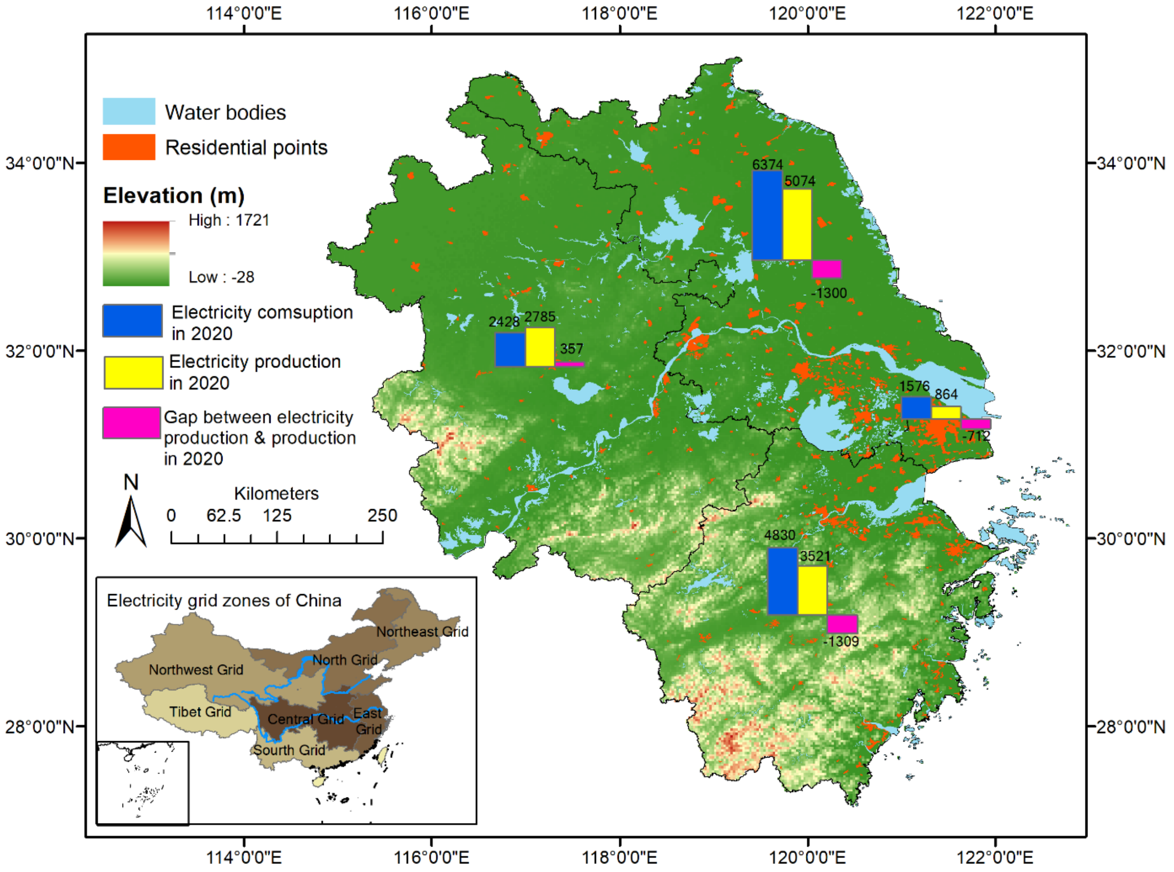


Figure 3.1 Map of the Yangtze River Delta region showing its electricity production and consumption in 2020

3.2.2 Methodology

With the aim of assessing the sustainability of electricity generation technologies, the synthesis research methods are shown in Figure 3.2, including: 1) selection of study objects (electricity generation technology with potential in the YRD region); 2) sustainability assessment (multi-criteria decision-making method), including selection, evaluation, weighting und use of sustainability indicators for ranking of electricity generation technologies.

The MCDM approach is implemented to rank the sustainability of electricity generation technologies that are currently developed or adopted in the Yangtze River Delta region, in China. The study is based on a set of sustainability indicators selected from literature reviews according to the scope of national and regional development. I design a hierarchy structure descending to different dimensions of sustainability and specific indicators of each dimension with the aim of providing sustainability ranking information for decision-makers (Saaty, 1988; Shaaban et al., 2018). Decision-makers subjectively establish weights of decision criteria based on pair-wise comparisons of the criteria. The weights of sustainability indicators are investigated through qualitative interviews conducted in January 2021 with decision-makers in regional energy planning. Synthesis of the decision-maker's judgments and values of these criteria are used for overall evaluations of different alternatives.

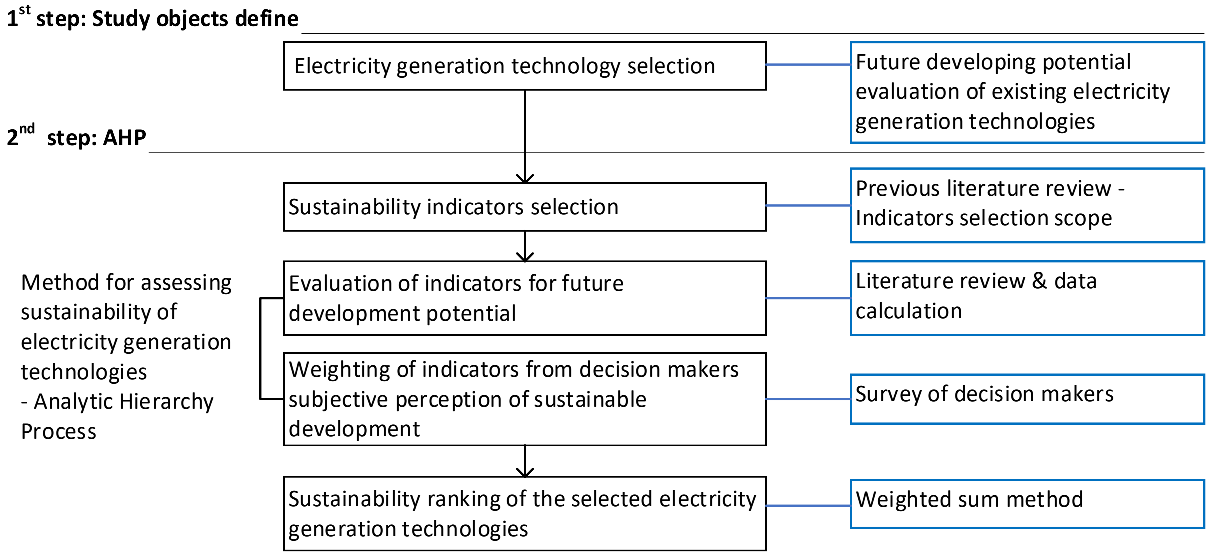


Figure 3.2 Summary of research steps and methodology.

3.2.2.1 Selection of electricity generation technology

In this research, the study objects are selected from the mainstream on-shore electricity generation technologies in China. By considering some regional-specific constraints, I reduced the study objects to seven types of technologies. This research does not consider off-shore wind power, centralized solar power, large-scale hydropower, and coal-combusted power due to the limited potential to develop in the study region (NEA, 2016b). Therefore, this research selects seven technologies, shown in Table 3.1. In order to avoid the sustainability variation caused by different technology schemes, the studied specific technology of each type of power is illustrated in Table 3.1. The specific technology schemes are established based on the most applied technology in China and the most suitable technology in the YRD region.

Table 3.1 The features of selected electricity generation technologies in YRD

Electricity source	Technology	Description application in YRD	References
Natural gas	Combined cycle or simple cycle with the carbon capture system	Not consider natural gas extracted from other fossil fuels. Lifetime around 30 years.	(Fan et al., 2016; Feng et al., 2014)
Nuclear	Pressurized water reactors (PWRs)	Capacity between 1000 and 1500 MW; Lifetime between 30 to 60 years.	(Feng et al., 2014; World Nuclear Association, 2020; Q. Yue et al., 2019)
Wind	On-shore wind power	Overall capacity around 50 MW; Individual wind turbine capacity between 800kW to 3MW; Annual operation time around 2100h; Lifetime 20 years.	(Y. Dong et al., 2015; Feng et al., 2014; Q. Yue et al., 2019)
Solar PV	Distributed solar PV Crystalline silicon and thin film	With a median radiation of 1700 kWh/m^2/yr; Annual operation time around 1700h; Lifetime between 25 to 30 years.	(Feng et al., 2014; Hou et al., 2015; Weng & Chen, 2017; Q. Yue et al., 2019)
Hydro	Pump-storage hydropower	Capacity around 1200-1600MW; Annual operation time around 3500h; Lifetime between 44 to 100 years.	(Feng et al., 2014; Jiang et al., 2018; Z. Li et al., 2017)

Biomass (straw)	Steam turbine	Annual operation time of 6,000 h, the biomass consumption rate is 1.4 kg/kWh, and 20-40km collection range;	(Feng et al., 2014; J. Liu et al., 2009; Pu et al., 2015; Q. Yue et al., 2019)
Waste to Electricity	Incineration	Waste is mainly generated from households, 20km collection range	(Ardolino et al., 2020; W. Zhao et al., 2016; Y. Zhao et al., 2012)

3.2.2.2 Selection of sustainability indicators

Sustainability indicators are functional tools that could assess the sustainability of electricity generation technologies. An indicator makes a particular issue measurable by quantifying its effects (IAEA, 2007; Sarangi et al., 2019). The indicators that arise from the particular issue provide decision-makers with information to determine which actions are devoted to sustainable development (Singh et al., 2012). Instead of developing a new set of indicators based on a theoretical framework, I select existing indicators through a literature review. This research selected indicators to present the research object following the country- or regional-specific electricity developing priorities. In China, electricity generation transition is encouraged in four aspects: satisfying a median-high speed economic growth rate, improving energy technologies, securing energy supply, and minimizing environmental impacts (Table 2). Relevant targets had been set in the 13th five-year plan, and the governmental working group will set up new precise targets in the 14th five-year plan by the end of 2021. According to these sustainable issues of national and regional development (Table 3.2), decision-makers' suggestions and indicators' data available, I selected relevant indicators, shown in Figure 3.3.

Table 3. 2 Goals of the development and related sustainability indicators

	2016-2020 (13th Five-year plan)		**Related sustainability issues**
Electricity system	**80% self-sufficient** 1. Power system safety increasing 2. Power system flexibility increasing		• Resource depletion • Energy security
Economic	Keep median-high economic growth rate		• Cost & Benefit
Environment	CO_2	**-18%**	• Climate change
	SO_2	Decrease	• Air quality • Human health impact
	NO_X	Decrease	• Air quality • Human health impact
	Particulate Matter (PM)	Decrease	• Air quality • Human health impact
Technology	**Power generation technologies improving** 1. Energy efficiency increasing 2. Desulfurisation and denitrification technologies improving 3. Carbon capture system improving		• Energy security • Climate change • Air quality

The information summarized from: General Office of the State Council of the People's Republic of China, 2019; Government office of Jiangsu Province, 2017; Government office of Shanghai, 2017; Government office of Zhejiang province, 2017; NDRC and NEA, 2016; NEA, 2016; State council, 2018.

3.2.2.3 Analytic hierarchy process to assess the sustainability

The analytic hierarchy process of electricity generation technologies sustainability is illustrated in Figure 3.3. The selected indicators cover four dimensions, including economic, environmental, social, and technical dimensions. The AHP analysis will achieve the goal of finding the most sustainable electricity generation technology through an integrated evaluation of the sustainability ranking of alternatives.

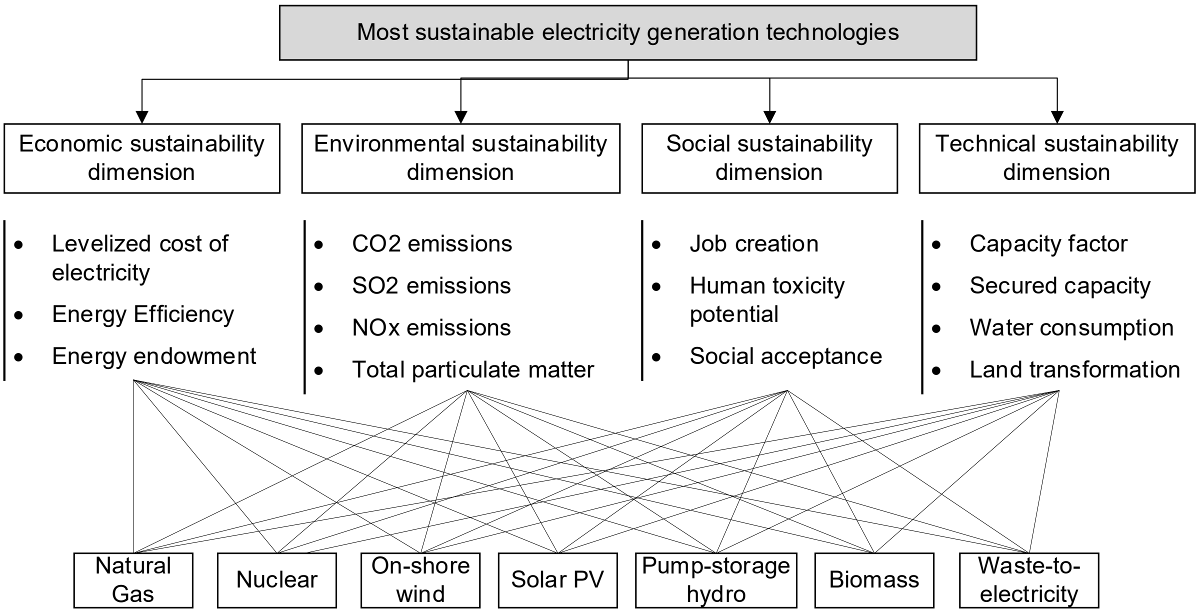


Figure 3.3 Sustainability hierarchy of electricity generation technologies

Some of the indicators' values are rated from the previous literature (e.g. levelized cost of electricity, energy efficiency, CO_2 emission, etc.). For instance, the CO2 emission from natural gas (NG) power plants varied greatly, with differences of up to one order of magnitude (i.e., 247-1890 g CO2-eq/kWh) (Hertwich et al., 2015; Usapein & Chavalparit, 2017). The high-value CO2 emission from the NG power plant was derived from a coal-based synaptic NG power plant. This variability was due both to the different technologies and to the methodological approaches used to assess them. Actual values vary considerably between individual schemes. Thus, it is necessary to impose restrictions on the selection of the research review. The reviewed researches are firstly required to be the most recent individual case studies in the study area of China and meet the requirement of the target technology scheme. However, I found that only a few pieces of literature fully satisfied these requirements. To respond to this challenge, it is necessary to combine the case studies in other study areas or include statistical research. Especially for indicators that are reviewed from the life-cycle analysis or life-cycle cost analysis, such as the LCOE, CO_2 emissions, NO_2 emissions, etc., the life-cycle should be restricted to the boundary of three life-cycle phases, including the first phase of fuel provision (from the fuel extraction, transportation to employment by the power plant); the second phase of infrastructure (commissioning and decommissioning); and the third phase of plant operation (operation, maintenance and residue disposal of power plants). Other indicators, such as energy efficiency, and secured capacity, are regardless of the life cycle of electricity generation technologies. Except for these indicators, the indicators of energy endowment and social acceptance are calculated from empirical data from a quantitative survey or national statistical report.

The judgment of decision-makers on the sustainability indicators is relying on their knowledge background. In order to compensate for this shortcoming, different methods have been applied. Maxim (2014) scaled the importance of each decision-maker based on their roles in the group decision-making process by adapting the weight of their judgment in the aggregated weight sum. Sibertin-Blanc and Zaraté (2014) used a cooperative decision-making approach to allow decision-makers to adapt their weight of indicators by sharing information. He applied an equal weight to the decision makers' judgment in the final aggregation. Jassbi (2014) classified the decision-makers based on their knowledge and behavior. The results of each group of decision-makers could be aggregated to the final decision matrix by either applying weighted average, maxi-min or parametric. Each interviewee's judgment shares equal weight in this research because each response from my survey is one of the most influential decision-makers. Meanwhile, to identify the different judgments of sustainable development from different group decision-makers, I classified the interviewed decision-makers as policymakers, experts and investors based on their behavior in the electricity sector.

3.2.2.4 Ranking the sustainability of electricity generation technologies

The various indicators with different units and measured in different ranges are required to be normalized to the (0 1) range to scale features and integrated into a utility score to rank the sustainability of alternatives. For example, some indicators are presented as measurements with different units, such as the levelized cost of electricity with USD/kWh, efficiency and capacity factor with percentage, emissions with kg/kWh, etc. Other indicators with the same unit but measured at different scales do not contribute equally to the analysis and might create a bias. For example, the emission values have the same units of g/kWh but range differently. The CO_2 emissions range from -500 to 2000 g/kWh and the SO_2 emission value is from 0 to 1 g/kWh. Thus, the min-max normalization is applied to scale features from the selected indicators.

Among these selected indicators, the positive indicators, such as energy efficiency, energy endowment, and job creation, are normalized by equation (3.1); the negative indicators, which adversely influence the sustainability, including Levelized cost of electricity, CO_2 emissions, and water consumption, are normalized by equation (3.2). Therefore, I reduced the minimum value by 10% for positive indicators and added 10% to the maximum value for negative values to avoid zero values.

$$(v - v_{min})/(v_{max} - v_{min}) \qquad \textbf{Equation 3.1}$$

$$(v_{max} - v_{min})/(v_{max} - v_{min}) \qquad \textbf{Equation 3.2}$$

where $\boldsymbol{v_{min}}$ is the minimal value of an indicator, $\boldsymbol{v_{max}}$ is the maximal value of an indicator.

By adding up the multiple results of the value of sustainability indicators and different weights for each, the sustainability of electricity generation technologies can be ranked. A weight sum approach is applied (equation 3.3).

$$\boldsymbol{Sus_i} = \sum_{j=1}^{j=n}(\boldsymbol{Weight_j} * \boldsymbol{Value_{ij}}) \qquad \textbf{Equation 3.3}$$

where $\boldsymbol{Sus_i}$ is the sustainability score of electricity technology i, $\boldsymbol{Value_{ij}}$ is the value of jth indicator of electricity technology i, $\boldsymbol{Weight_j}$ is the weight of jth indicator, and n is the number of indicators.

3.2.2.5 Qualitative survey with decision-makers

Overall, two surveys were designed and conducted for this research. The first one is a qualitative survey to investigate how decision-makers subjectively define the sustainability of electricity generation technology by weighting the sustainability indicators. The second survey is a quantitative survey designed to evaluate the social acceptance of each electricity generation alternative. The survey was performed in January 2021 with the assistance of the local research partners at Fudan University in Shanghai.

In the first survey, the target interviewees were required to be the policymakers, experts and energy investors in electricity investment or electricity planning. In total, 35 decision-makers were contacted through email and phone, of which 12 agreed to be interviewed in the Yangtze River Delta region. The responding decision-makers included 2 electricity planners from the government, 5 experts from universities and institutes working as thinktanks, and 5 investors from the state-owned energy investment enterprise. Because of the interviewee's concern about Covid-19 exposure risk towards face-to-face communication, half of the interview was conducted through online-meetings. The interviews are designed based on a structured questionnaire, including the initially selected indicators. Decision-makers were first asked to evaluate the selected indicators' adequacy and judge whether other important additional indicators were not included in the study. Afterward, the interviewees were asked to rate the importance of sustainability indicators through pair-wise comparisons. The results indicated that all the initially selected indicators were appropriate in this study, and an additional indicator of energy endowment should be included in the economic dimension.

The second survey is based on an online questionnaire, “Tencent questionnaire”, which works as a plug-in to the most-used social software in China. Therefore, the questionnaire was fast distributed and assessed early on the phone by the responders. In total, I have recovered 70 valid answers. In this simple quantitative survey, the responders were asked to answer four questions, including selecting the background knowledge level of the different powers; selecting the acceptable level of the power installation in the YRD region; selecting the acceptable level of the power installation in the nearby area of their residential location; ordering the electricity generation alternatives according to their acceptability.

3.3 Results

3.3.1 General sustainability evaluation of electricity generation technologies in China

3.3.1.1 Normalization of sustainability indicators' value

I presented the indicators’ value by the average of each indicator’s value set in Table 3.3. Various indicators are presented as measurements with different units or measured at different scales, required to be normalized. The normalization method is described in section 3.2.2.4. Figure 3.4 presents the normalized value by each dimension.

Table 3.3 Indicator value of electricity generation technologies in general

		NG	**Nuclear**	**Wind**	**PV**	**Hydro**	**Biomass**	**WTE**
ECO	**Levelized cost of electricity** (USD/kWh)	0.02	0.05	0.07	0.06	0.05	0.08	0.32
	Energy efficiency (%)	47.50	33.00	54.00	15.77	90.00	25.33	30.33
	Energy endowment (%)	0.00	0.02	0.03	0.03	0.03	0.10	0.20
ENV	**CO$_2$ emission** (g/kWh)	527.08	36.99	22.71	57.71	13.90	-240.00	1112.25
	SO$_2$ emission (g/kWh)	0.14	0.04	0.02	0.20	0.03	0.27	0.12
	NO$_x$ emission (g/kWh)	0.78	0.06	0.04	0.14	0.02	0.65	1.04
	Total particulate matter (g/kWh)	0.37	0.02	0.01	0.04	0.07	0.12	0.09
SOC	**Human toxicity potential** (kg 1,4 DCB‡ eq./kWh)	0.38	0.03	0.04	0.14	0.03	0.76	0.64
	Job creation (jobs/MWa)	1.16	1.13	3.68	9.64	14.55	3.48	1.90
	Social acceptance (ordinal scale)	21.34	20.67	28.76	28.28	27.61	17.46	18.77
TEC	**Secured capacity (%)**	84.50	84.50	50.00	0.00	50.00	85.00	85.00
	Capacity factor (%)	42.00	90.00	38.00	20.00	40.00	65.00	65.00
	Water consumption (%)	0.91	2.51	0.27	0.13	18.96	98.75	2.52
	Land transformation (km^2 /TWh)	0.31	0.12	2.04	0.38	5.56	14.12	0.05

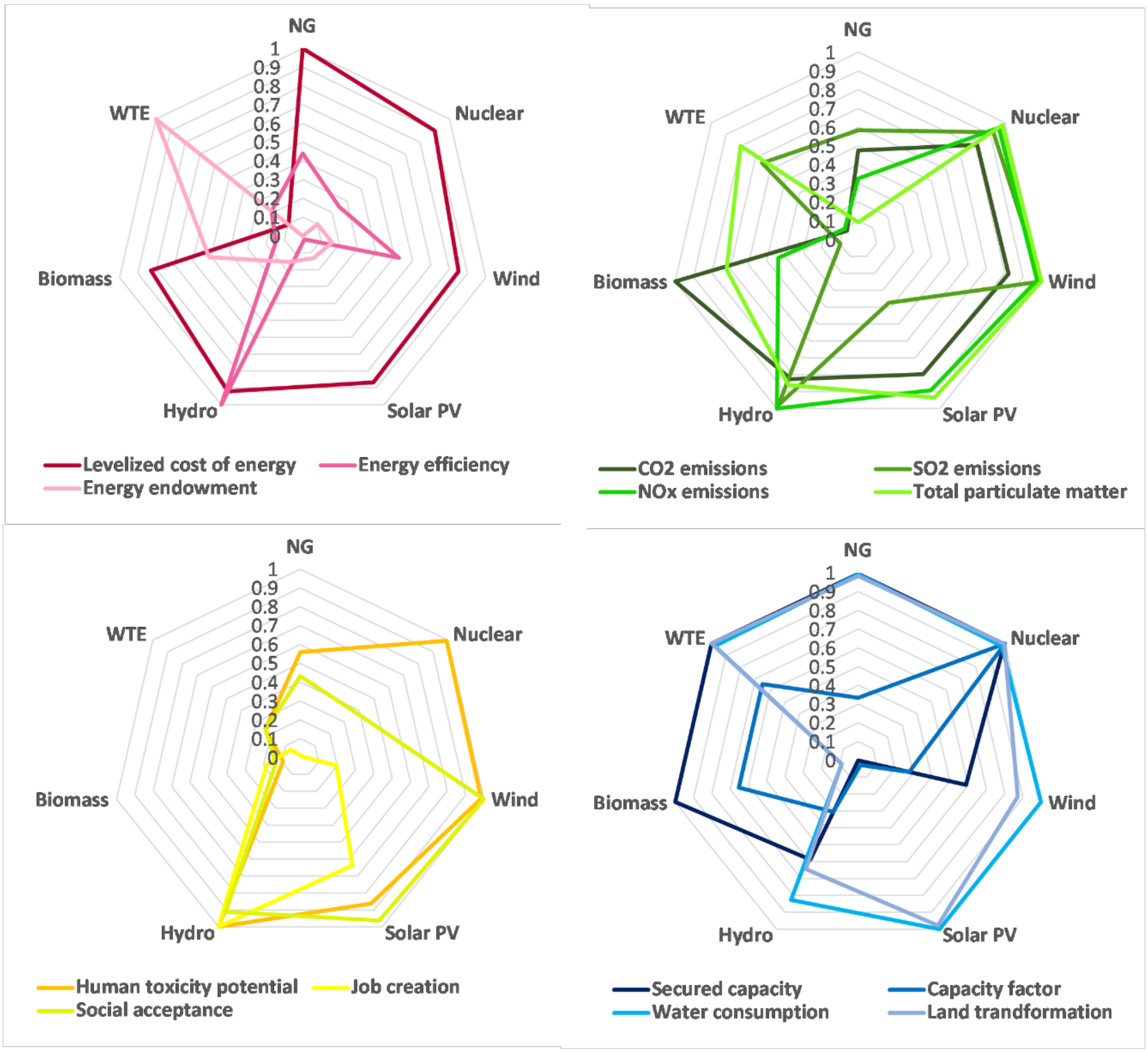


Figure 3.4 Normalized multi-criteria evaluation of electricity generation technologies.

Figure 3.4 shows that the conventional electricity generation technology NG has the lowest LCOE, which obtains the highest score. In China, the LCOE of most renewable power has decreased in recent decades because of the technology improvement, which synchronously increased the investment fix cost and decreased the operation and maintenance cost (NDRC, 2019). The lowest score of LCOE is created by waste to electricity (WTE) due to the high labor cost in the waste collecting and transporting processes. In contrast, for the energy endowment indicator, WTE ranks highest compared to other technologies due to the high availability of waste in this region (19.57% of national waste availability). In addition, pumped-storage hydropower obtains the highest energy efficiency score, which is two times higher than the other technologies.

In the environmental dimension, nuclear, pumped-storage hydro, on-shore wind and solar photovoltaic (solar PV) power obtain very high scores in general except for the SO_2 emissions of solar PV, resulting in the silicon input in the infrastructure stage. All the scores of NG power in the environmental dimension are lower than 0.6. The other three electricity generation alternatives obtained a relatively lower score in the environmental dimension. Biomass and WTE technologies emit a large amount of

NO_2 and SO_2 emissions in the incineration stage. Notably, I do not include the indicator of waste in the environmental dimension, which could highly decrease the environmental sustainability of nuclear power.

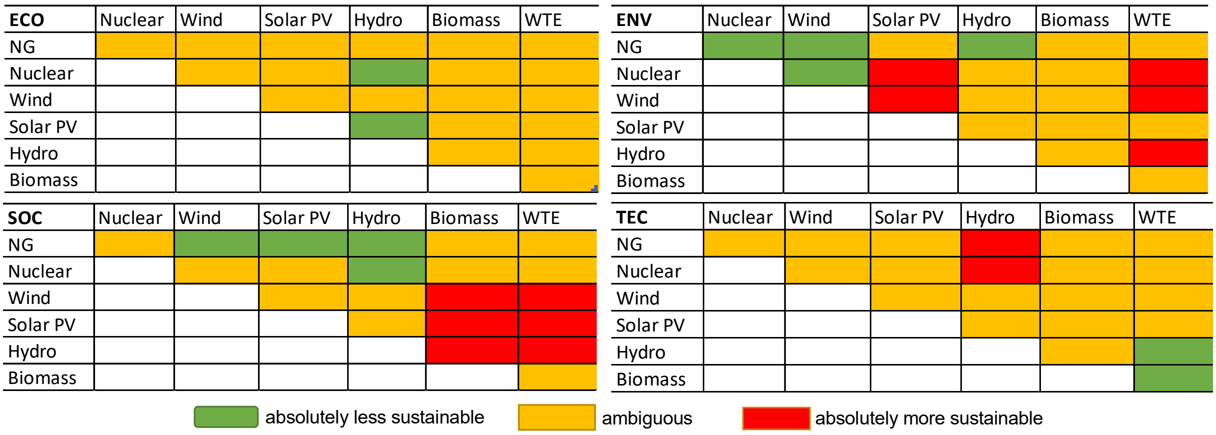
The most significant differences are shown in the social dimension. Biomass and WTE power obtained the lowest score in each social indicator, and pump-storage hydropower obtains very high scores in all social indicators. Biomass and WTE still apply the incineration technology, resulting in high SO_2, NOx, and total particulate matter (TPM) emissions, resulting in low scores of human toxicity potential and social acceptance. However, improving technologies could solve these shortages.

In the technical dimension, nuclear power obtains a very high score in each technical indicator, specifically in the capacity factor indicator, which is relatively lower in other electricity generation alternatives. The other three technologies with high supply security are NG, biomass, and WTE power. In comparison, the renewable electricity technologies of wind, solar PV, and hydro are relatively less secure in energy supply.

3.3.1.2 Objective sustainability evaluation of electricity generation technologies

The objective sustainability ranking of electricity generation technologies is ambiguous. To understand the general objective sustainability of electricity generation technologies, I illustrate a pair-wise comparison matrix to present the relative sustainability in each dimension (Figure 3.5). In the pair-wise comparison, only a few absolute better or absolute worse exists. Therefore, the subjective weighting of the indicators is the critical component resulting in the subjective sustainability ranking of electricity generation technologies.

In summary, there is no technology that is evaluated as absolutely more or less sustainable than another technology in the overall dimension. In the economic dimension, only nuclear and solar PV are absolutely less sustainable than pump-storage hydropower. In the economic dimension, the value of environmental indicators highly relies on the upstream equipment manufacturing processes and the fuel resources of the electricity generation technologies. The on-shore wind is absolutely more sustainable than NG, nuclear, solar PV, and WTE technologies in the environmental dimension. Among these four energy technologies, nuclear power is evaluated as more sustainable than the other three technologies. Unlike the other dimensions, the feature in the social dimension is more clear. The on-shore wind, solar and pump-storage hydropower are absolutely more sustainable than NG, biomass, and WTE technologies. In the technical dimension, pump-storage hydropower is absolutely less sustainable than NG, nuclear and WTE power due to its low supply security, high water consumption, and high land occupation.



ECO	Nuclear	Wind	Solar PV	Hydro	Biomass	WTE
NG	🟨	🟨	🟨	🟨	🟨	🟨
Nuclear		🟨	🟨	🟩	🟨	🟨
Wind			🟨	🟨	🟨	🟨
Solar PV				🟩	🟨	🟨
Hydro					🟨	🟨
Biomass						🟨

ENV	Nuclear	Wind	Solar PV	Hydro	Biomass	WTE
NG	🟩	🟩	🟨	🟩	🟨	🟨
Nuclear		🟩	🟥	🟨	🟨	🟥
Wind			🟥	🟨	🟨	🟥
Solar PV				🟨	🟨	🟨
Hydro					🟨	🟥
Biomass						🟨

SOC	Nuclear	Wind	Solar PV	Hydro	Biomass	WTE
NG	🟨	🟩	🟩	🟩	🟨	🟨
Nuclear		🟨	🟨	🟩	🟨	🟨
Wind			🟨	🟨	🟥	🟥
Solar PV				🟨	🟥	🟥
Hydro					🟥	🟥
Biomass						🟨

TEC	Nuclear	Wind	Solar PV	Hydro	Biomass	WTE
NG	🟨	🟨	🟨	🟥	🟨	🟨
Nuclear		🟨	🟨	🟥	🟨	🟨
Wind			🟨	🟨	🟨	🟨
Solar PV				🟨	🟨	🟨
Hydro					🟨	🟩
Biomass						🟩

🟩 absolutely less sustainable 🟨 ambiguous 🟥 absolutely more sustainable

Figure 3.5 General sustainability comparison matrix across different dimensions.

3.3.2 Assessment and ranking of the electricity generation sustainability in the YRD

The weighted sum method could integrate these indicator values with the weights of the indicators to present the sustainability of electricity generation technologies based on decision makers' subjective developing priority in the Yangtze River Delta region.

3.3.2.1 Sustainability ranking by decision-makers in YRD

The next step of AHP is assigning a weight to each indicator (section 3.2.4). The weight of the sustainability dimensions and the subsequent weight of indicators have resulted from the validated survey data, which passes the consistency measures. Figure 3.6 shows the average weight of sustainability dimensions and indicators according to the judgment of overall decision-makers.

The economic dimension of electricity generation technology is most significant for decision-makers, followed by environmental and technical dimensions. However, the social dimension has often been neglected by decision-makers. In particular, energy efficiency with the weight of 0.15 is perceived to be the most important for sustainable development, followed by LCOE, energy endowment, and SO_2 emissions. On the other hand, the least essential indicator is job creation with a weight of 0.1, followed by water consumption and land transformation (Figure 3.6). The resulting weight of indicators from the survey can be applied to the AHP to investigate the sustainability ranking of electricity generation technologies based on the average judgment of overall decision-makers.

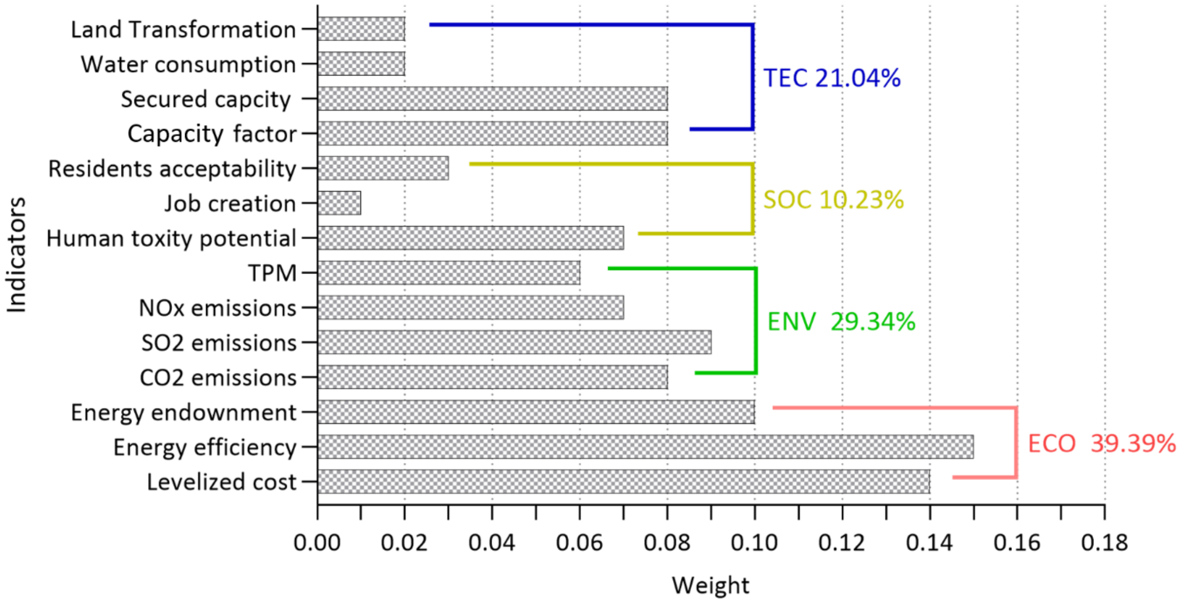


Figure 3.6 Weight of sustainability dimensions and indicators

Sustainability can be assessed by applying the weights from survey data generated from stakeholders' preferences. The sustainability ranking of electricity generation technologies is shown in Figure 3.7, where pumped-storage hydropower is the most sustainable electricity generation technology in the YRD region, followed by nuclear and on-shore wind power. The study does not consider the indicator of nuclear accidents, nuclear waste disposal, or other risks which might drag down the sustainability of nuclear power. Moreover, as the only fossil-fuel power, natural gas power has been ranked in the middle, which results in a significant advantage in Levelized cost, stable supply character, and all negative environmental-social impacts. Notable, some renewable solar powers have been ranked low due to the insufficient secured capacity and the capacity factor, which could be improved by integrating storage devices. The least sustainable WTE plant has considerable shortcomings in both environmental and social dimensions.

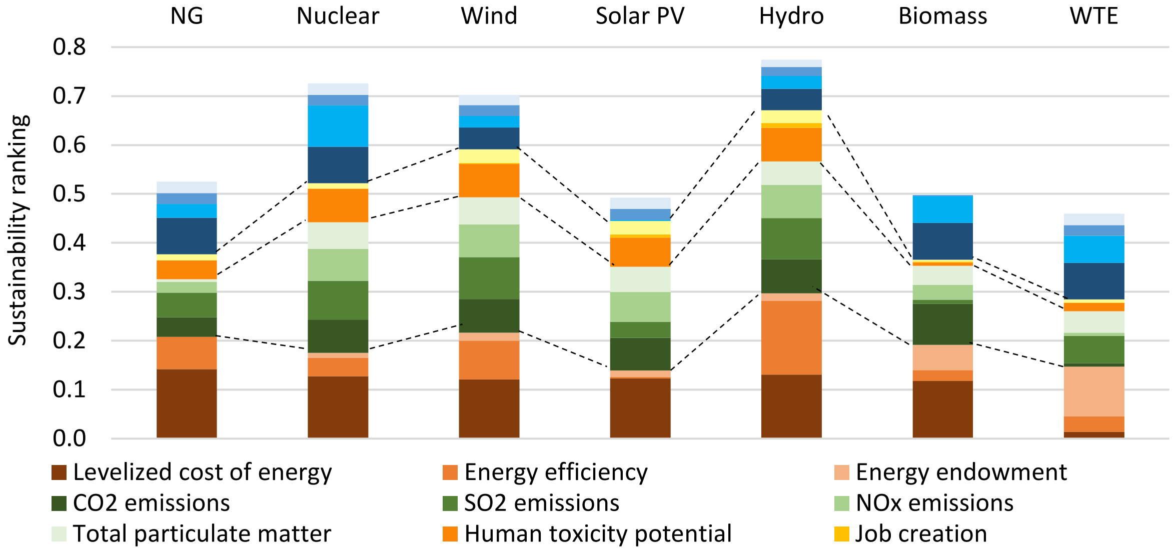


Figure 3.7 Sustainability of electricity generation technologies in YRD

3.3.2.2 Sustainability ranking from different group decision-makers

The survey was conducted based on three groups of decision-makers, including investors from energy investment companies, experts from universities and institutes and working as think tanks for energy planning, policymakers from the energy department of the provincial-level development and reform commission. Figure 3.8 shows the comparison judgment for the sustainable dimension of these three groups of decision-makers. The ordering importance of each dimension is mostly the same in each group of decision-makers following the order of economic, environmental, technical, and social, except the inverse order of environmental and technical dimensions for policymakers. To be more specific, policymakers believe the improved desulphurization and denitrification technologies can minimize the negative environmental impact, and thus they attach great importance to securing the energy supply, which directly affects the living standard of citizens (O'Connor & Cleveland, 2014). Different from other decision-makers, experts tend to strike a balanced development between the four dimensions. Thus, experts rank more considerable importance to the social dimension among all decision-makers more than the other two groups. In contrast, investors are much more partial to the economic dimension.

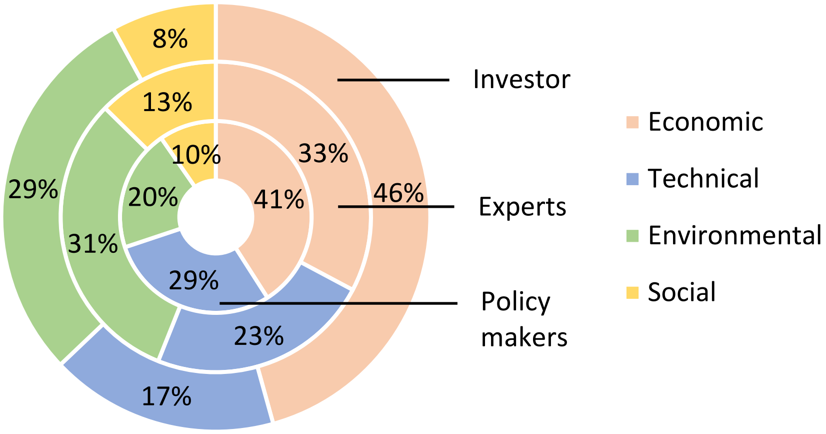


Figure 3.8 Weight of sustainability dimensions by different groups of decision-makers

The weight of indicators from different groups of decision-makers can be applied to investigate the sustainability ranking of alternatives by different decision-makers. In order to differentiate the ranking of electricity generation technologies between different groups of decision-makers, I applied the weight of indicators from different groups of decision-makers. The ranking scores of each alternative resulted from the AHP (Figure 3.9).

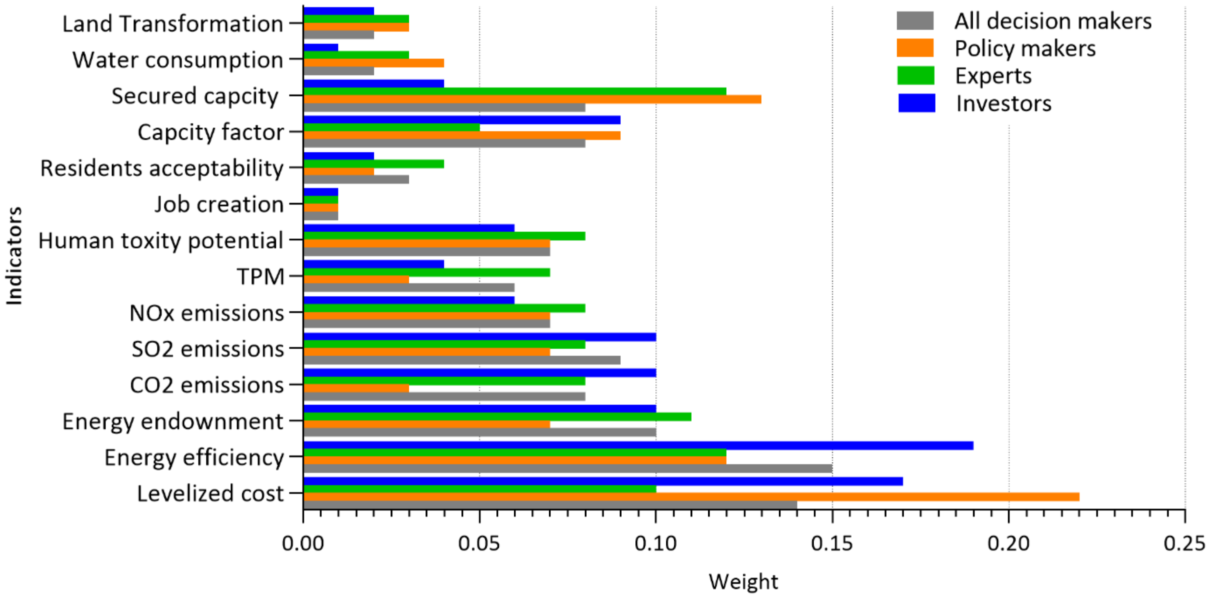


Figure 3.9 Weight of sustainability indicators by different groups of decision-makers

Figure 3.10 shows the sustainability ranked by different groups of decision-makers. On-shore wind, nuclear, and pumped-storage hydropower have been ranked highest by all three groups in the comparison. In contrast, the other four types of electricity generation technologies have been ranked lower. As the weighting described in section 4.2, from investors' perspective, the priority of economic development is over 46%, which results in the highest sustainable rank of pumped-storage hydropower. Although economic development is also essential for policymakers and experts, the technical dimension, especially electricity supply security, has also been significant. Thus, nuclear power and pumped-storage hydropower have been both ranked high by policymakers and experts. On-shore wind power has been ranked at a similar sustainable level (around 0.70) by all decision-makers. Experts ranked the other four lower sustainable electricity generation technologies very different from the other two groups of decision-makers due to their higher priority in environmental and social development and lower priority in economic development. Therefore, solar power has been ranked higher sustainable, and NG power has been ranked least sustainable.

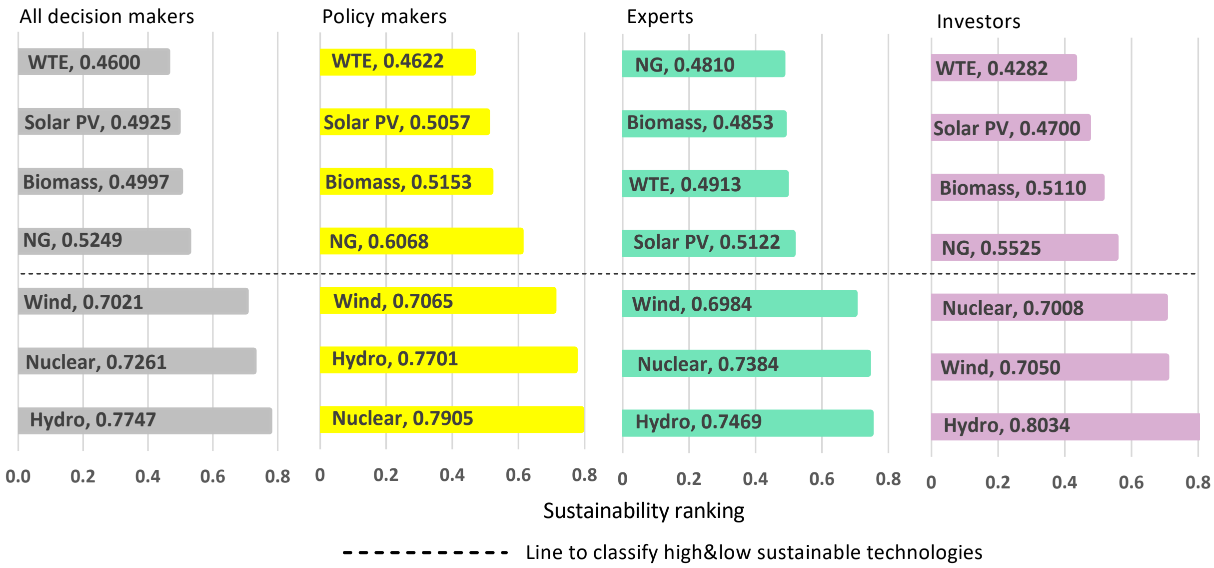


Figure 3.10 Sustainability ranking by different groups of decision-makers

3.4 Discussing and enhancing the sustainability of electricity generation

This section compares the result of this research with some previous research in other regions and then discusses the current electricity generation mix in the YRD region. Moreover, I will provide some suggestions to enhance the sustainability of specific types of electricity generation technologies.

According to the results, the most sustainable electricity generation technologies are pump-storage hydropower, nuclear power, and on-shore wind power. Hydropower has been suggested to be the most sustainable electricity generation technology regardless of the results in previous studies (Ahmad et al., 2017; Atilgan & Azapagic, 2016; Maxim, 2014). Pumped-storage hydropower with a capacity of 1200-1600MW has also been evaluated to be the most sustainable technology in this research, with pumped-storage hydropower being the most sustainable in both economic and social dimensions. However, the sustainability of hydropower is very low in the Liaoning province of China, resulting from the low energy resource potential (Q. Yue et al., 2019). These differences arise from the different ecological and geographic conditions of study areas. Except for the study area, the study scope is also a critical issue that influences the sustainable level of an electricity generation option. For instance, for the given sustainability indicators nuclear power is ranked second in my research, which is dissimilar to other research and includes more indicators of social aspects (Ahmad et al., 2017). Besides, the sustainability of NG power ranked middle, followed by solar PV, biomass, and WTE.

I believe my research is most suitable for the study area, the Yangtze River Delta region. The indicator selection and evaluation have strictly followed my research object, the national and regional development goal. The objective values of the selected indicators were collected from the literature that demonstrates the impact of electricity generation technologies in China or calculated with empirical data from regional and national statistical reports. As the subjective character of sustainability, I employed the weighting method AHP to understand the preferences of different decision-makers. The aggregation ranking from different groups of decision-makers does present different preferences for sustainable development. As long as the indicators selection, evaluation and weighting are still based on the specific study objects and study area, the MCDM approach can be a powerful tool to support decision-makers addressing interdisciplinary ranking problems.

Figure 3.11 shows the installed capacity of alternative electricity generation technologies. The installed thermal power accounts for 69% of the whole installed power capacity in the YRD region. The high percentage mainly results from the high availability of coal resources in China. The current active coal power plant is implemented after 2005 and will be gradually phased out considering its specific economic, technical, and environmental indicators (R. Cui et al., 2020). Compared with coal-fired power, NG power has a lower capacity, limited by the natural gas fuel reserve shortage. The second higher installed capacity is solar PV (13%), which does not fit the sustainable development goal of the decision-makers. These resulted from the spatial suitability of solar PV installation in the YRD region and the national promotion of the photovoltaic industry. The YRD region has well-developed industries, with many concentrated industrial parks, a large area of water surface for the aquaculture industry, and a cluster of agricultural greenhouses. All these facilities are suitable to install the distributed photovoltaic. Therefore, solar PV has been populated in the YRD region. The hydropower capacity only accounts for 6%, which is limited by the spatial installation potential of hydropower plants. The local geographic suitable sites for hydropower plants have successfully installed hydropower plants. Thus, the future developing direction is to install the pumped storage hydropower plants. Wind and nuclear power also have more possibility to be developed in the future. Although the biomass and WTE installation capacity account for the smallest share in the YRD, they are almost saturated in this region. This is resulting from the conflict between food supply and biomass power feedstock provision in the YRD region (Shu et al., 2017). To better develop biomass power in the future, energy planners could increase the security of biomass power feedstock provision by encouraging biomass raw material production and improving sustainability through technology innovations (J. Zhu et al., 2020).

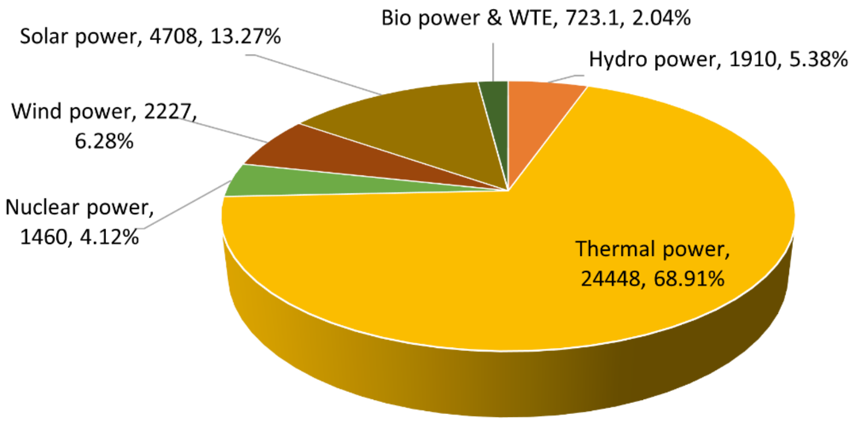


Figure 3.11 Installed power capacity in the YRD region in 2020 (Unit: 10MW)

In order to improve the sustainability of the mixed electricity generation system in the YRD region, the most sustainable electricity generation technologies, including pump-storage hydropower, nuclear power, and on-shore wind power, should be encouraged to develop in the study region. However, there are still challenges to implementing these technologies. The challenges for pump-storage hydropower are the long-term construction duration (6-7 years) and the difficulties of rational siting (X. Yan et al., 2019). The improvement of the regional transmission network could create more suitable citing locations for pump-storage hydropower. For nuclear power, problems generated from the mining of uranium resources, nuclear fuel recycling, and nuclear waste disposal raise obstacles to expanding nuclear power. Increasing the investment for mines prospecting, uranium import, and improving the technology development of fusion reactors to promote the utility rate of fuel could be feasible developing strategies for the future (Yongping Wang et al., 2020). As a great substitute for conventional power, wind power has been widely and rapidly developed and applied in China. However, without well-formulated manufacturing standards, fast wind technology development increases the safety risks of wind turbines, which can be decreased by standardized industrial management (WWF & RSA, 2020). The local land resource scarcity has also limited the development of large-scale on-shore wind farms. A distributed wind turbine could be a suitable way to develop wind power in the YRD region. In addition, solar PV also has a high potential to be further developed in the study region once the manufacturing process of silicon film has been improved. With the national promotion strategies of the photovoltaic industry, the manufacturing process will be quickly improved to minimize the negative environmental impacts of solar PV (Solarbe, 2021). Moreover, the solar-PV connected grid system should be better established to increase supply security. The installation capacity should be increased to overcome these challenges.

Table 3.4 Developing goals of the power structure in the national "five-years plan" in China (CEC, 2020; NDRC & NEA, 2016; NEA, 2016b)

Power structure	**12th FYP (2010-2015)**	**13th FYP (2015-2020)**	**State by the end of 2020**	**Projection of 14th FYP (2020-2025)**
Non-fossil power consumption	12%	15%	15.5%	18.5%
Non-fossil power capacity	35%	39%	45.2%	49.1%
Hydro (100 GW)	2.97	3.4	3.4	3.7
Pump-storage hydro (100 GW)	0.23	0.40	0.36	0.65
Nuclear (100 GW)	0.27	0.58	0.52	0.7
Wind (100 GW)	1.33	2.1	2.4	3.8
Solar (100 GW)	0.42	1.1	2.4	4.0
Fossil power capacity	65%	61%	54.8%	50.9%
Coal power capacity	59%	55%	50.4%	45.5%
Coal (100 GW)	9	<11	10.8	12.5
NG (100 GW)	0.66	1.1	0.95	1.5

The past "five-year plan" of the power structure emphasized the increase of non-fossil fuel and NG power (Table 3.4). By the end of 2020, most targets of the 13th FYP have been achieved, except the pump-storage hydro power and the nuclear power. In addition, the planned development of solar PV capacity has been doubled. To reach “carbon neutral” by the end of 2060, the new electricity development plan (14th FYP) would mainly target increasing the share of non-fossil fuels, specifically pumped-storage hydropower and wind power. The national and provincial energy administration is currently improving the pricing mechanism and setting a long-term development plan for pumped-storage hydropower (People’s Government of Anhui province, 2021; Xinhua News Agency, 2021). “Beijing Declaration on Wind Energy” promised to ensure an annual increase of wind power capacity installation of more than 50 GW in the following five years (2021-2025) and more than 60 GW after 2025 (*Beijing Wind Energy Declaration Issued*, 2020). Nuclear power and solar power are also encouraged to increase steadily. The new province-level electricity plan also states the necessity to promote innovation and development of photovoltaic modules, wind turbines, gas turbines and other core components of renewable power plants (People’s Government of Anhui province, 2021). It thus improves the sustainability of renewable electricity generation technologies. Besides, NG power is still encouraged to be developed in the short term to cooperate with renewable power to ensure the electricity supply. The national and regional development priority of the electricity generation system does fit the sustainability ranking results, except for nuclear. Nuclear has been ranked high for the selected sustainability indicators and stakeholders in my research. However, the safety concerns of nuclear power decelerate the installation. More advanced technologies and strict security measures are required for nuclear power development.

Although this sustainability assessment has considered the developing preferences of decision-makers, there are also other factors still necessary to be considered by the governmental authorities in future energy planning. There are other factors influencing future energy planning, such as the spatial geographic siting potential for electricity generation technologies, the local supply-demand market, and institutional promotion or restriction for the specific type of technology industries. To be more specific, the geographic condition of a particular region determines the suitability of establishing a specific type of electricity generation plant (Pergola et al., 2020; Tercan et al., 2020). The feature of the electricity supply-demand market does incline decision-makers’ preferences for electricity generation technologies. As China’s largest electricity and fossil fuel importer, the YRD region has been provided many financial supports by decision-makers for wind and solar PV power, which could increase the electricity supply security without limitation of energy resources (Ji & Zhang, 2019; World Resources Institute, 2021b). On the other hand, the central government has released many critical regulations for nuclear power plants, which slow down the development of nuclear power (NEA, 2015). In order to fulfill the decision-makers’ demand of considering these factors, I will further consider the spatial citing potential of alternative electricity generation technologies and the temporal variation of decision-makers’ preferences in future research.

3.5 Conclusion and Policy Implications

This article aims to assess and enhance the sustainability of electricity generation technologies by applying a localized empirical dataset in the most significant electricity-importing region of China, the Yangtze River Delta region. Unlike previous research, which chose many technologies as the study objects, this study only selected seven technologies with great potential to develop in the specific study region. I aim to emphasize the practical significance of this research by choosing indicators relating to sustainable development issues of the study area and applying the empirical data to the weight of the indicators and some of the value of indicators. This research might be the first to assess the sustainability of the potential electricity generation technologies in the Yangtze River Delta region, crossing economic, environmental, social, and technical dimensions.

The research results show that pump-storage hydropower, nuclear power and on-shore wind power are evaluated as the most sustainable electricity generation technologies in the YRD region. Moreover, Solar PV has relatively lower sustainability but a higher potential to develop in the future. Therefore, it is crucial to enhance the manufacturing process of silicon film to minimize the negative environmental impact and improve the sustainability of solar PV. On the one hand, this research could be referable for decision-makers to design the future electricity generation mix plan. On the other hand, the sustainability assessment serves as an altering signal to remind the electricity sector to keep on the sustainable developing path.

Based on the results from this research, policy implications are suggested: 1. Promote the expansion of electricity transmission networks to increase the possibility to develop pump-storage hydropower. 2. Introduce the advanced technology of fusion reactors of nuclear power since the utility rate of fuel is a significant burden to expanding nuclear power establishment. 3. Efforts should be made to address the institutional constraints of the silicon film manufacturing process to limit its negative environmental impacts.

Although the MCDM approach can be a powerful tool to assess the sustainability of electricity generation technologies, the sustainable indicators vary between different development paths of different countries. The selected indicators of MCDM should adapt to the specific energy transition goal of a certain country or region. Therefore, the results could only be referred to other regions or provinces of China. Moreover, the sustainability of electricity generation technologies is not the only issue that the decision-makers considered in energy planning. The geographic spatial suitability, localized supply-demand market, and national institutional promotion/regulation also work as essential factors during energy planning. Thus, future research could be the specific analysis of the spatial suitability of electricity generation technologies. Furthermore, to associate these factors, I could further develop an agent-based model to simulate energy planning in the future.

Chapter 4: An agent-based spatial energy planning model for sustainable electricity generation

Abstract

Global interest in energy planning is rising as a result of the energy crisis aggravated by the Russian-Ukrainian War and the low-carbon energy transition outlined in the Paris Agreement. Previous studies incorporated perceptions of stakeholders from different sectors into quantitative models to initiate simulation scenarios. However, the dynamically changing stakeholder perceptions in response to the environment, experiences, and interactions with one another are insufficiently revealed. Addressing this gap, I develop an agent-based spatial energy planning model that integrates spatially resolved socioeconomic and infrastructural conditions to simulate the system transition of electricity generation, with empirical data from the Yangtze River Delta region. In particular, I apply the VIABLE model framework to the decision-making process of heterogeneous agents, who can adapt their investment decisions in electricity generation technologies at each iteration autonomously or in exchange with other agents. Finally, based on agents' individual or group decision scenarios the model depicts the future spatial energy landscape. Results show that the negotiated group decision scenario yields a more realistic and acceptable future energy landscape for the Yangtze River Delta region.

Keywords: Agent-based Modeling, Energy Landscape, Group Decision, Negotiation

4.1 Introduction

Motivated by the climate goal of the Paris Agreement and the energy crisis in fuel supply, a transition to a secure low-carbon electricity system has currently a high priority in many countries. Specific plans are required to regulate energy systems and support national or regional developing targets (Bhatia, 2014; Waisman et al., 2019). A secure low-carbon energy transition pathway explicitly needs to consider the spatial energy resources potentials (Y. Peng, Azadi, et al., 2022), transmission capacities, social-economic factors, and the inputs from different stakeholders. (Bhatia, 2014; Lombardi et al., 2020; Neumann & Brown, 2021). To fulfill the demand for sustainable energy planning, previous research developed various energy system/planning models (S. L. Chang et al., 2020; Mougouei & Mortazavi, 2017). The cross-sectoral synergies of energy planning models or frameworks became the main research focus to simulate or optimize future low-carbon energy landscapes (M. Chang et al., 2021; McGookin et al., 2021). In particular, the engagement of the stakeholders drawn from the institutional departments, academia, energy investment companies and other interest groups adds complexity and uncertainty but facilitates a better systematic understanding of reality (McGookin et al., 2021; Mougouei & Mortazavi, 2017). Therefore, more research attempts to engage relevant stakeholders (McGookin et al., 2021).

Stakeholders' perceptions can be involved in energy planning research through qualitative research, including surveys, interviews, workshops, etc. Structured workshops are applied to understand the stakeholders' opinions on specific evaluations and a step further to participate in long-term scenario development, focusing on possible future energy system evaluations (Ernst et al., 2018; Flacke & De Boer, 2017; Pfenninger et al., 2014). For instance, Carla et al. (Alvial-Palavicino et al., 2011) gathered visions from different stakeholders through discussion of structural renewable power development actions at the community level. The observed collaboration, competition, and negotiation between stakeholders have increased experts' interest in the group decisions of various stakeholders (Alvial-Palavicino et al., 2011; McGookin et al., 2021).

Due to their difficulty in quantification, stakeholder engagement is frequently ignored in quantitative energy models (Fattahi et al., 2020). To understand the engagement of stakeholders, many experts translate stakeholder perceptions into scenarios in optimization or simulation models to create integrated energy system maps, such as carbon capture and storage scenarios, high electricity consumption scenarios, and renewable energy scenarios (H. Chen et al., 2020). Optimization models search for energy pathways to minimize or maximize one particular factor (such as minimizing the energy supply cost or GHG emissions) (Shaaban et al., 2022). The MARKAL/TIMES (The Integrated MARKAL-EFOM System) uses environmental and economic indicators to assess the impacts of various energy technologies throughout their entire life cycle from energy extraction, supply, conversion and distribution, to end-use consumption (Xie et al., 2021). This bottom-up approach has been widely used on a national scale to minimize the total cost of energy supply (maximum surplus) or minimize net greenhouse gas emissions in the energy sector for different scenarios (Vaillancourt et al., 2020). One example of the simulation model is the LEAP (long-range energy alternative planning) model, which has been used to evaluate mitigation policies and find acceptable trade-offs between economic benefits and carbon reduction at the national level (Alsabbagh et al., 2017). Both MARKAL/TIMES and LEAP can project the environmental and economic impacts of various scenarios to determine the best energy planning strategy (Xie et al., 2021). These equation-based models break down the system into technical components and reduce the complexity of reality (Bale et al., 2015). Although these models incorporate stakeholder inputs through scenarios, stakeholders' iterative perceptions adapted from previous experiences and the dynamically changed socioeconomic conditions could not be sufficiently interpreted without feedback loops.

Agent-based modeling (ABM) can overcome the limits of equation-based models of energy systems, but its application to energy planning research is still rare. Some ABM has emerged to investigate the feasibility of agent-based electrification strategies with renewables. For example, Alfaro (Alfaro et al., 2016) applied ABM to simulate complex cross-sector energy systems and incorporated the central energy planner as an executive agent to find out suitable electrification strategies. Other agent-based models were derived using the VIABLE (Values and Investments for Agent-Based Interaction and Learning for Environmental Systems) framework developed by BenDor and Scheffran (BenDor & Scheffran, 2019) and have been used to predict sustainable, cost-effective, or optimal energy crop landscapes based on iterative decisions of multiple agents (Scheffran et al., 2007; Shu et al., 2017). In 2019, Shaaban et al. integrated GIS (geographic information systems) with ABM to simulate decisions for multiple agents in the energy sector of Egypt, spanning a time horizon from 2015 to 2100 (Shaaban et al., 2019b). These models have efficiently revealed the complexity of energy systems, including the cross-sector life cycle of energy systems and spatially explicit energy resource potentials.

To portray possible future energy landscapes, agent-based group decision models are a suitable tool to capture stakeholder engagements. However, there are still several limitations: First, although previous agent-based models incorporated multiple agents, energy models neglected social stakeholders as the energy system was managed, controlled, and consulted by policymakers, investors, or experts. Second, decision-making was often represented only by one executive stakeholder, such as the central energy planner in Alfaro's (Alfaro et al., 2016) model and a farmer in the optimal energy crop landscapes ABM (Scheffran et al., 2007). Third, the interplay between stakeholders has not yet been investigated, including collaboration, competition, and negotiation.

In order to fulfill these research gaps and combine the advantages of quantitative energy planning/system models, this paper proposes an integrated agent-based energy planning model. First, Geographic Information Systems (GIS) are applied to assess the spatial energy potentials and visualize a heterogeneous environment for the model. Second, multi-criteria decision analysis (MCDA) and cost-benefit analysis (CBA) are used to depict multiple stakeholders' decision processes; Third, the ABM covers three stakeholder types, including investors, policymakers, and the public, as decision-makers to simulate system-level energy landscapes individually or interactively. The novelty of this model lies in integrating ABM and Group decision approaches to simulate future sustainable spatial energy mix plans. This model is also possibly to be applied in a smaller spatial area at the city level or on a larger scale at the national level. In this paper, I applied the energy planning model to the Yangtze River delta region to answer the major research question: Which potential future electricity-mix landscapes would better secure a sustainable electricity supply in China?

The paper is structured as follows: Section 4.2 describes the overall methodology of the proposed agent-based group decision model. Section 4.3 presents the individual and group decision results from the model simulations. I compare the simulation results with the governmental energy planning in Section 4.4. The conclusions are presented in Section 4.5.

4.2 Methodology

4.2.1 Modeling framework and environment

In this research, I propose integrated agent-based modeling to characterize individual and group decisions regarding electricity generation technologies. As Figure 4.1 shows, each type of agent is assumed to be rational in the decision-making processes. The agents learn from their previous decisions, and dynamic environment and synchronously adjust their actions in the next iteration to dynamically increase values (BenDor & Scheffran, 2019). An extended closed-loop feedback cycle is formed when actors adapt their priority of choosing different potential electricity generation technologies (BenDor & Scheffran, 2018), including natural gas, nuclear, wind, solar, hydro, biomass, and WtE (waste-to-electricity) powers. The agent could make an individual decision according to its highest priority or join in group decisions by interplaying with others. Different group decisions are tested to simulate energy landscapes. The hypothesis is that equal-weight group decisions would form a more sustainable energy landscape and negotiation group decisions would form the most realistic energy landscape in the study region. I expect to result in a landscape dominated by low-carbon electricity technology in 2060.

To illustrate and validate how this model works in practice, this paper uses empirical data from the Yangtze River Delta region of China. The data inputs include spatially resolved topographic, socioeconomic, and infrastructure conditions, sustainable indicators and feed-in tariffs of different electricity generation technologies, electricity demand in 2020, and survey data from the Yangtze River Delta region. The whole model starts in the year 2020 and ends in 2060. I first present the essential components of the model. Second, I will show the individual and group decision-making procedures of agents. This model is presented under the ODD+ protocol (Overview, Design concepts, Details) (Grimm et al., 2020).

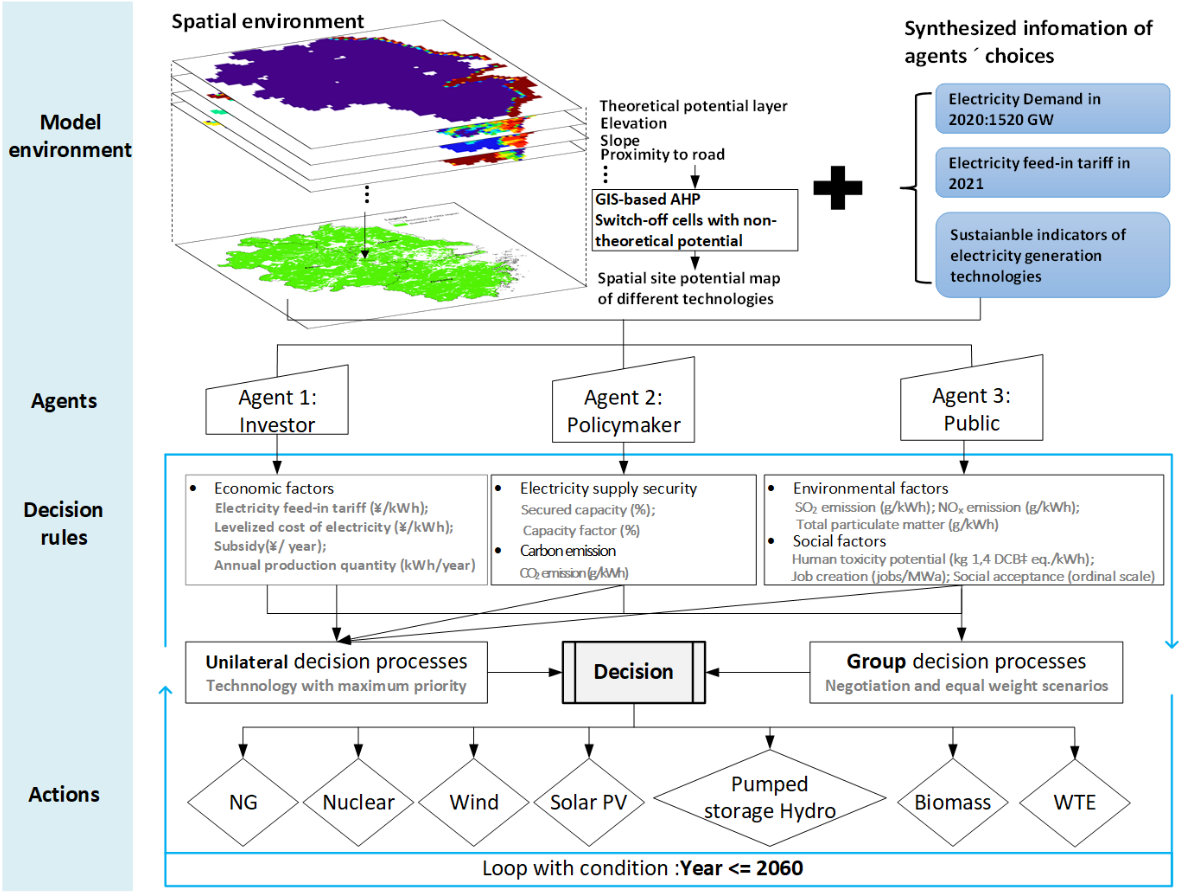


Figure 4.1 Model framework

The modeling environment is a composite of the spatial environment and the synthesized information of the local market. The spatial environment information presents the spatial site potential of various low-carbon electricity generation technologies. The synthesized information includes changing electricity demand, feed-in tariff, and the sustainable indicators of low-carbon electricity generation technologies.

The siting potential maps propose a suitability index for implementing alternative power plants, ranked from 0.1 to 1. The map is calculated by Geographic Information System (GIS)-based hierarchical process (AHP) functions by considering the spatial theoretical resources potential, as well as environmental, economic, and social criteria [2]. Since the GIS-based AHP calculates the outcomes by a weighted sum of criteria layers, spatial cells which have non-theoretical potential also obtain suitability indices. However, these spatial cells should be excluded while they are legally forbidden or have no technical potential (spatial theoretical potential is zero) to implement the relevant technologies. For example, 3km distance around protected areas are not allowed to install nuclear power plants. Therefore, as long as electricity generation technologies have zero theoretical potential in certain spatial units, they will not be available as a potential option for spatial decision-makers. More details can be found in Appendix 2.

The synthesized information is changing over the years based on the empirical data in 2020 in the Yangtze River Delta region (YRD region). First, the electricity demand was 1520.75 TWh in 2020 (Tsinghua University, 2020), increasing in the following years. The rate of increase in the first five years (2021-2025) is 5.6% per year, which is predicted to decrease by 0.2 every five years (World Resources Institute, 2021b). After 2045, the increasing rate is expected to be zero, and the total electricity demand in the YRD region will keep stable. Second, the detailed feed-in tariffs of electricity from alternative technologies are gathered (Table 1) and will be changing with the market share. Third, other information refers to the sustainability indicators of alternative low-carbon technologies, including the social, economic, and environmental attributes of various energy systems. The values of the sustainable indicators are gathered in China through literature reviews in my previous studies (Y. Peng, Yang, et al., 2022) and shown in Table 4.1.

Table 4.1 Feed-in tariff and sustainability indicators of electricity from alternative technologies (adapted from (Y. Peng, Yang, et al., 2022))

		NG	Nuclear	Wind	PV	Hydro	Biomass	WTE
ECO	Electricity feed-in tariff (Yuan/kWh)	0.4155	0.43	0.4153	0.4153	0.35	0.75	0.65
	References	(NDRC Shanghai, 2021; World Resources Institute, 2021a)	(NDRC, 2021b)	(Cinda Securities, 2021)	(Polaris solar energy, 2021)	(NDRC, 2021c; NDRC Jiangsu, 2019)	(XiangCai Securities, 2021)	(Xiang Cai Securities, 2021)

	Levelized cost of electricity (Yuan/kWh)	0.12	0.30	0.40	0.36	0.19	0.48	0.84
ENV	CO_2 emission (g/kWh)	527.08	36.99	22.71	57.71	13.90	-240.00	1112.25
	SO_2 emission (g/kWh)	0.14	0.04	0.02	0.20	0.03	0.27	0.12
	NO_x emission (g/kWh)	0.78	0.06	0.04	0.14	0.02	0.65	1.04
	Total particulate matter (g/kWh)	0.37	0.02	0.01	0.04	0.07	0.12	0.09
SOC	Human toxicity potential (kg 1,4 DCB‡ eq./kWh)	0.38	0.03	0.04	0.14	0.03	0.76	0.64
	Job creation (jobs/MWa)	1.16	1.13	3.68	9.64	14.55	3.48	1.90
	Social acceptance (ordinal scale)	21.34	20.67	28.76	28.28	27.61	17.46	18.77
TEC	Secured capacity (%)	84.50	84.50	50.00	0.00	50.00	85.00	85.00
	Capacity factor (%)	42.00	90.00	38.00	20.00	40.00	65.00	65.00

4.2.2 Agents

This model defines three types of agents who are the decision-makers in the energy planning system, including investors, policymakers, and the public. Agents are located in each spatial cell and adapt their decisions on various electricity technologies to achieve specific targets (such as profit maximization) in the study region. I defined an initial priority of technologies and their most considered indicators of sustainability development for each agent type through interviews and surveys. In January 2021, a qualitative survey was carried out to investigate decision-makers' priority of installing different electricity technologies and how they subjectively define a sustainable electricity generation system by selecting the most relevant and concerning factors. In the survey, the target interviewees included investors, policymakers, and the public in the Yangtze River Delta region. Interviews are designed based on a structured questionnaire. The interviewees were first asked to evaluate their pair-wise priority of selecting alternative electricity generation technologies. Afterward, they were asked to rate the importance of sustainability factors.

Agents' two main attributes result from the survey, shown in Table 4.2 and Figure 4.1. The first attribute, the initial priority $\boldsymbol{p_{i,n}(t = 0)}$ of agent i for alternative electricity generation technology n, has been determined through their pair-wise evaluation of willingness to implement different technologies. Table 2 shows the resulting values. Solar power is the most preferred technology among all agents, followed by wind and hydropower. The second attribute represents the most considered indicators (Figure 1) for each type of agent during energy planning. Investors are only caring about revenue-related indicators, including feed-in tariff, Levelized Cost of Electricity (LCOE), governmental subsidy, and annual production quantity. Policymakers are most concerned about the CO2 emission with a weight of 0.4392, followed by the secured capacity and capacity factor (Table 3). Capacity factor refers to "a ratio of actual electrical energy output to the maximum possible electrical energy output over a period" (IEA, 2019b), and the secured capacity of electricity generation technologies could be counted as securely available capacity at times of peak demand (IEA, 2012). The national government set the target to reach carbon neutrality by 2060 (Farand & Darby, 2020). Carbon reduction actions are taken forward in the electricity generation sector. In contrast, the public only considered social and environmental factors which influence their daily life. The relevant weights of different indicators are shown in Table 4.3.

Table 4.2 Agents' initial priority for alternative electricity generation technologies

i \ n	NG	Nuclear	Wind	Solar	Hydro	Biomass	WtE
Investor	0.222	0.147	0.172	0.214	0.120	0.085	0.040
Policymaker	0.174	0.096	0.240	0.248	0.168	0.045	0.031
Public	0.106	0.094	0.247	0.238	0.225	0.033	0.058

Table 4.3 Weight of sustainable indicators for policymaker and public

	Policymaker			Public					
Indicator	CO_2 emission	Secured capacity	Capacity factor	SO_2 emission	NO_x emission	Total particulate matter	Human toxicity potential	Job creation	Social acceptance
Weight	0.4392	0.3286	0.2322	0.2204	0.2173	0.2084	0.2132	0.0301	0.1106

4.2.3 Decision rules of unilateral agents

Fig. 3 illustrates the decision-making process of unilateral agents. Each year, agents select their most preferred electricity generation technology for the spatial cell of their locations. The model begins with adjusting an initial priority $\boldsymbol{p_{i,n}(t=0)}$ in 2020 according to the spatial site potential $\boldsymbol{SF_n}$. The spatial site potential $\boldsymbol{SF_n}$ of the different technologies have been assessed by ranking their suitability for implementation in the spatial area in the authors' previous research (Y. Peng, Azadi, et al., 2022). While the model runs year by year, the agents react to each year's socioeconomic conditions and re-evaluate their priorities $\boldsymbol{p_{i,n}(t)}$ for electricity generation technologies $\boldsymbol{n}$ towards a better outcome value $\boldsymbol{V_{i,n}(t)}$. Each year $\boldsymbol{t}$, agents adapt their priorities $\boldsymbol{p_{i,n}(t)}$ by comparing the marginal value of one technology with the weighted average marginal value of all technologies (equations 4.1 and 4.2). Therefore, for each individual agent, the technology with the highest priority $\boldsymbol{max\ p_{i,n}(t)}$ is the best choice for that year.

$$p_{i,n}(t) = p_{i,n}(t-1) + a_i * p_{i,n}(t-1) * \left(v_{i,n}(t-1) - \sum_{n=1}^{m} p_{i,n}(t-1)\ v_{i,n}(t-1) \right) \qquad \textbf{Equation 4. 1}$$

$$v_{i,n}(t) = V_{i,n}(t) / \left(\sum_{n=1}^{m} V_{i,n}(t)\right) \qquad \textbf{Equation 4. 2}$$

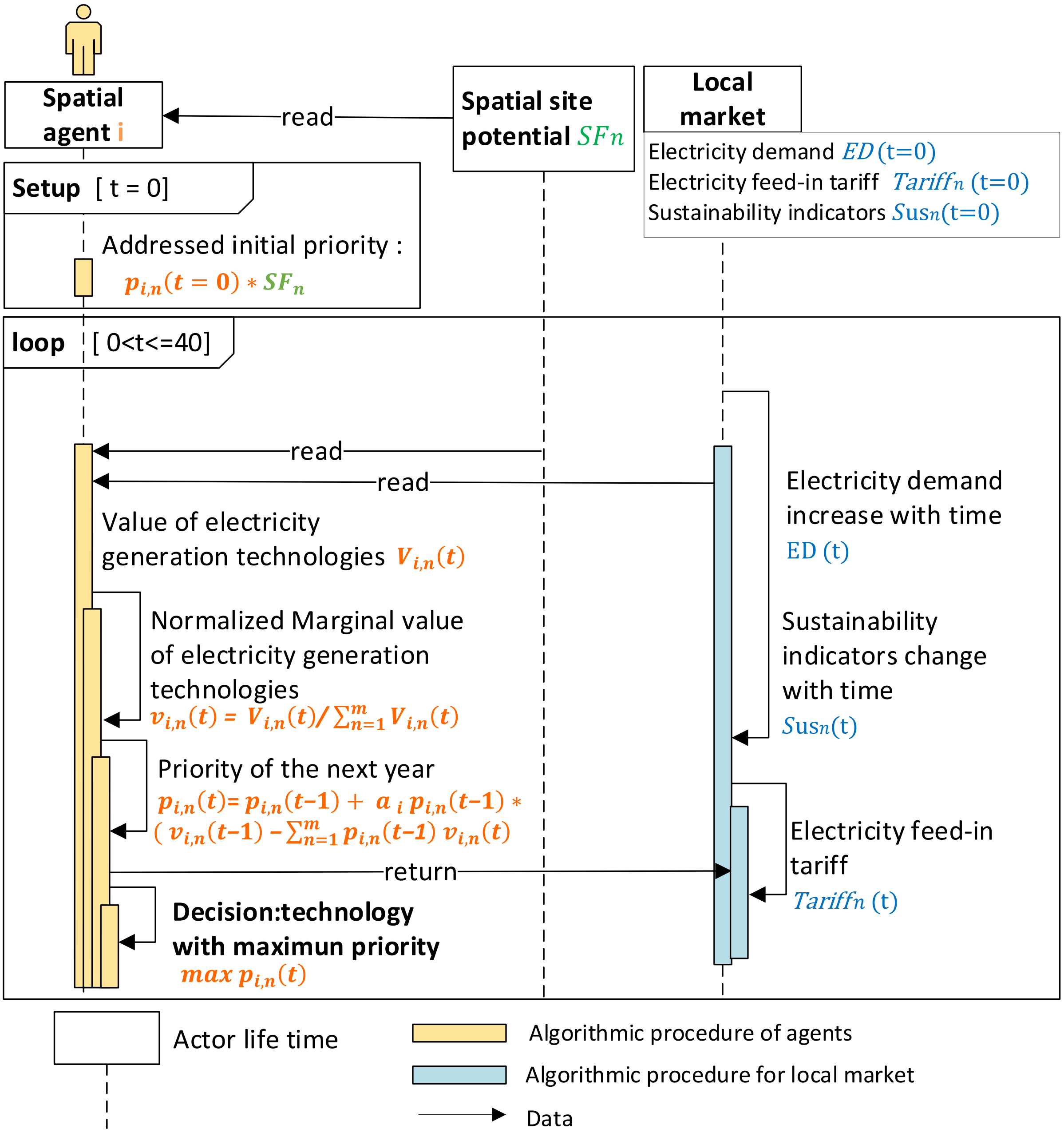


Figure 4.2 Framework of unilateral decisions

The outcome value function $V_{i,n}(t)$ varies for each agent in response to its considered indicators for future electricity generation. Investors ($i = 1$) only consider the annual revenue they could gain from electricity production (Equation 4.3). Therefore, investor value is based on a simplified cost-benefit function (Mishan & Quah, 2007), which includes the direct cost and benefit of power generation. The annual revenue is a function of the feed-in tariff of electricity $Tariff_n(t)$, the Levelized Cost of Electricity $LCOE_n$, the quantity of electricity production $EQ_n(t)$ and the subsidy $Subsidy_n$ received from the government. Investors could also consider the spatial site potential SF_n of technology in their value function $V_{1,n}(t)$.

$$V_{1,n}(t) = SF_n * ((Tariff_n(t) - LCOE_n + Subsidy_n) * EQ_n(t)) \qquad \textbf{Equation 4.3}$$

Policymakers ($i = 2$) and the public ($i = 3$) tend to consider technical, social, and environmental criteria in their decision process, which is measured with different units and ranges (Table 4.1). Therefore, I normalize these criteria and use the multi-criteria decision-making (MCDM) process to integrate these criteria. The value of policymakers and the public is the weighted sum of their considered sustainable indicators (Equation 4.4). The relevant weights of indicators for policymakers and the public ($\boldsymbol{W_{i,j}}$) are resulting from the survey data shown in Table 4.3.

$$\boldsymbol{V_{2\ or\ 3,n}(t) = SF_n * (\sum W_{i,j} * Indicators_j)} \qquad \textbf{Equation 4.4}$$

In the context of current stresses on reaching carbon peak and carbon neutrality in China, policymakers' most substantial concerns are to reduce CO2 emissions and secure the electricity supply. Consequently, secured capacity $\boldsymbol{SC_n}$ and capacity factor $\boldsymbol{CF_n}$ of electricity generation technologies are considered in the decision process. The value function $\boldsymbol{V_{2,n}}$ is the weighted sum of these three factors (Table 3). The public only has indirect influences in the decision-making process of energy planning. However, they are the actors who received direct environmental and social impacts from the technology selection. Hence, the public works as an essential agent in this model and considers environmental (SO_2 emissions $\boldsymbol{SO_{2\ n}}$, NO_x emissions $\boldsymbol{NO_{x_n}}$ and total particulate matter $\boldsymbol{TPM_n}$) and social factors (Human toxicity potential $\boldsymbol{HTP_n}$, Job creation $\boldsymbol{JC_n}$ and Social acceptance $\boldsymbol{SA_n}$) in selecting its preferred energy technologies (Table 4.3).

4.2.4 Agents' group decision rules

With multiple participating stakeholders, individual participation in group decision-making can be considered, either based on averaging or negotiation interplay in the group (Marreiros et al., 2007). I build two group decision-making processes shown in Figure 4.3 based on the theory of social decision scheme (SDS) (Green & Taber, 1980; Stasser, 1999). The first is named a negotiation decision rule, which is based on the concession and tradeoff of the agents (Xianrong et al., 2014). In reality, energy planning is determined by investors and policymakers, who have the authority to join in the energy planning negotiation. The public indirectly influences the negotiation process. Second, I simulate the energy landscape under an equal weight group decision rule with the same participation of all stakeholders (Hinsz, 1999). In the equal-weight scenario, agents are assumed to have the same authority in energy planning. Therefore, the agents reach an agreement based on the average of all the individual members' priorities. Therefore, in this case, the group priorities of different technologies in each spatial cell are calculated based on each 'stakeholder's priorities of technologies.

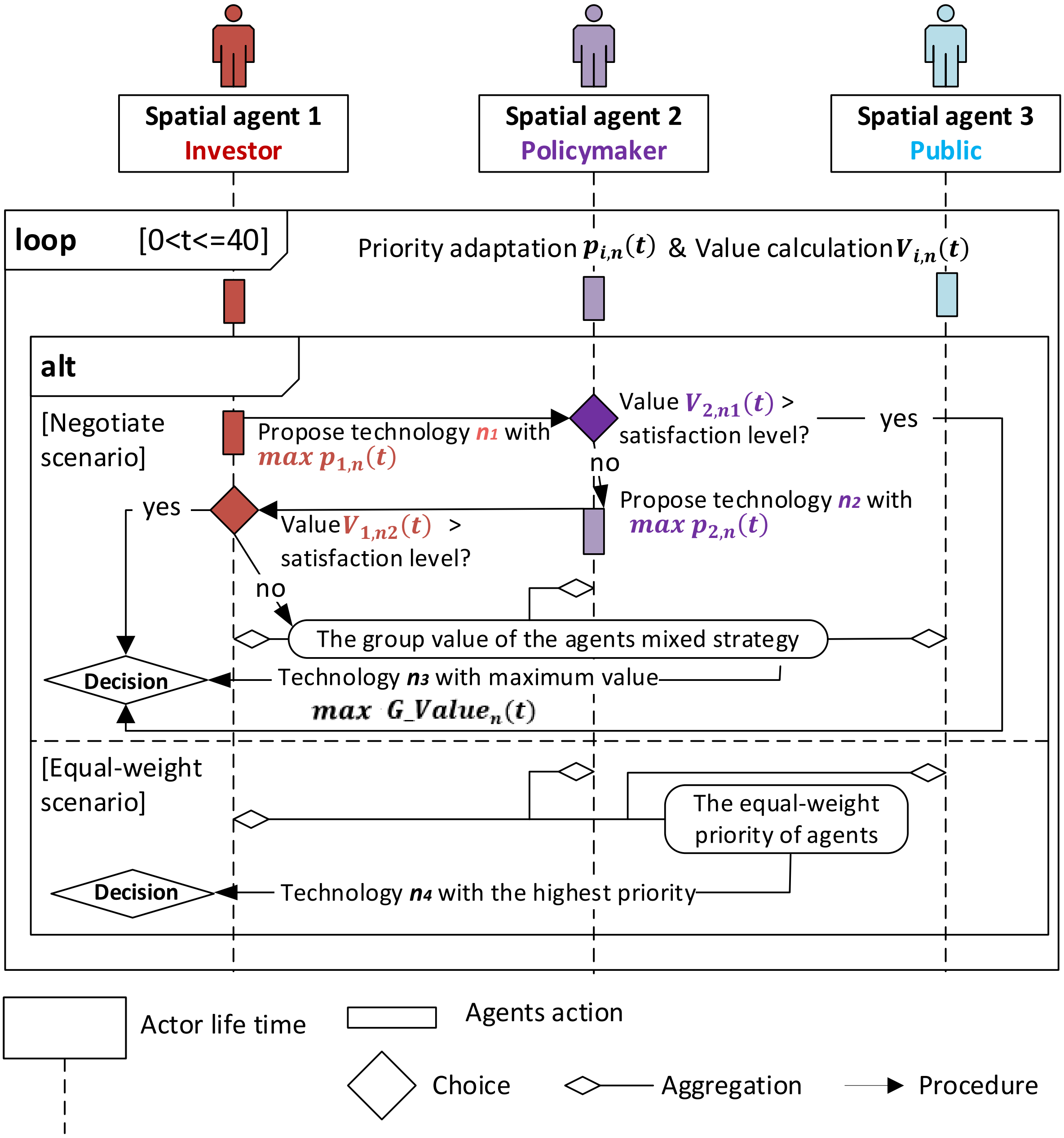


Figure 4.3 Framework of group decision

In this model, the agent negotiation decision rule is characterized by the simplified approval process of China's power plant installation project (Figure 4.3). The investors initially evaluate the feasibility of establishing certain power plants in a spatial area based on the spatial site potential, and secondly, estimate the value ($V_{1,n}(t)$)) they could gain from different choices and subsequently adapt their priority of alternative technologies (IEC, 2018). Investors working as a proposer first suggest a feasible and profitable technology with maximum unilateral priority as the initial negotiation proposal n_1. Afterward, policymakers from the provincial or national-level Development and Reform Commission will act as a monitor to evaluate the project n_1 according to the carbon emission impacts and the electricity supply security ($V_{2,n}(t)$). If the policymakers can obtain their minimum required value (minimum satisfaction level) by choosing the energy technology n1 proposed by the investor, they would compromise and agree to choose n_1 even if it is not their optimal choice. In practice, the minimum satisfaction level is a complex value that can include environmental impact assessment, social stability risk assessment, resource assessment, environmental impact assessment, safety pre-evaluation, etc. In this model, I defined the minimum satisfaction level as the negotiator's bottom-line value that the negotiator must reach by choosing technologies. The minimum satisfaction level should be determined by negotiators through workshops. Without the following up field trip, I currently set the minimum satisfaction level to 0.4, representing a medium value that negotiators can obtain by selecting different technologies.

If the policymakers agree with initial proposal n_1, the process is ended, and the initial proposal becomes the negotiation outcome. If the agreement is not reached, the policymakers will suggest counter-proposals for a technology n_2, which also needs to be able to satisfy investors' required minimum economic welfare (minimum satisfaction level). The investors' minimum satisfaction level is also set to 0.4. If the investors do not obtain the minimum satisfaction level by selecting technology n_2, the negotiation fails.

Finally, if the negotiation between investors and policymakers fails, this scenario determines a deal n_3 with the maximum group utility. All agents join in the decision, and the group utility of technology can be calculated based on the agents' mixed strategy. In this model, each agent adapts its priorities $\boldsymbol{p_{i,n}(t)}$ of different technologies in each time interval, which can be seen as the possibility to select technologies, and the values for agents to choose technologies also change in each time interval. Therefore, to identify the technology with maximum group utility, I applied game theory to find the optimal choice based on agent mixed strategies. The mixed strategies of agents are shown in Table 4. One agent's utility in choosing a technology is the value the agent can obtain while other participants make their choices. Each term in equation 4.5 represents the corresponding utility that each agent can obtain by choosing a technology n. Agents may result in different optimal choices, and the optimal choice of an individual agent may not be the optimal choice of the group, which could lead to a prisoner's dilemma. The group utility of each technology $\boldsymbol{Utility_n(t)}$ is the sum of all agents' utility in selecting technologies (Equation 4.5). To maximize the utility of the group, I will choose the energy technology with the maximum group utility $\boldsymbol{max\ Utility_n(t)}$. More insights into this scenario will be shown in section 4.3.4.

$$\boldsymbol{Utility_n(t) = (V_{1,n}(t) * \begin{pmatrix} p_{2,1}(t) \\ p_{2,2}(t) \\ \vdots \\ p_{2,n}(t) \end{pmatrix} * \left(p_{3,1}(t)\ p_{3,3}(t) \ldots\ p_{3,n}(t)\right) + (V_{2,n}(t) * \begin{pmatrix} p_{1,1}(t) \\ p_{1,2}(t) \\ \vdots \\ p_{1,n}(t) \end{pmatrix} *}$$

$$\boldsymbol{\left(p_{3,1}(t)\ p_{3,3}(t) \ldots\ p_{3,n}(t)\right) + (V_{3,n}(t) * \begin{pmatrix} p_{1,1}(t) \\ p_{1,2}(t) \\ \vdots \\ p_{1,n}(t) \end{pmatrix} * \left(p_{2,1}(t)\ p_{2,3}(t) \ldots\ p_{2,n}(t)\right)} \quad \textbf{Equation 4.5}$$

Table 4.4 Mixed strategies of agents in selecting different technologies

		public								
		NG $p_{3,1}(t)$				Nuclear $p_{3,2}(t)$				…
		policymaker				**policymaker**				...
		NG $p_{2,1}(t)$	Nuclear $p_{2,2}(t)$	Wind $p_{2,3}(t)$	…	NG $p_{2,1}(t)$	Nuclear $p_{2,2}(t)$	Wind $p_{2,3}(t)$	...	...
Investor	NG $\boldsymbol{p}_{1,1}(\boldsymbol{t})$	$V_{1,1}V_{2,1}V_{3,1}$	$V_{1,1}V_{2,2}V_{3,1}$	$V_{1,1}V_{2,3}V_{3,1}$	…	$V_{1,1}V_{2,1}V_{3,2}$	$V_{1,1}V_{2,2}V_{3,2}$	$V_{1,1}V_{2,3}V_{3,2}$	...	...
	Nuclear $\boldsymbol{p}_{1,2}(\boldsymbol{t})$	$V_{1,2}V_{2,1}V_{3,1}$	$V_{1,2}V_{2,2}V_{3,1}$	$V_{1,2}V_{2,3}V_{3,1}$	…	$V_{1,2}V_{2,1}V_{3,2}$	$V_{1,2}V_{2,2}V_{3,2}$	$V_{1,2}V_{2,3}V_{3,2}$	...	...
	Wind $\boldsymbol{p}_{1,3}(\boldsymbol{t})$	$V_{1,3}V_{2,1}V_{3,1}$	$V_{1,3}V_{2,2}V_{3,1}$	$V_{1,3}V_{2,3}V_{3,1}$	…	$V_{1,3}V_{2,1}V_{3,2}$	$V_{1,3}V_{2,2}V_{3,2}$	$V_{1,3}V_{2,3}V_{3,2}$	...	...
	PV $\boldsymbol{p}_{1,4}(\boldsymbol{t})$	$V_{1,4}V_{2,1}V_{3,1}$	$V_{1,4}V_{2,2}V_{3,1}$	$V_{1,4}V_{2,3}V_{3,1}$	…	$V_{1,4}V_{2,1}V_{3,2}$	$V_{1,4}V_{2,2}V_{3,2}$	$V_{1,4}V_{2,3}V_{3,2}$	...	...
	…	...	...	...	...	...	...	...	...	...

Compared to the negotiated scenario based on reality, the equal weight group decision scenario is an ideal case in which all three agents equally join in the decision-making processes (Figure 4.3). All the sustainability indicators considered by different agents would be included in the decision-making. Although the public's perception is not directly considered in energy planning, I assume the public also joins in the group decision. The group priority of different technologies is calculated by the weighted sum function of priorities of all three types of agents with the same weight (Equation 4.6). Afterward, the technology with maximum priority can be found for each spatial cell based on the group priority $\boldsymbol{p}_{\boldsymbol{group,n}}(\boldsymbol{t})$.

$$\boldsymbol{p}_{\boldsymbol{group,n}}(\boldsymbol{t}) = \mathbf{1/3} * \boldsymbol{p}_{\mathbf{1},\boldsymbol{n}}(\boldsymbol{t}) + \mathbf{1/3} * \boldsymbol{p}_{\mathbf{2},\boldsymbol{n}}(\boldsymbol{t}) + \mathbf{1/3} * \boldsymbol{p}_{\mathbf{3},\boldsymbol{n}}(\boldsymbol{t}) \qquad \textbf{Equation 4.6}$$

The main difference between the equal weight and the negotiation group decision scenarios is that instead of considering the agent's values ($\boldsymbol{V}_{\boldsymbol{i,n}}$) in each time interval, marginal values (for future sustainable development) are considered in the unilateral scenario. The ideal group decision scenario is built for desirable sustainable development in the future. Therefore, it does not consider the immediate values caused by its selection. As a result, I expect to see an energy landscape fully covered by highly sustainable technologies.

4.3 Results

4.3.1 Comparison of technology priorities across agents

Figure 4.4 compares the changes in the average priorities of various technologies across all spatial cells for the three agents (investors, policymakers, and public) throughout the period 2020 - 2060 (i.e., 0 – 40 ticks in NetLogo). The average priority of 2020 shown in Figure 4 is the value obtained by adjusting the initial priority based on the spatial site potential and can be called as the starting priority. It can be observed for each agent that starting average priorities of solar PV and wind in 2020 are higher than the initial priority (Table 4.2). This results from the general high spatial site potential of solar and wind power over the study area. The starting priority of NG varies substantially between agents because NG delivers high economic benefits to investors and ensures the security of the energy supply, whereas it has high carbon emissions and negative environmental impacts. There are other electricity generation technologies (nuclear, biomass and waste-to-electricity) starting with very low priorities and remaining low for the whole period.

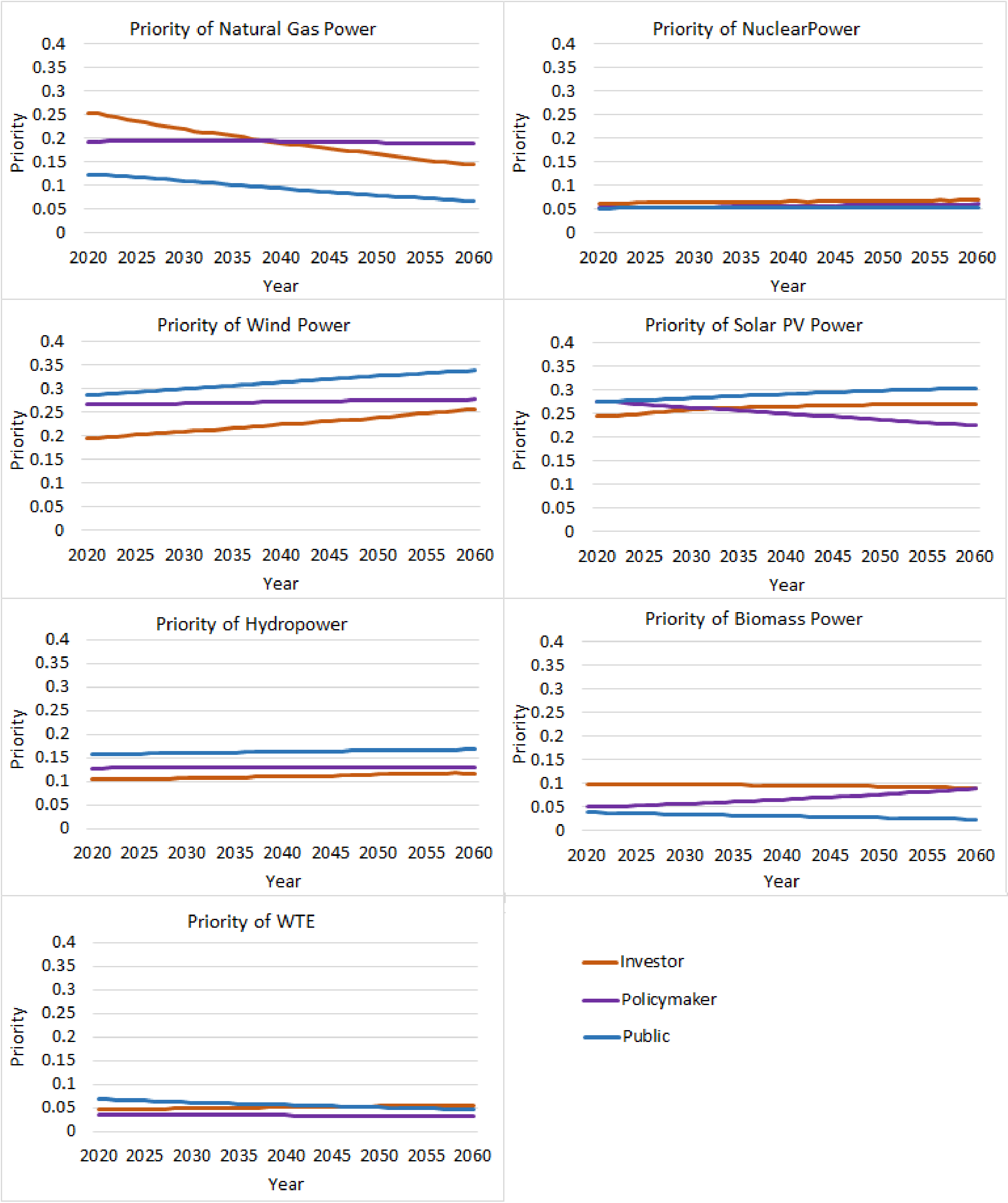


Figure 4.4 The average priorities of each agent type (investor, policy maker, and publics) on selecting different technologies for electricity generation.

The priority of agents in natural gas-fired power is gradually declining throughout the simulation period, especially for investors and the public. Although natural gas has high economic advantages (low Levelized Cost of Electricity), its low spatial site potential leads to lower investing priorities. The low spatial theoretical site potential of natural gas results from heavy reliance on external imports. The public assigns decreasing priority to Natural Gas power because it leads to high carbon emissions or air pollution (SO2, NOx, TPM). Compared with investors and the public, policymakers highly weigh the supply security of technologies. Therefore, policymakers' priority of natural gas power decreases slightly.

Investors' priority of PV and wind energy will continue to rise. As the priority of natural gas decreases, its production and market share also decrease. Under these circumstances, solar PV and wind power, which have high spatial potential, are gaining larger market shares with the decreasing feed-in tariffs. Accordingly, investors' priority of PV and wind energy will continue to rise. In addition, policymakers and the public are attaching increasing priority to wind power because it is clean, safe, and has a moderate level of security of supply. Another clean energy alternative, solar, is becoming less preferred by policymakers because of its low electricity supply security.

The agents' priorities are very different between biomass and WTE power. Biomass power is at disadvantage in the market competition due to low initial priorities and high LCOE. Therefore, the investors' priority of biomass power keeps decreasing. In comparison, although the LCOE of WTE technology is also high, WTE is more competitive because of the high site potential caused by the local sufficient waste resources. So, the investors' priority of WTE slightly increase. Policymakers will rank biomass power as a higher priority because of its strong carbon sequestration capacity throughout the biomass growing phase of the whole life cycle. However, the current generation technologies have low public acceptance of biomass and WTE because the stink smell and waste generated during power generation dramatically affects their daily life. Nevertheless, I do not rule out that public acceptance will increase in the future with continuous innovations in desulfurization, deacidification, and waste treatment technologies.

In addition, the priority of hydropower and nuclear power increases slightly in areas with theoretical potential due to their low-carbon, consistent supply features, and public acceptance.

4.3.2 Energy landscape for unilateral scenarios

In Figure 4.5, the map shows each agent's unilateral decision, which is the technology with the highest priority, in the years 2021 and 2060. It is easy to find that the spatial coverage of nuclear and hydropower almost does not change from 2021 to 2060 for all three types of agents. The southwest hilly areas especially suit hydropower and have low-level spatial suitability for other technologies because of the higher elevation, steeper slopes, and under-developed transportation connections, which would cause high investment costs and technical difficulties for other technologies. Therefore, in this area hydropower has been ranked with higher priority for all agents for the whole period. Nuclear power is primarily selected in the coastal region due to the high spatial siting potential around the coastal area and its low-carbon and high supply-security features. The north coastal region is also highly suitable for other technologies because of its flat geographic condition, highly constructed natural gas pipeline, high-voltage transmission grid, and high theoretical potential of wind and solar PV power (wind and solar resources). Thus, NG, solar PV and wind power also have high priority in some coastal areas for different types of agents.

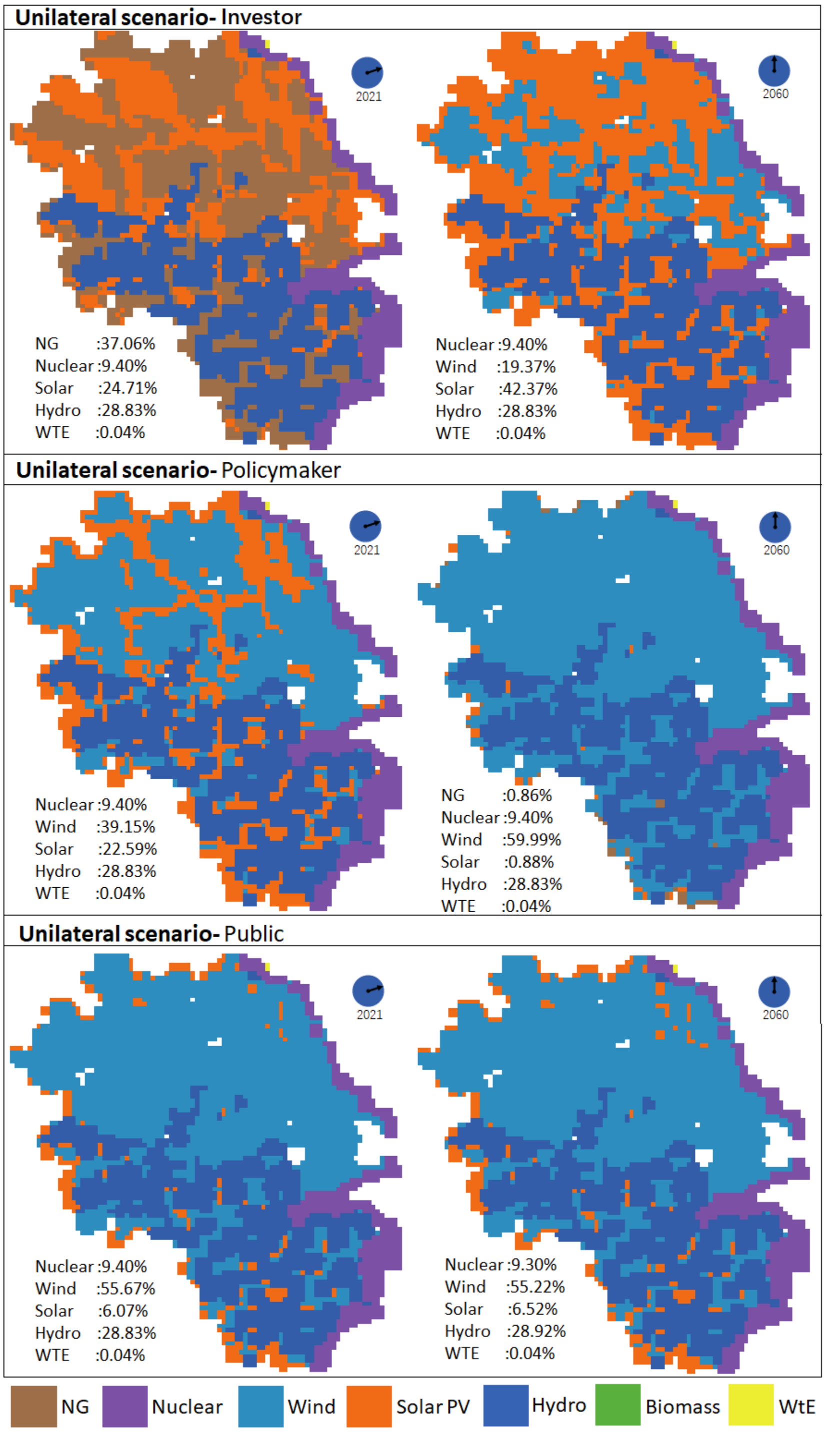


Figure 4.5 Energy landscapes of each agent's unilateral decision in the years 2021 and 2060

In the unilateral decision scenario, natural gas power starts as a predominant technology in 37.06% of the spatial cells. Although the spatial suitability is high for solar PV, wind and biomass power in the northeastern spatial cells, NG has become the dominant technology in most spatial cells because of its highest starting priority in 2020. The remaining spatial areas are covered by solar PV, hydro, nuclear, and WTE technologies. With the model running, solar PV and wind power gradually replace NG, reaching 42.37% and 19.37% coverage by 2060 because NG only has high spatial site potential in the spatial cells adjacent to natural gas pipelines. Therefore, investors obtain high economic returns only in these finite spatial cells by choosing NG. Therefore, as the model runs, in the most northern spatial cells, investors start to choose solar PV and wind power, which have high spatial site potentials. This enables solar PV and wind power to seize the market and lower the feed-in tariff. Therefore, in the later years, solar PV and wind receive higher priority even in spatial cells with high NG potential since they can deliver higher annual revenue with low feed-in tariffs and high production.

In the policymaker unilateral decision scenario, wind power covers 39.15% of spatial cells, which is followed by hydro (28.83%), solar PV (22.59%), nuclear and WTE. Although solar PV has the highest average starting priority in 2020 and a high spatial site potential in most spatial cells, it fails to become the dominant power due to its low marginal value, which results from its lowest security capacity and capacity factor among all technologies. Since policymakers are seeking technology, which is more secure and stable for energy supply, solar PV coverage declines while wind coverage increases at a high rate, eventually reaching substantial coverage (59.99%) in 2060.

In the public unilateral decision scenario, with the highest average starting priority, high spatial site potential, and clean features, wind power obtained an overwhelming coverage (56.15%) in 2021. Environmental and social influences are the most important decision factors for the public in selecting technologies. Therefore, as the cleanest technology, wind power wins the highest social acceptance. Subsequently, with the model running, the public's priority of wind power keeps increasing and becomes the preferable technology in 55.22% of spatial cells in 2060.

No agents chose biomass power as their primary choice in 2021, which resulted from the agent's very low initial priority for biomass. Since 2006, China has started to promote the development of biomass power significantly. The announcement of the Renewable Energy Law in 2006, especially the renewable electricity tariff subsidy policy, provided financial support and attracted many investors. However, the rapid development of the biomass power industry during the past 15 years brought many problems. Firstly, the high cost of biomass fuels and the lagging of subsidies have disappointed investors. Secondly, current biomass power generation technology is lagging behind. China's mainstream biomass power generation boilers use circulating fluidized bed technology, modified from traditional coal-fired boilers. It cannot leverage the advantages of biomass energy but causes a large amount of pollution and reduces public acceptance. Third, the government's early announced subsidy policy attracted many investors who did not hold well-qualified technics, which resulted in a disorganized image of the biomass power industry. Policymakers subsequently lost faith in the biomass power sector. Therefore, the agents' initial priorities of biomass power are very low and could not largely increase without great effort in improving biomass power subsidy policy, technological innovation, and industry reshuffling.

4.3.3 Energy landscape for group decisions

The energy landscapes of negotiation group decision and equal weight group decision scenarios in the years 2021 and 2060 are presented in Figure 4.6. Maps show the selected technologies under negotiated and unilateral group decision rules. The same applies to the unilateral scenarios, in which the southwest hilly areas with high hydro site potential are dominated by hydropower, and the eastern coastal regions with high nuclear site potential are dominated by nuclear power for the whole simulation period.

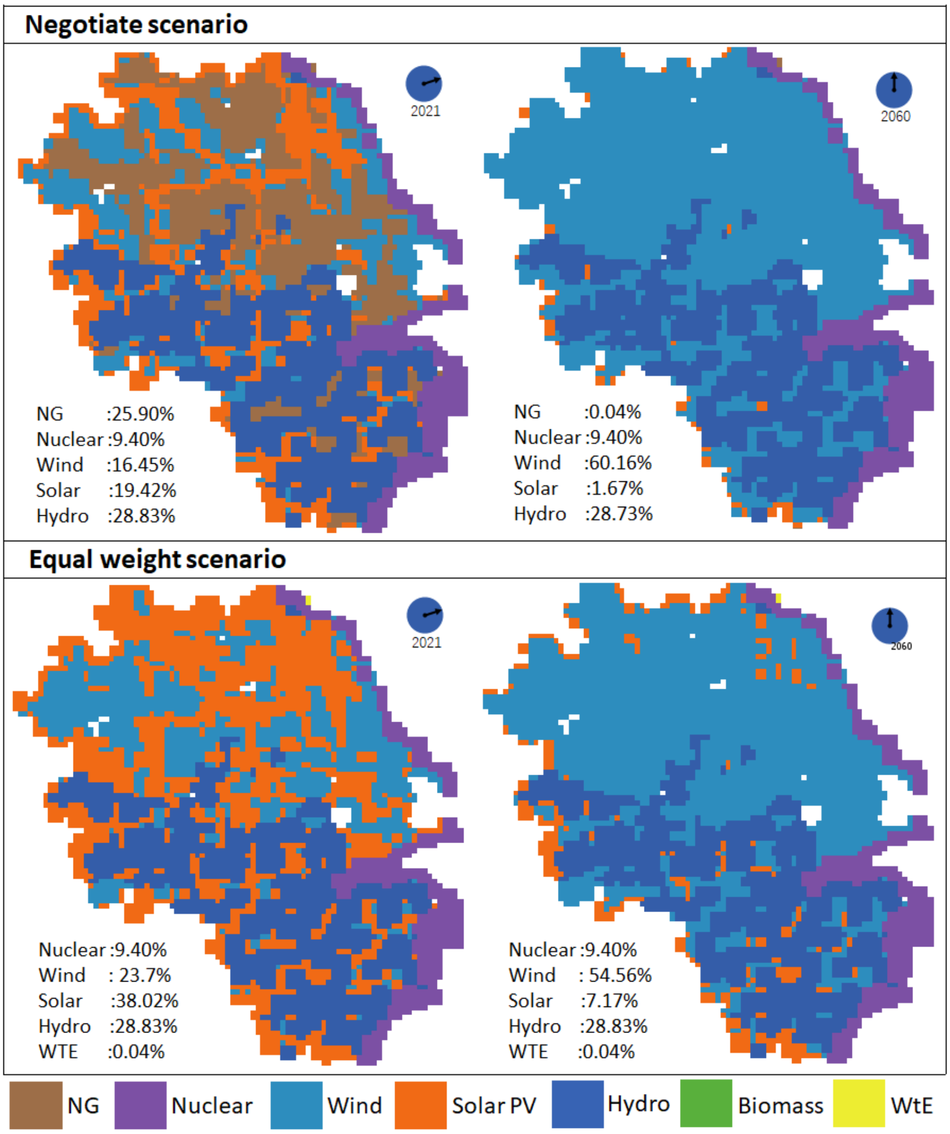


Figure 4.6 The map of the most recommended technology under negotiation and equal weight scenario in the years 2021 and 2060

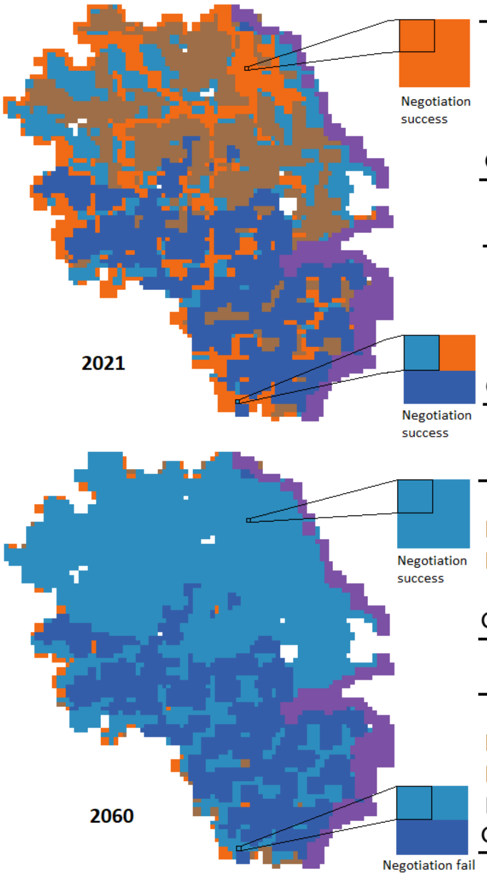
In the negotiation scenario, in 2021, except for the areas covered by hydropower and nuclear, NG covers most of the remaining spatial cells, reaching 25.90%, followed by solar PV (19.42%) and wind (16.45%). As shown in Figure 5, in 2021, investors first proposed solar PV and NG in most spatial cells. However, solar PV does not satisfy policymakers' minimum requirement of carbon emissions and electricity supply security in some cells with low spatial site potential. In these cells, wind power is proposed by policymakers as an alternative and subject to a secondary evaluation by investors. If the annual economic benefits generated by wind power meet the requirements of the investors, wind power will be selected. If this negotiation process fails, the technology with the maximum utility benefit will be selected based on the mixed strategy of all agents. At any time, wind power generates the largest utility in most spatial cells in the Northeast region because it is a clean energy source with very low carbon emissions, high public acceptance, relatively secure power supply capacity, and substantial site potential across the study area. As the model runs, when investors' priority for NG gradually decreases, the technology proposed by investors becomes solar and wind in most spatial cells. However, solar PV is unable to meet the minimum satisfaction level of policymakers due to its unreliable power supply capacity. Therefore, wind energy will be chosen according to the second proposal or maximum utility of agents mixed strategy. Consequently, in 2060, wind power will cover most spatial cells (60.16%).

In the equal-weight scenario, the landscape started with a dominant coverage of solar PV (38.02%) in 2021. This was because solar PV had a high equal weighted priority in most spatial cells. As the model runs, more highly sustainable technologies are chosen over the study region by including the public in the group decision. In my model, different agents are caring about different sustainable factors. Investors only care about revenue; policymakers care about carbon emission and supply security; the public cares about the technologies' socio-environmental influences. Therefore, the sustainable landscape results from the integration of all agents' priorities. The spatial coverage of nuclear and hydropower will not change because of its socio-economic, environmental advantages and high spatial site potential. The largest difference shown is in the northeast, where wind power gradually replaces solar PV as the most recommended technology in many spatial cells. This is because wind power is considered as the best (most sustainable) choice when integrating the revenue, environmental, and social impact factors (Y. Peng, Yang, et al., 2022). Therefore, wind power will become the primary choice in the spatial cells with high wind site potential. In 2060, 92.79% of the spatial area is covered by highly sustainable technologies, including wind, hydro and nuclear power.

The recommended technologies in the model spatial cells are determined based on the spatial circumstances and decision makers' preferences. The suggested landscape can provide valuable, informative input for future energy planning. To supply the energy demand of the study area does not require the overall coverage of electricity generation technologies, which means the map only represents the most recommended technologies in the spatial cell under different scenarios but does not require overall installation. By comparing the two scenarios presented, I find that the energy landscapes have significant differences between these two scenarios in early 2021. It results from different group decision mechanisms. In the early phase of the negotiation scenario, investors and policymakers still rate NG with high value. Therefore, NG has been recommended in many spatial cells. In comparison, under the equal weight scenarios, more environmental and social impacts have been considered, so wind power became a highly recommended technology in 2021. However, by 2060, the energy landscapes will become similar, with dominant wind power in most of the areas in the study region, because wind power is the most sustainable technology (Y. Peng, Yang, et al., 2022), which obtains a large value for each agent. In the future, more group decision scenarios can be modeled, such as the central tendency and consensus-based decision schemes (Hinsz, 1999).

4.3.4 Insights of negotiation group decisions

To better understand the group negotiation decision process, I selected agents of two random spatial cells to trace and observe their decision process. The concrete decision results and related data are shown in figure 4.7. The color in the enlarged cell represents the decision on energy technology in the negotiation scenario. The tables show the agents' utilities in selecting each technology and the collective group utility under the agents' mixed strategies. The utility tables are the calculation results of the selected agents from Table 4.4 and equation 4.5.



	NG	Nuclear	Wind	Solar PV	Hydro	Biomass	WTE
Investor	0.04	0	0.22	0.24	0	0.03	0.02
Policymaker	0.11	0	0.1	0.08	0	0.08	0.01
Public	0.05	0	0.21	0.22	0	0.01	0.01
Group Utility	0.22	0	0.53	0.55	0	0.13	0.05

	NG	Nuclear	Wind	Solar PV	Hydro	Biomass	WTE
Investor	0.01	0	0.17	0.16	0	0.03	0.02
Policymaker	0.10	0	0.08	0.06	0	0.07	0.02
Public	0.05	0	0.17	0.15	0	0.01	0.01
Group Utility	0.17	0	0.42	0.36	0	0.12	0.05

	NG	Nuclear	Wind	Solar PV	Hydro	Biomass	WTE
Investor	0.013	0	0.147	0.120	0	0.028	0.016
Policymaker	0.054	0	0.124	0.109	0	0.074	0.023
Public	0.041	0	0.226	0.188	0	0.028	0.012
Group Utility	0.108	0	0.497	0.417	0	0.131	0.051

	NG	Nuclear	Wind	Solar PV	Hydro	Biomass	WTE
Investor	0.013	0	0.087	0.071	0	0.030	0.013
Policymaker	0.053	0	0.076	0.065	0	0.079	0.020
Public	0.040	0	0.134	0.111	0	0.030	0.010
Group Utility	0.106	0	0.297	0.247	0	0.138	0.042

Figure 4.7 Examples of agents' negotiation results and utility on selecting different technologies in 2021 and 2060

Agents reach negotiation agreements with investors and policymakers in these two selected spatial cells in 2021. Agents agree to select solar power in the selected north cell and wind power in the selected south cell through negotiation. The negotiation process results in the technology which has maximum group utility. It validates the negotiation process as effective communication between agents, which could lead to better results. As an example, the utility table of agents in the north cell shows that without negotiation, the policymakers would rationally select natural gas power as their decision. Through the negotiation, policymakers make a concession to agree on solar PV, which leads to better group utility.

In the two examples of 2060, agents reach an agreement in the selected north cell and cannot reach negotiation agreements in the selected south cell in Figure 4.7. In the north cell, each agent can win the highest utility by choosing wind power, regardless of which technology others choose. They also quickly reach an agreement on wind power as the negotiation result. In the south cell, neither policymakers would agree on investors' proposed wind technology nor investors could make the concession. The negotiation process fails, and the final group decision turns on the technology with maximum group utility.

In the negotiation scenario, although there is no guarantee of reaching a negotiation agreement between investors and policymakers, agents’ final group decisions tend to achieve better group utilities.

4.3.5 Future projected energy mix and model validation

This section presents the future projected energy mix based on the decision from unilateral and group decision scenarios. Second, I compare the simulation results with the statistical data of the electricity production mix in 2021. Since the model started with the simulation in 2021, I can only validate it through the historical electricity production data in 2021.

According to the projected study of electricity consumption, the growth rate in YRDR in 2020 is 5.6%, decreasing by 20% every five years (Cinda Securities, 2021). Therefore, it is possible to calculate the future electricity consumption. Second, I subtract the electricity generation data for 2020 (1249.7 TWh) (National Bureau of statistic China, 2022) from the projected electricity consumption to obtain the required additional electricity demand. Third, I calculate the future additional electricity generation for each technology by multiplying the spatial coverage of different technologies with the projected electricity demand for different years. Finally, by adding the additional electricity production for each technology to the existing production data in 2020 (Table 4.5), the projected energy mix for 2021 and 2060 is shown in Table 4.6, respectively.

Table 4. 5 Installed capacity and electricity production in 2020 in the YRDR

	Installed capacity (MW)	Installed capacity (%)	Electricity production (TWh)	Electricity production (%)	Full load hours (hrs) *
Thermal power	244480	68.85	1008.8	80.72	4126
Nuclear power	14600	4.11	106.7	8.54	7308

Wind power	22270	6.27	34.1	2.73	1531
Solar power	47080	13.26	43.8	3.50	930
Hydropower	19100	5.38	30.7	2.46	1607
Biopower	7567	2.13	25.6	2.05	3383

*Calculated based on the installed capacity and electricity production

There are two remarkable findings from comparing simulation results and empirical data in 2021 (Table 4.6). First, the simulated results of thermal power are closer to the reality in the investor unilateral decision scenario and negotiation scenario. The term "thermal power " refers to the electricity produced from fossil fuels combustion technologies, such as coal-fired, oil-fired, and gas-fired power plants. In these two scenarios, the projected share of thermal power production is larger than 70% since investor participation enables the coverage of natural gas. It is evident that economic benefits are considerably more important than environmental and social factors in reality. Second, the high shares of wind, solar, and hydropower are derived from the agents' high willingness to develop low-carbon clean powers since the beginning of the simulation (2020). However, the power generation system cannot be transformed in a short period, and it takes 5-6 years to plan and implement new generation facilities. Therefore, renewable power production will not increase as fast as agents expected. Moreover, in the future energy landscape model, I need to consider the time factor for power generation facility construction.

In 2060, I found that thermal power production will reduce to about 34%, and renewable power will reach more than half of the electricity production in every scenario. It means that only a few or no thermal power capacity will be newly added to the existing power generation system in comparison with the current energy mix system. Wind, solar, and hydropower will be largely developed in the future.

Table 4.6 Empirical and projected electricity production in 2021 and 2060 in the YRDR

	Investor		PM		Public		Negotiation		Equal weight		Empirical data	
	TWh	%	TWh	%	TWh	%	TWh	%	TWh	%	TWh	%
Thermal power	1109.25	72.94	1008.8	66.33	1008.8	66.33	1079.00	70.95	1008.80	66.34	1149.92	79.64
	1008.8	34.29	1023.35	34.79	1008.80	34.29	1009.48	34.32	1008.80	34.29		
Nuclear power	132.17	8.69	132.17	8.69	132.17	8.69	132.18	8.69	132.18	8.69	121.79	8.43
	265.75	9.03	265.75	9.03	264.06	8.98	265.75	9.03	265.75	9.03		
Wind power	34.1	2.24	140.21	9.22	184.99	12.16	78.69	5.17	98.34	6.47	49.34	3.42
	361.84	12.30	1049.15	35.66	968.44	32.92	1052.03	35.76	957.27	32.54		
Solar power	110.77	7.28	105.03	6.91	60.252	3.96	96.44	6.34	146.85	9.66	58.79	4.07
	760.7152	25.86	58.69	2.00	154.12	5.24	72.06	2.45	165.12	5.61		
Hydro power	108.84	7.16	108.84	7.16	108.84	7.16	108.84	7.16	108.84	7.16	24.53	1.7
	518.5137	17.63	518.51	17.63	520.04	17.68	516.82	17.57	518.51	17.63		
Bio power	25.708	1.69	25.708	1.69	25.708	1.69	25.60	1.68	25.71	1.69	39.51	2.74
	26.27681	0.89	26.28	0.89	26.28	0.89	25.60	0.87	26.28	0.89		

🟦 Projection in 2021 🟨 Projection in 2060 ⬜ Empiricial data in 2021

4.4 Discussion

This section compares the government's installed capacity targets for the 14th Five-Year Plan (Table 4.7) with the projected power generation results (Table 4.8).

In Table 7, the projected renewable energy generation is collected from provincial government working papers. It is easy to see that renewable energy generation is planned to reach more than 30% of the total installed electricity capacity in 2025. This is much higher than in 2021 (25.48%). However, the planned capacity increase cannot meet the projected electricity production in this model. Table 8 shows the projected electricity generation results in 2025. The projected share of non-renewable and renewable power production in Table 9 is similar to the targeted share of installation capacity in Table 8, which means the full load hours of non-renewable and renewable power need to be similar to reach the simulated electricity productions. However, it is challenging for renewable energy plants to reach the high full load hours as thermal plants. In 2021 (Table 4.5), thermal and nuclear power had 4126 and 7308 full load hours, respectively. In contrast, renewable powers, including wind, solar PV, and hydro, had a lower full load hour (around 1000) in 2021. Therefore, it is unlikely that renewable and non-renewable generation plants will operate for the same full load hours to produce a similar proportion of electricity as their installed capacity. In addition, I calculate the number of full load hours required to produce simulated electricity with the government projected capacity (Table 4.8). I can see that the numbers of the full load hours in the grey-shaded cells are over the hours of one year, which are theoretically unattainable.

Table 4.7 Target renewable power capacity of 14th FYP (2020-2025)

	Non-renewable power (%)	Renewable power (%)	Wind power (MW)	Solar power (MW)	Hydro power (MW)	Bio power (MW)	Ref
Shanghai	64	36	1800	2700		400	(NEA Shanghai, 2020)
Jiangsu	68	32	26000	26000	3950	3000	(NEA Jiangsu, 2020)
Zhejiang	64	36	6410	27500	15260	3000	(NDRC Zhejiang & NEA Zhejiang, 2021)
Sum			34210	56200	19210	6400	

Table 4.8 Projected renewable power production in 2025 in YRDR

	Power production						Full load hours*			
	Non-renewable	Renewable	Wind	Solar	Hydro	Bio	Wind	Solar	Hydro	Bio
	%		TWh				hrs			
Investor	65.82	34.18	34.10	368.71	204.08	25.83	997	6561	10624	4035
Policymaker	63.31	36.69	315.97	133.25	204.08	25.82	9236	2371	10624	4035
Public	63.31	36.69	369.15	80.08	204.08	25.82	10791	1425	10624	4035
Negotiation	64.74	35.26	202.41	220.56	204.08	25.6	5917	3925	10624	4000

Equal weight	63.31	36.69	225.06	224.17	204.08	25.82	6579	3989	10624	4035

*Calculated based on the target capacity in Table 4.7 and projected electricity production in Table 4.8

The comparison shows that the agent's expected energy transition in this model is quicker than the current government plan. Therefore, high production of renewable power has been projected. As section 3.4 described, it results from the high initial priority of agents. All the agents in the model have a high priority in developing renewable powers in the YRDR. The simulated energy transition is even quicker when the agents' adaptation rate ($\boldsymbol{\alpha}_i$) is set to a higher value. However, the energy system could not transit as quickly as their preferences in the real world. Consequently, there is a time lag between the change in agent decisions and the transition of energy systems. This temporal factor should be considered in the future development of the energy planning model.

Another big challenge in this model is the agents' priority based on the immediate perception of the interviewed agent. Their perception could change not only by the value of their decisions but also by external factors, such as the innovation of electricity generation technologies, carbon capture technologies, and even the interaction with other agents. Furthermore, decision-makers' perceptions could be influenced by their social networks, media, national policy, experiences, etc. These uncertainties of immediate decision makers' opinions would significantly impact energy planning.

4.5 Conclusion

I presented an agent-based model to provide insights into energy planning, then empirically validated the model in the Yangtze River Delta region of China. The model advances the agent-based energy system and planning approach by including public perspectives and characterizing the interplay of multiple decision-makers in the group decision. This approach not only has the advantages of the decision feedback loop brought by ABM but also draws on traditional quantitative energy system models. The portrayed agents update benefits from different technologies and have adaptive priorities for selecting particular energy pathways in each iteration. In addition, spatial agents have the ability to assess the spatial explicit datasets and behavior based on the resource potential and the socioeconomic conditions in each spatial cell. In the unilateral scenario, the depicted agents choose investments solely. In the group decision scenario, agents' decisions are also influenced by the preferences of other agents yielding a group decision.

This paper tests different decision scenarios to find the electricity-mix landscape that better secures a sustainable electricity supply for the future. The simulation results show that the preferable energy pathways in the short term are natural gas and solar PV powers, shifting toward mixed renewable energy generation systems, particularly wind and hydropower, in the long-term transition. In addition, in 2060, most scenarios show low coverage of Solar PV and biomass. Solar photovoltaic and biomass power generation technologies should continue innovations to better adapt to the future energy transition.

The unilateral scenario results show that all agents prefer hydro in the southwest hilly regions and nuclear power in the east coastal region. In the initial period of the model, investors consider natural gas generation as a recommendable choice, but wind and PV will gradually replace natural gas by 2060. Policymakers gradually shift their preference from PV to wind. The public's preference for renewable energy gradually increases, except for WTE.

The negotiation scenario is a more realistic energy planning scenario where agents can negotiate with other agents to achieve a compromise over different preferences and payoffs. The negotiated landscape is not only targeting future development but also considers the immediate value resulting from the decision. If negotiation failed, agents would select the technology which offers the highest group utility. The negotiation scenario will not necessarily lead to the optimal energy mix. However, it is a more plausible scenario that jointly considers the interests of the majority of negotiators. The results of the negotiation scenario indicate that the Yangtze River Delta region is likely to continue the development of natural gas power in the short term to ensure sufficient electricity supply. In the long term, a shift toward mixed renewable energy generation systems, especially wind and hydropower, was resulted. Such a long- and short-term electricity plan will ensure a reduction in negative social and environmental impacts and increase the security of the energy supply without reducing economic efficiency.

This model can be used in practice as a decision-support tool for energy planning. With the innovation of power generation technologies and the fluctuation of international NG prices, the data in the model can be kept updated to predict short-term energy planning. In addition, the model data temporal update can increase the accuracy of the energy landscape long-term projections.

Chapter 5: Sustainable energy planning under narratives of socioeconomic scenarios

Abstract: Energy-related activities are large contributors to carbon emissions, other anthropogenic environmental issues, and social externalities. Conversely, the development of energy systems will be influenced by economic conditions and the institutional guidance of energy development strategies. Sustainable energy development strategies require adaptive changes under different socioeconomic pathways. In this chapter, I structure the variations of different shared socioeconomic pathways (SSPs) into different energy demand growth rates, energy technological innovation levels, stakeholder authority in decision-making, and electricity-pricing policies. Using the agent-based model developed in Chapter 4, the energy landscapes pursued by decision-makers are simulated under different SSPs.

5.1 Introduction

Energy planning, on the one hand, directly impacts socioeconomic development and, on the other hand, is directly linked to the challenges of climate change mitigation and adaptation. The electricity production of various electricity generation technologies and its relevant amount of resource consumption, carbon emissions, and pollutants directly influence climate change. As the Yangtze River Delta region consumes a large amount of electricity, spatial sustainable energy planning under different socioeconomic pathways is important for global climate change. Conversely, different socioeconomic pathways will affect the energy transition. For a region, the outcome of the energy transition depends on the regional development objectives and the regional socioeconomic structure (IRENA, 2018). This study presents and simulates the energy landscape results from the agent-based modeling developed in Chapter 4 based on five quantitative shared socioeconomic pathways (SSPs).

Shared socioeconomic pathways (SSPs) are designed to be combined with Representative Concentration Pathways (RCPs) to investigate how climate change mitigation could achieve emission reductions under different socioeconomic development conditions (Riahi et al., 2016). SSPs are based on five narratives describing broad socioeconomic trends that could shape future society. It includes SSP1 with the most sustainable green development, SSP2 following the historical socioeconomic development rate, SSP3 characterized by global rivalry, SSP4 describing an inequality development scenario, and SSP5 rising with rapid fossil-fuel development.

The energy landscape model established in Chapter 4 is based on the historically increasing rate of electricity demand, which has been validated as an efficient short-term projection tool to support decision-maker sustainable energy planning. However, long-term sustainable energy planning should dynamically consider regional socioeconomic conditions. To understand the impact of socioeconomic conditions on energy planning, this chapter attempts to investigate the change in agent preferences in selecting different technologies by coupling the shared socioeconomic pathways (SSPs).

This chapter first describes the electricity generation system assumptions at the regional level based on SSPs and then demonstrates the agent-based model to project the future energy landscape. In detail, I structure the variations of different shared socioeconomic pathways (SSPs) into different model parameters, including energy demand growth rates, energy technological innovation levels, stakeholder authority in decision-making, and electricity-pricing policies.

The structure of this chapter is as follows. In Section 5.2, I introduce the scenarios that have been calculated for each SSP. The agent transitioning electrical plan is presented in Section 5.3 under various socioeconomic scenarios. Finally, Section 5.4 discusses the results and indicates directions for future research.

5.2 Methodology

In this chapter, I develop five different socioeconomic pathways based on the agent-based model developed in Chapter 4 to investigate the impacts of socioeconomic development on energy planning.

5.2.1 Electricity system assumptions under SSPs

The methodology framework is depicted in Figure 5.1 in accordance with the key steps in the development of SSPs, which include narrative development, quantifying scenario assumptions, and elaborating socioeconomic scenario drivers (such as electricity intensity, technological innovation, and stakeholder engagements) via the developed quantitative agent-based model (Chapter 4). This study first discusses the regional assumptions for the power production system based on SSP storylines and then illustrates the energy landscape under various scenarios.

The scenarios are based on electricity production system assumptions and altered through a synthesis of information, stakeholder engagements, and the participatory policies of the energy landscape model. Socioeconomic conditions will influence the subnational electricity market through local consumption rate changes, technological innovation, which further rise in competition between different electricity generation technologies. Moreover, the engagement of policy-makers, investors and the public will change in different socioeconomic pathways.

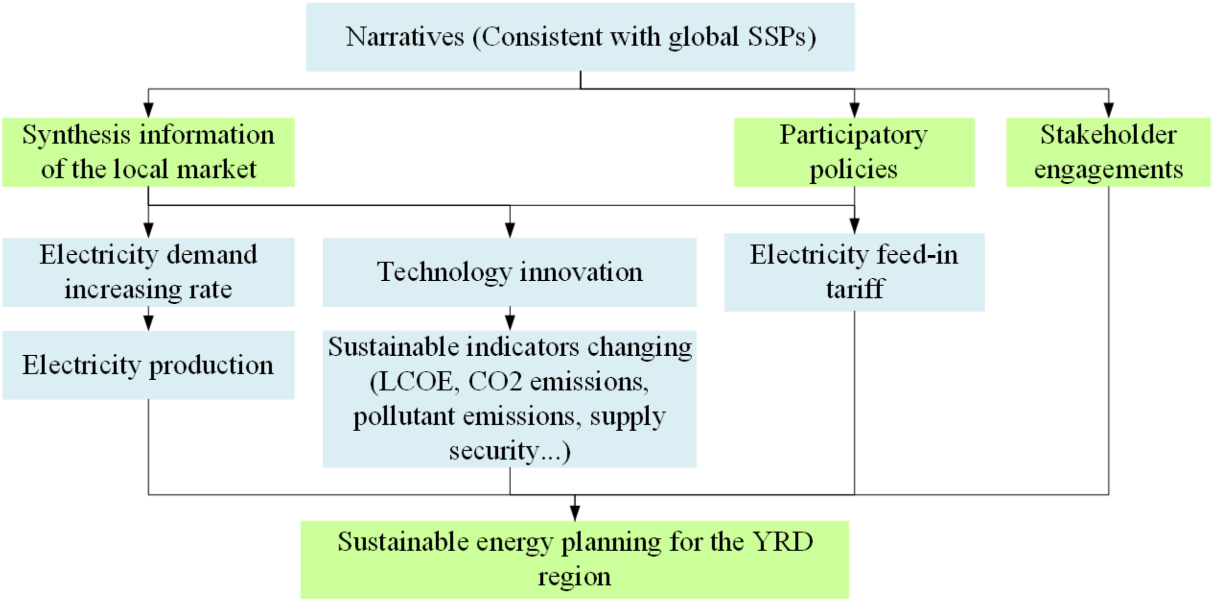


Figure 5.1 Methodology Framework

Table 5.1 summarizes the assumptions of key factors dynamically influencing the future energy landscape, including the increasing rate of electricity demand, technological innovation speed, stakeholder engagements, and pricing policies.

SSP1 describes a sustainable development scenario in which citizens are living an electricity-saving lifestyle, renewable technologies are greatly enhanced, and policies supporting electricity generation systems and socioeconomic factors are considered. It is supposed to result in a high proportion of renewable energy-mix landscapes, which could also ensure energy supply security, low emissions, and positive socioeconomic effects. Therefore, the growth rate of electricity demand is assumed to decrease quickly in the future and reach zero by 2030. The technology will also be highly innovative. All stakeholder engagements will be equally considered, and electricity-pricing policies will be an effective function in this scenario.

SSP2 proposes intermediate mitigation and adaptation challenges for future development. It can be considered a business-as-usual scenario with similar features to historical electricity system development. The electricity demand will increase according to the growing rate projection of the local historical electricity consumption. Technological innovation and policy-maker engagement are assumed to be at the medium level.

SSP3 depicts a rocky road of electricity system development, which represents the highest challenges for the future. Therefore, the electricity growth rate is assumed to be high, and the innovation of technologies is assumed to be low. SSP3 also specifically represents regional rivalry. The competitiveness among countries will be downscaled to the subnational region, resulting in high engagement of investors. The worse inequality within the study area will result in low engagement of policy-makers and an uncontrolled-pricing policy of electricity feed-in tariffs.

SSP4 is is an inequality scenario. As China's most economically advanced region, electricity demand and technological innovation have increased quickly in the YRD region. Policy-makers highly regulate the market with a high engagement in energy planning and controlled feed-in electricity tariffs.

SSP5, the fossil-fuel development scenario, has a high increasing rate of electricity demand and weak technological innovation, as well as less engagement of policy-makers and less effective pricing policies.

Table 5.1 Assumptions under the SSPs

Scenarios	The increasing rate of electricity demand	Technology innovation	Stakeholder engagement	Pricing policy
Baseline	medium	Medium	Equal weight engaged with other decisionmakers	Controlled feed-in Tariff
SSP1	Low	High	Equal weight engaged with other decisionmakers	Controlled feed-in Tariff
SSP2	Medium	Medium	Policymaker engagement accounts for 2/7 of the decision-making	Controlled feed-in Tariff
SSP3	High	Low	Policymaker engagement accounts for 1/4 of the decision-making	Fully open pricing market
SSP4	High	High	Highest policymaker engagement	Controlled feed-in Tariff
SSP5	High	Low	Lowest policymaker engagement	Fully open pricing market

5.2.2 Electricity demand growth rate

The historical electricity demand growth rate is 5.6% in 2020, which will stepwise decrease every five years (World Resources Institute, 2021b). Figure 5.2 shows the projection in the blue line. As table 5.1 shown, the increasing rate of electricity demand varied between scenarios. I use a decreasing quadratic function with time as the dependent variable (Equation 5.1) to present projected electricity demand growth rates under different scenarios.

$$\boldsymbol{EDrate_{sc}} = (\mathbf{1}\text{-}\,(\,\boldsymbol{\beta} * (\boldsymbol{t} - \mathbf{2020}))^{\mathbf{2}}) * \mathbf{0.056} \qquad \textbf{Equation 5.1}$$

Figure 5.2 shows the electricity demand growth rate $(\boldsymbol{EDrate_{sc}})$ from 2020 to 2060, where **t** represents the simulation years, and $\boldsymbol{\beta}$ is determined by the year in which the electricity demand growth rate falls to zero. When electricity demand increases at a medium level, $EDrate_{sc}$ is assumed to decrease to zero in 2045, the same as the projection rate. Therefore, $\boldsymbol{\beta}$ is assumed to be $\frac{1}{25}$ under SSP2. For the high-level growth rate, I assumed that the electricity demand will stop increasing until the last simulation year 2060 (the year that China planned to reach carbon neutrality), in which $\boldsymbol{\beta}$ has a value of $\frac{1}{40}$. According to the 15-year gap between medium and high levels, the low-level growth rate is set to reach zero in 2030 (the year that China targets to reach carbon peak) with $\boldsymbol{\beta}$ equal to $\frac{1}{10}$.

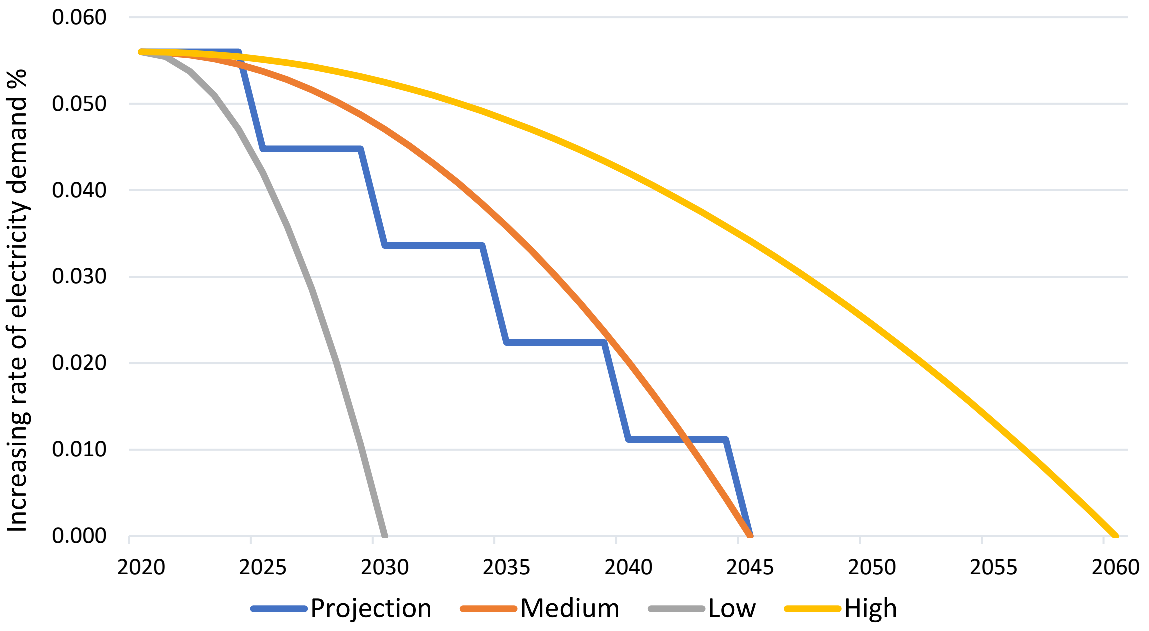


Figure 5.2 The change of electricity demand increasing rate under different scenarios.

5.2.3 Technological innovation

In total, 14 indicators were considered in the energy landscape model. However, only six indicators are related to electricity technology innovation, as shown in Table 5.2. Technological innovation is only assumed for the nonfossil-fuel technologies, while these electricity generation technologies are still immature and will be improved in the next decade. Therefore, the changes in these indicators are presented as a linear function (Equation 5.2).

$$\boldsymbol{Indicator_k(t) = Indicator_k(t-1) * (1+\gamma)} \qquad \textbf{Equation 5.2}$$

The indicator $Indicator_k(\boldsymbol{t})$ is assumed to be changed between 2020 and 2030. The values of negative indicators decrease, and the values of positive indicators increase with time $\boldsymbol{t}$. The growth rate $\boldsymbol{\gamma}$ is assumed to be a random value in the ranges listed in Table 5.2.

Table 5.2 Growth rate of technology-related indicators for nonfossil technologies.

γ	Levelized cost of electricity	CO_2 emission	SO_2 emission	NO_x emission	Total particulate matter	Secured capacity
High	a random number from -0.01 to -0.015					a random number from 0.01 to 0.015
Medium	a random number from -0.005 to -0.01					a random number from 0.005 to 0.01
Low	a random number from 0 to -0.005					a random number from 0 to 0.005

Moreover, the LCOE of NG power is assumed to increase between 2020 and 2030 at a different rate for each SSP. In SSP1, the growth rate is assumed to be the lowest, which is presented as a random number between 0 and 0.005. In SSP5, the fossil-fuel development scenario, the promotion of fossil fuels results in a higher growth rate (random number between 0.01 and 0.015). The other scenarios applied a medium-level increase in the LCOE of NG power.

5.2.4 Stakeholder engagement

Figure 5.3 depicts stakeholder engagement in the decision-making processes in each spatial cell. Scenario 1 is the most sustainable scenario, in which all stakeholders are equally engaged in decision-making. In this agent-based, energy-landscape model, stakeholders consider different development factors. The investor only considers the economic input-output value, which represents annual welfare. Policy-makers only consider the carbon emissions and electricity supply security factors. In addition, the public also cares about other socioeconomic factors, including pollution emissions, job creation, social acceptance, etc. Therefore, stakeholder engagement can be seen as a different weighting of future sustainable development factors.

In the more mitigation- or adaptation-challenging pathways, Scenarios 4 and 5, economic development was considered the most important factor in which investors become the most important decision-maker, accounting for 50% of engagement. In comparison, in SSP4, policy-makers are assumed to be more highly engaged due to the better guidance to satisfy the electricity supply in the economically advanced YRD region.

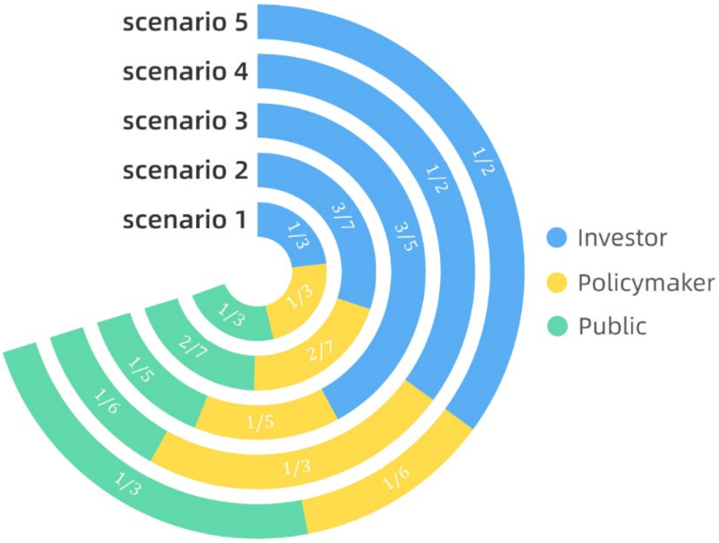


Figure 5.3 Stakeholders' engagement under different scenarios

5.2.5 Pricing policy

There are generally two types of pricing patterns: cost-based pricing, i.e., the "cost + profit + tax" pricing pattern (Johansson et al., 2012), which is the electricity-pricing pattern under the monopoly operation of the electricity industry; or the competitive pricing, which introduces competition in power generation and sales, and the electricity price is determined through competition in the electricity market (ECECP, 2020). In China, before 1985, the electricity sector was a state-owned monopoly industry in which electricity prices were determined by a cost-plus pattern (Electricity Law of the People's Republic of China, 2019). In 2002, the electricity reform plan was implemented, which aims to liberalize the power sector (Williams & Kahrl, 2008). One of the main objectives is to build up market-based competitive pricing mechanisms and regional wholesale power trade.

Table 5.3 shows the pricing mechanism under the condition of market-free or market-control. The "market free" refers to the market-based competitive pricing mechanisms, in which price changes with the change in market share electricity production $EQ_n(t)/\sum_1^n EQ_n(t) - EQ_n\ (t-1)/\sum_1^n EQ_n(t-1)$. As section 4.2.3 mentioned, $EQ_n(t)$ refers to the quantity of electricity production. The "market control" represents the current China electricity pricing mechanism. According to the most recent notice from the Chinese central government, the feed-in electricity tariff will be formed in accordance with the "guide price + competitive allocation" method (NDRC, 2021b, 2021a). The guide price will be based on the benchmark price of coal-fired power generation, which is recognized as the standard price in the model. The feed-in tariffs also change along with the market competition as the spring mechanism under "market free", but the changes are not allowed to exceed 1.2 times or be lower than 80% of the standard price (China Galaxy Securities, 2019).

The governmental pricing control mechanism contributes to regulating the electricity market and avoiding the instability of electricity prices due to inequality of development between regions. Therefore, in scenarios 1, 2, and 4, the pricing control policies are assumed to be necessary to implement. In Scenarios 3 and 5, electricity pricing follows the competitive pricing pattern. When the market share increases in comparison to the previous year, the electricity feed-in tariff $Tariff_n\ (t)$ will decrease according to the change.

Table 5.3 Pricing mechanism

Market free	
$Tariff_n\ (t) = Tariff_n\ (t-1) * (1 - (EQ_n\ (t)/\sum_1^n EQ_n(t) - EQ_n\ (t-1)/\sum_1^n EQ_n(t-1)\ ))$	
Market control (with governmental price control policy)	
$Tariff_n\ (t) > 1.2$ * Standard-price	$Tariff_n\ (t) = 1.2$ * Standard-price
$Tariff_n\ (t) < 0.80$ * Standard-price	$Tariff_n\ (t) = 0.80$ * Standard-price

5.3 Results and discussion

5.3.1 The sustainability of technologies in 2060 under different scenarios

With technological innovation and the cost increase of natural gas, the sustainability of technologies would largely change with the model runs. To better understand the impact of technological innovation, I applied the updated indicator value (Appendix 3) to the analytical hierarchical processes used in Chapter 3 to assess the sustainability of each technology by the weighted sum function. Table 5.4 shows the sustainability (represented by integrated normalized values) of different technologies under each scenario in 2060.

Table 5.4 Sustainability of different technologies under each scenario

	NG	Nuclear	Wind	Solar PV	Hydro	Biomass	WTE
SSP1	0.427	0.728	0.686	0.495	0.775	0.499	0.487
SSP2	0.460	0.718	0.675	0.484	0.761	0.474	0.473
SSP3	0.460	0.714	0.670	0.480	0.756	0.464	0.472
SSP4	0.427	0.737	0.689	0.500	0.777	0.494	0.489
SSP5	0.504	0.708	0.668	0.476	0.758	0.467	0.459

Compared with the sustainability assessment in 2021 (Figure 3.10), it is easy to see that technologies become more sustainable in SSPs 1 and 4. With the high technological innovation rate, renewable power becomes more sustainable by lowering the LCOE and environmental impacts and increasing electricity supply security. Although wind power remains more sustainable than solar PV, the gap between them is shrinking. In addition, the levelized cost of NG power continues to increase from 2020 to 2030, lowering the sustainability of NG power.

In SSP5, although NG power is evaluated to be less sustainable than in 2021, the fossil-fuel development scenario shows a more sustainable feature in 2060 in comparison with other scenarios. The sustainability of renewable power in SSP5 is lowest due to the low technological innovation rate, which leads to high LCOE and low supply security of renewable powers. Therefore, even if the LCOE of NG becomes very high in SSP5 due to market competition, NG power will be comparatively more sustainable. With the same technological innovation rate in SSP3, the sustainability of renewable power is also low.

In SSP2, the sustainability of renewable technologies is at a medium level compared to other scenarios because of the medium-level innovation rate.

5.3.2 Average group priorities under different scenarios

Figure 5.4 shows the average group priority for alternative technologies over all spatial cells under different scenarios. The group priorities for hydro, nuclear, and biomass power are generally increasing under all SSPs. In particular, pumped storage hydropower is one of the most sustainable technologies, with economic, social, environmental and technological advantages. Compared to other technologies, the priorities for NG, wind, and solar PV are very high at the beginning (2021) and vary differently between socioeconomic pathways.

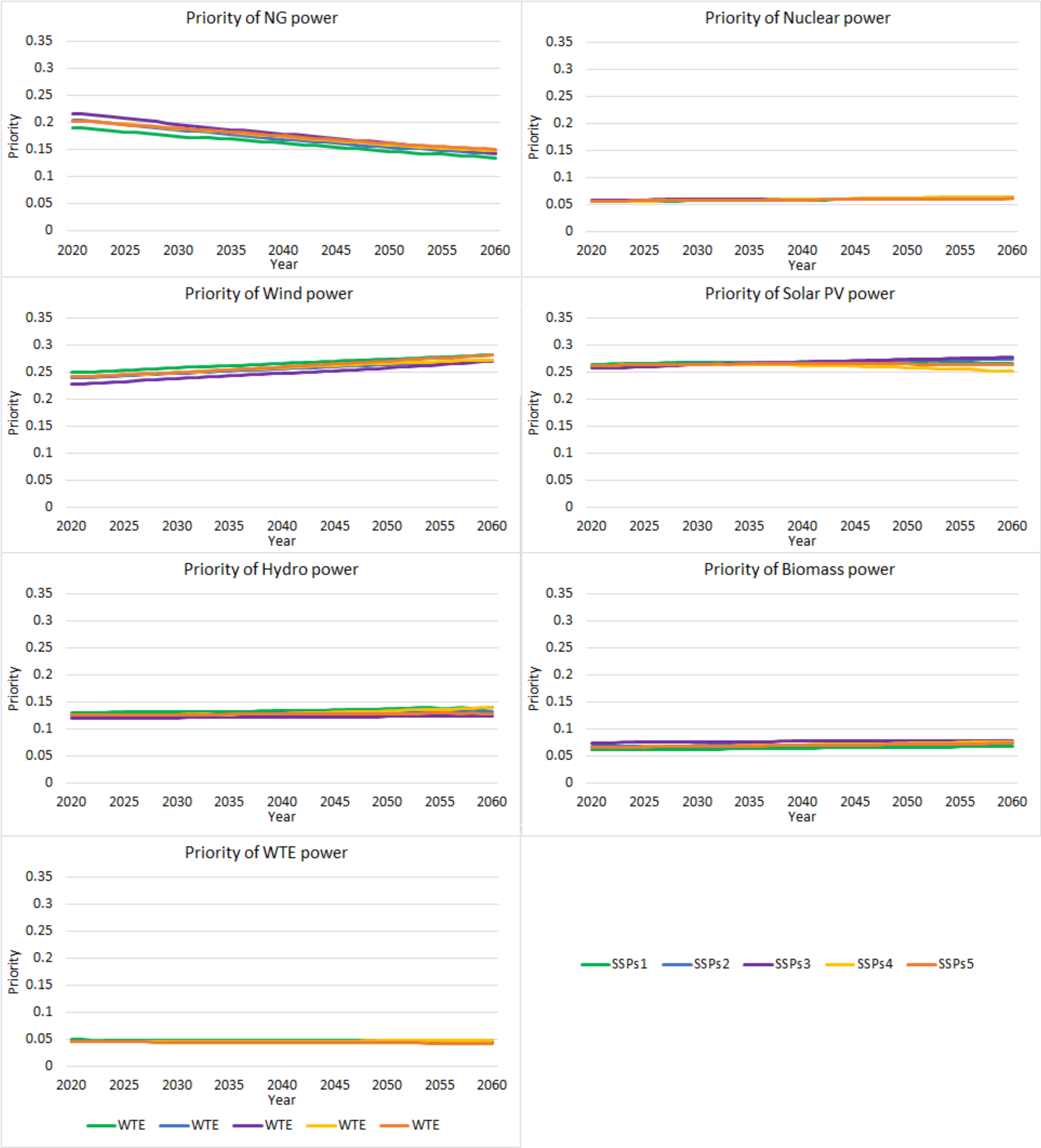


Figure 5.4 The average group priorities for technologies under each scenario.

In all scenarios, the group priority for NG power technology is gradually decreasing. NG power loses market competence with the increase in national fuel prices and more innovative nonfossil fuels. Therefore, the priorities for NG decreased during the simulation. In SSP5, the decreasing rate of NG priority is less significant. Under the quick electricity demand and more considerable authority of policy-makers, electricity supply security becomes a crucial criterion. In addition, in SSP5, fossil-fuel development could not truly motivate the supply of natural gas due to the increased LCOE. However, NG gains higher sustainability and obtains higher priority with model runs in comparison with other scenarios.

The group priorities for wind continue to increase in all scenarios. In SSP1, wind power is highly innovative with higher electricity supply security capacity than other renewables. With the high innovation rate in SSP1, wind power electricity supply security increases quickly, and LCOE continues to decrease over the next ten years. In addition, the low engagement of investors in SSP1 results in a high initial priority for wind power in 2021. Therefore, wind power becomes much more sustainable than other technologies and obtains the highest priority during the simulation period. Although the technological innovation rate is also high in SSP4, the highest policy-maker engagement will deliver technologies with high supply security. As a result, the priority growth of wind power is limited in SSP4.

Compared with wind power, the average group priority for solar PV will only slightly increase in SSPs 1, 2, and 3 and decrease in other scenarios because solar PV has unsolved environmental (high-carbon and air-pollution emissions) and technical problems (low supply security). Although the sustainability of solar is better improved in SSP1 because of the highest innovation rate, its sustainability is still lower than many other power sources; therefore, the priority is not much improved with model runs. In SSP4, the average priority for solar PV decreases. Despite the high rate of technological innovation in SSP4, solar PV priority decreases because of intense competition from other nonfossil fuels. In addition, the high engagement of investors will increase the importance of solar PV's economic impacts, lowering agent priority for solar PV.

Other renewable technologies will also become preferable in the future due to technological innovations. In particular, in SSPs 1 and 4, all technologies are highly innovated, and the competition between the nonfossil technologies creates uncertainties in the priority change. WTE technology is the only renewable technology with priority slightly decreasing over time in all scenarios because the current WTE technology employed in China is mostly incineration technology. It has many shortages, including large amounts of PM emissions, high operation costs, high requirements for the size of fuel particles (waste), and prone to coking. Unless its technology can be substantially improved in the next few years, it may become a better choice for future technological selection.

5.3.3 Priority for different technologies under different scenarios in 2060

Figure 5.5 shows the group priority in all spatial cells in 2060. In general, the priority for nuclear is largely skewed right because it is very high in the coastal spatial cells and is zero in the large inland areas. The priorities for hydropower are also skewed to the right, with a high priority of approximately 0.6/0.7 in the near river areas with high elevation drops. The box plot of hydropower is comparatively tall compared with other technologies in all scenarios due to the very different site potential across all spatial cells.

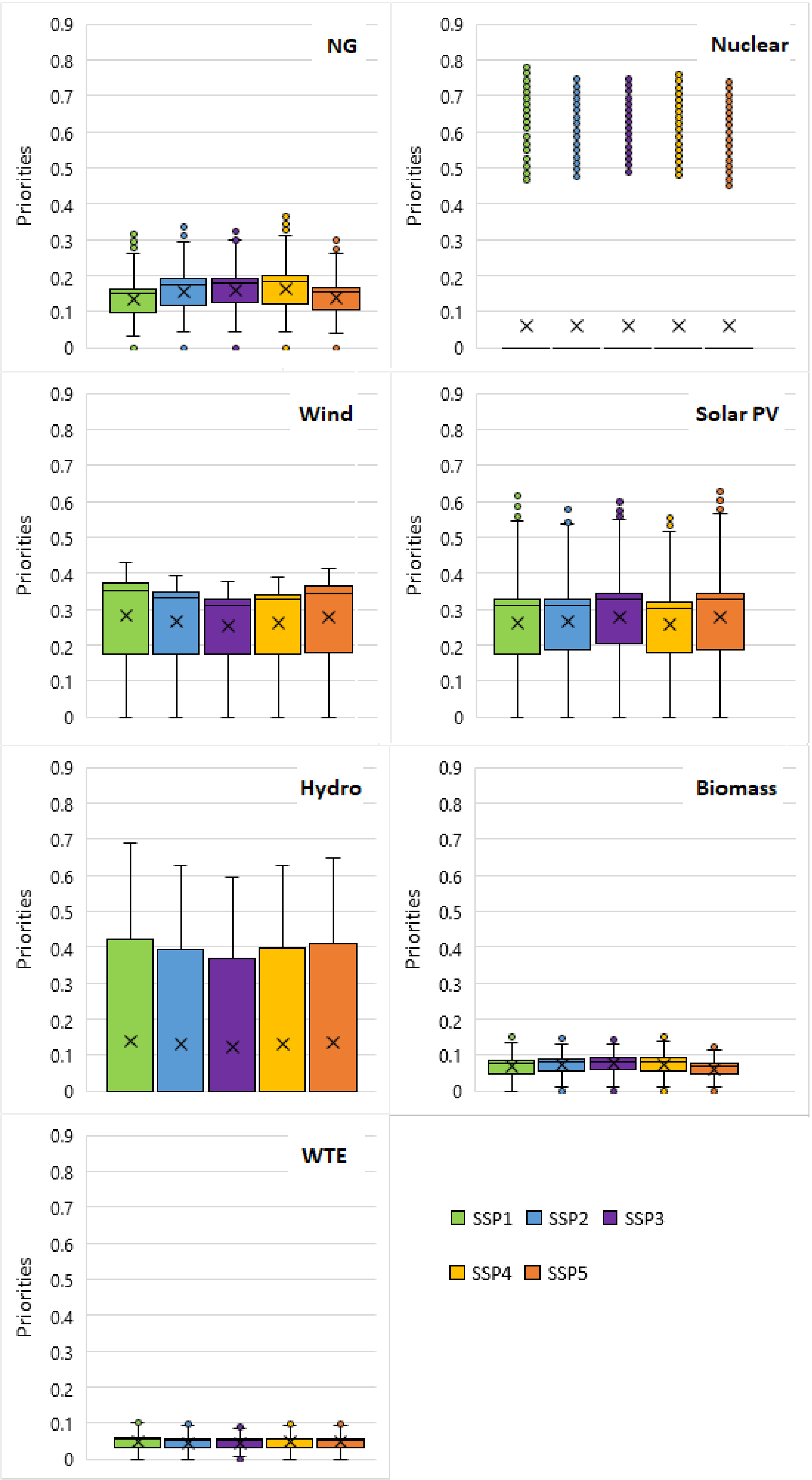


Figure 5. 5 Box plots of group priorities under different scenarios in 2060.

NG power group priorities of agents are lowest in both SSP1 and SSP5. In comparison, the interquartile range of NG priorities is lowest, from 0.09 to 0.16, in the most sustainable scenario, SSP1, and from 0.10 to 0.16 in the fossil-fuel development scenario, SSP5. The SSP1 scenario results in low sustainability of NG and high sustainability of other nonfossil, low-carbon technologies. Therefore, the priority for NG power is the lowest, and the priorities for other technologies are higher in SSP1 than in the other scenarios. In particular, agents' highest priority for hydropower almost reaches 0.7. SSP5 is very different from SSP1. With slow technological innovation, the sustainability of nonfossil technologies is lower in SSP5, and the sustainability of NG power reaches a high value of 0.504 (Table 5.4). However, the priority for NG power is low in SSP5 for the following reasons: first, the high engagement of investors would emphasize the economic factors in the decision-making processes; second, with the promotion of fossil fuel, the natural gas fuel price largely increases, which decreases the competitiveness of NG power in the market; and third, the quickest growth rate of electricity demand accelerates market competition, which will lower the priority for NG power. Under this circumstance, the agents' priority for NG is low in SSP5.

In general, agent group priorities for renewable power are higher in SSPs 1 and 5 and lower in SSPs 2, 3 and 4, except for the priority for solar PV in SSP3. In SSP3, the higher engagement of investors will grant solar PV, which has an economic advantage (lower LCOE), with higher priorities in many spatial agent groups.

5.3.4 Energy landscape under different scenarios

Figure 5.5 depicts the technology with maximum group priorities, which refers to the most recommended technology in each spatial cell in 2021 and 2060. It is easy to find specific spatial cells with the highest priority for nuclear power or pumped-storage hydropower. This results from the high priority of all stakeholders, the high sustainability of these two technologies, and the high spatial-site advantages.

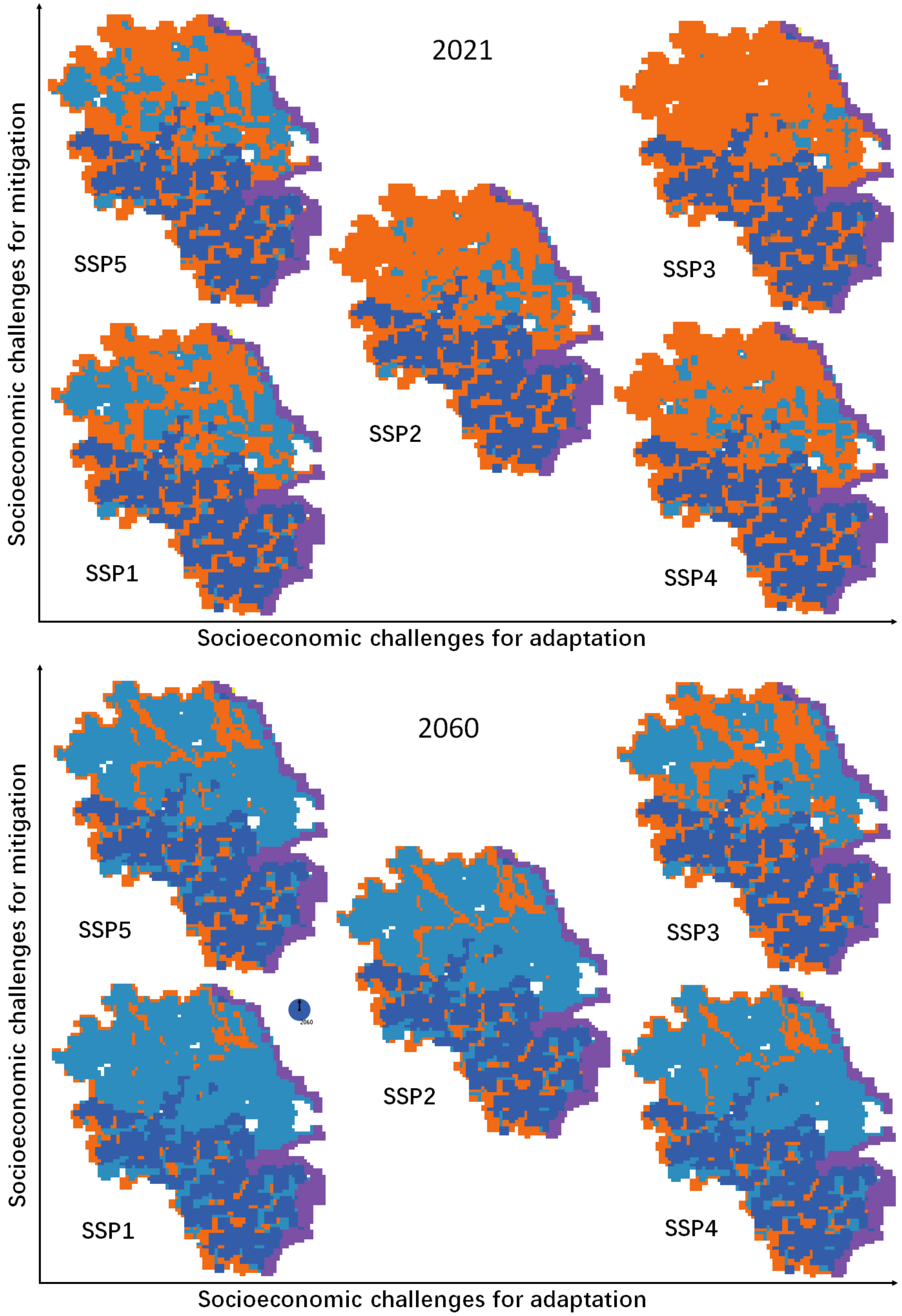


Figure 5. 6 Map of the maximum priority technology in 2021 and 2060 under different scenarios.

In 2021, the agents' most preferable technology was solar PV, with the highest average priority. However, wind power technology is highly distributed in a large number of spatial cells due to its high spatial suitability. The energy landscape under SSP1 is the most sustainable pathway, combined with renewable and low-carbon power. In particular, the coverage of wind power is much higher in SSP1 than in the other scenarios. Chapter 3 verified that wind power was the most sustainable technology in 2021. In addition, all stakeholders have a very high priority for distributed solar PV, which is oriented by the high initial group priorities in the northern part of the YRD region. In other scenarios, fewer spatial areas have the maximum priority for onshore wind power compared to SSP1 because of the high engagement of investors. The initial status of the energy landscape is not influenced by the dynamic changes in the innovation rate, electricity demand growth rate, and pricing policies but is largely influenced by the authority of each agent in the decision-making process. In SSP3, the engagement of investors is highest, with a weight of 60%, which results in the most extensive solar PV coverage.

In 2060, with the rapid technological innovation in SSP1, all renewable technologies are more sustainable. However, wind power still has higher sustainability and has become the primary choice in the northeast, where it is more suitable for wind power installation. Similar to SSP1, the technological innovations are relatively high in SSP4, and the coverage of wind power is also high. Additionally, the large wind coverages of SSP2 and SSP5 are caused by increased sustainability and strong market competition resulting from the highest energy demand, respectively. For SSP3, although the innovation rate is low and the energy demand growth rate is high, the coverage of solar power is relatively high due to the highest weight of investors and the low weight of policy-makers in the decision-making process. Policy-maker involvement is limited to 20%, which represents a low requirement of electricity supply security and low consideration of carbon emissions. Therefore, the high coverage of solar PV in SSP3 results from the low consideration of electricity supply security and the high consideration of economic welfare. In summary, the energy landscape of SSP3, which results from the most adaptive and mitigative challenging socioeconomic conditions, would create a higher challenge for the energy transition.

5.4 Conclusion and outlook

This study describes how agent priorities change based on different SSPs. The SSP implementation was based on assumptions of the energy demand growth rate, electricity tariff policies, stakeholder engagement, fossil-fuel pricing, and technological innovation of the SSP narratives. The SSP scenarios are fully integrated with the agent-based model. The results show that both the sustainable scenario, SSP1, and the fossil-fuel development scenario, SSP5, could result in a more sustainable energy-mixed system with high development priorities for renewable power and lower priorities for fossil-fuel combustion power.

Without a quantitative projection of the electricity system under different socioeconomic pathways, this chapter could only illustrate the correlation between agent priority and different socioeconomic pathways. The SSP scenarios are currently only artificial, which provides ideas for extending the agent-based, energy-landscape model to better implement it in long-term energy planning. The dynamic changing parameters in the SSP scenarios should be replaced by the electricity demand projection model, technological innovation projection model, carbon tax-related policies, electricity tariff policies, and models of the macroeconomy under different SSPs. The agent-based, energy-landscape model should be coupled with other projection models for different parameters.

Chapter 6: Summary and Conclusion

6.1 Summary

This thesis comprehensively assesses the spatial energy resource potential of different power generation technologies and the socioeconomic status in the Yangtze River Delta region of China. It further analyzes the combined environmental and socioeconomic impacts of different power generation technologies and develops simulation models for the future sustainable energy transition. In addition, it also investigates the correlation between socioeconomic pathways and future energy planning. This chapter addresses the research questions raised in Chapter 1 related to the overall study by summarizing the major findings from the previous chapters.

With the emergence of global fossil-fuel scarcity and carbon emission reduction needs, achieving a sustainable energy transition has become a challenge. As a major electricity consumer and carbon emitter, how China designs its future power generation system will have significant social, economic, and environmental impacts.

China's rapidly developing power generation system has been dominated by coal-fired power generation. The transition of energy systems from coal-dominated to a mixed sustainable system requires various considerations, such as spatial suitability, the likely impacts of power technologies, localized supply and demand markets, and stakeholder involvement. To comprehensively include these factors in energy planning, this research used a mixed method to investigate how decision-makers could achieve a sustainable energy transition based on the existing energy production system by answering the following research questions:

Q1: How to efficiently allocate spatial potential in energy planning?

Chapter 2 provides a comparative overview of the regional-siting potential of various low-carbon power plants in the Yangtze River Delta of China. Many previous studies have assessed the spatial resource potential of various renewable energy sources. However, the comparison of the site selection potential of different energy technologies in a spatial area has not been explored. The novelty of this chapter is that I developed a power plant site potential mapping tool with geographic information system (GIS)-based hierarchical analysis (AHP) to compare the spatial-siting potential of alternative low-carbon power plants.

The chapter first identified a suitable area of 381613.95 km2 (78% of the local area) for power plant siting. Second, for natural gas, solar PV, biomass and WtE power, more than 30% of suitable areas are considered to have high site potential. More than 90% of suitable areas have medium site potential for wind power. However, NG and biomass power are not encouraged due to fossil fuel and food shortages. Solar photovoltaics and waste-to-electricity are encouraged to be established in the long term.

The produced microscale spatial site potential maps could support future power plant allocation. This research supports in taking further steps in the comparison of power plant spatial suitability and providing decision-makers with more applicable information for energy planning.

The spatial suitability maps using different criteria, including the spatial resource potential and topographic, economic and social criteria, resulting from this chapter function as the initial raster data input for the agent-based energy-planning model. These spatial suitability maps using different criteria will join to form the model environment.

Q2: What are the socioeconomic and environmental impacts of electricity generation technologies, and which is the most sustainable technology?

Chapter 3 assesses the sustainability of the seven mainstream electricity generation technologies in China by considering the social, economic and environmental impacts. The objective impact of electricity generation technologies is summarized by a literature review of a variety of impact indicators (Appendix 1). The objective sustainability ranking of power generation technologies is ambiguous, with no single technology being rated as more or less sustainable than another. Moreover, to further understand how stakeholders in the Yangtze River Delta region subjectively assess the sustainability of power generation technology, I assign stakeholder preferences to the weights of various indicators. How stakeholders weigh different sustainability indicators resulted from the survey and interviews conducted in January/February of 2021 (Appendix 4). Therefore, the results of the subjective sustainability of different technologies can only present the situation in China.

Objectively, the value of the indicator shows the environmental, economic, social, and technical impacts of various power generation technologies. For instance, pump-storage hydropower has the most negligible negative impact on society; nuclear power has the most advanced technical features for securing a constant power supply; NG power has the least economic cost; pumped-storage hydro and onshore wind have a relatively weak impact on the environment. When the perceptions of stakeholders are considered, the results show that pumped storage hydropower, nuclear power and onshore wind power are evaluated as sustainable power generation technologies in the Yangtze River Delta region. Pumped storage hydropower with a capacity of 1200-1600 MW is evaluated as the most sustainable technology.

In addition, the sustainability of solar photovoltaic power generation is relatively low in accordance with the existing silicon thin-film manufacturing process. To enhance its sustainability, efforts should be made to address the negative environmental impacts of the silicon thin-film manufacturing process. It is also important to introduce advanced waste treatment technology for nuclear power and improve fuel utilization. This research can inform policy-makers in designing future power system development plans.

The resulting indicator value from this chapter also functions as the data input to support the decision-making process of heterogeneous agents in the agent-based, energy-planning model in Chapter 4. The values were assessed by agents and joined in their multicriteria decision-making process or cost-benefit analysis to support their choice.

Q3: Which potential future electricity-mix landscape would better secure a sustainable electricity supply in China?

In Chapter 4, to simulate the energy transition in the Yangtze River Delta region, I develop an agent-based model that provides insight into sustainable energy planning. The model combines the strengths of conventional quantitative energy system models, including the study area's spatial resource potential, the assessment of the environmental impacts of energy technologies, and the advantages of ABM to reflect the dynamic changes in stakeholder perceptions of the energy plan. The spatial site potential maps from Chapter 2 and the sustainable indicator value from Chapter 3 function as the input data in Chapter 4. Stakeholders, including investors, policy-makers, and the public, are simulated as model agents equipped with adaptive priorities to select energy pathways for energy planning. In addition, agents can acquire spatial site potential (Chapter 2), the study area's socioeconomic conditions, and technological sustainability (Chapter 3). Agents could individually make decisions or jointly reach a group decision.

The simulation results show that the preferable energy pathways in the short term are natural gas and solar PV power, shifting toward mixed renewable energy generation systems, particularly wind and hydropower, in the long-term transition. The simulated results are closer to the reality in the investor unilateral decision scenario and negotiation scenario, in which the projected share of thermal power production was larger than 70% in 2021. It is evident that economic benefits are considerably more important than other factors in energy planning. In the long term, renewable power will reach more than half of the electricity production in every scenario. In addition, in 2060, most scenarios show low coverage of solar PV and biomass. Solar photovoltaic and biomass power generation technologies should continue innovating to better adapt to the future energy transition.

The decision-making process for sustainable energy transition is a complex issue. This model can be used in practice as a supportive tool for energy planning. With the innovation of power generation technologies and the fluctuation of international NG prices, the data in the model can be updated to predict short-term energy planning. In addition, the model data update can also increase the accuracy of the long-term energy landscape projections.

Q4: How could future socioeconomic conditions influence the future energy-mix plan?

On the one hand, energy planning will have a direct impact on socioeconomic development, and climate change, on the other hand, is limited by socioeconomic development pathways. In the energy-planning model developed in Chapter 4, agent adaptation of priorities and decision-making processes are affected by socioenvironmental parameters. Therefore, I developed abstract SSP scenarios based on shared socioeconomic pathways to understand the correlation between energy planning and future socioeconomic conditions.

The SSP scenarios include assumptions on the energy demand growth rate, electricity tariff policies, stakeholder engagement, fossil-fuel pricing, and technological innovation of the SSP narratives. The SSP scenarios are fully integrated with the agent-based model. The results show that both the sustainable scenario, SSP1, and the fossil-fuel development scenario, SSP5, could result in a more sustainable energy-mix system with high-development priorities for renewable power and lower priorities for fossil-fuel combustion power.

Although the SSP scenario developed in Chapter 5 is abstract, it provides a new perspective on potential energy-planning strategies under different socioeconomic pathways. The fossil-fuel development scenario (SSP5) does not necessarily lead to the rapid development of thermal power but rather increases the share of renewable energy due to higher market prices of fossil-fuel resources resulting in this scenario. In contrast, the sustainable development scenario (SSP1) will lead to sustainable energy-mixed systems that can secure a low-carbon electricity supply.

For future studies, the SSP scenario-involved parameters can be replaced by model coupling, e.g., the energy demand growth rate can be simulated by applying the conventional energy system model TIMES or electricity and fossil-fuel prices can be projected by economic-forecasting models.

6.2 Conclusion and outlook

This research aims to determine **how to deliver a sustainable energy-mix plan to secure electricity supply in the Yangtze River Delta region in 2060**. First, the spatial conditions, in particular the spatial resource potential, topographic conditions and local infrastructure, are assessed and normalized to be comparable values of different electricity generation technologies. This represents the spatial suitability to implement various technologies, which support stakeholders in understanding the environment. Second, the socioeconomic, environmental and technical impacts of technologies are assessed and used to determine the subjective sustainability of alternative technologies through the integration of stakeholder perceptions. The impacts of technologies could provide stakeholders with information and support to evaluate what could result from choosing certain technologies. Third, stakeholders would individually adapt their priorities for technologies step by step or jointly change their decisions through negotiation. Either the unilateral or group scenarios target a better spatial energy-mix plan. Finally, I also explore the impact that different future socioeconomic development scenarios would result on energy planning.

The themes introduced by these objectives are certainly complex, but the broad conclusions drawn in this thesis demonstrate that this complexity can be decomposed using a consistently mixed research approach. The findings of this thesis, summarized in this chapter, demonstrate feasible future energy-planning schemes in the YRD region that can provide a viable and practical reference for energy planners. This model can be used for long-term energy planning if the model data are kept up to date.

The importance of stakeholders in the energy transition has been shown in many studies. The energy resource potential of the study area and the impact of various energy technologies on the social environment have been considered by many models. However, the public interest and the interactions between stakeholders have rarely been examined. The main novelty of this research is that it considers the public interest and proposes and practices a negotiated stakeholder strategy. The paper simulates a mixed energy system based on the public perspective and stakeholder negotiations. This study shows that the public is critical of the pollution, noise, and odor generated by energy technologies in their daily lives, and therefore hydropower and nuclear power, which are installed far from the city, as well as wind power, are the optimal choices in public-decision scenarios. Stakeholder negotiation results are a realistic and achievable scenario that secures electricity supply, low-carbon development, and high efficiency. This thesis also proposes a future research direction and tests it by introducing abstract future socioeconomic development pathways to investigate their potential impacts on future energy-mix systems.

To date, there are still several limitations on data and models that need to be overcome. First, due to the COVID-19 pandemic, it was difficult to have more stakeholders respond to the interview, and some of the responders could not meet face-to-face. The model simulation results show that stakeholder preferences for technologies and their perception of sustainable development goals significantly influence spatial energy planning. As such, to achieve more representable energy landscapes, studies should include more stakeholders to reduce uncertainties.

Second, the agent-based model does not include the temporal factor of realizing the agent-decided energy landscape. Therefore, the bias would be emergent in long-term energy planning because the construction to implement the expected energy landscape takes years. Future research should include time factors in energy planning. More recommendations for future research are listed below:

- The agent-based model can be coupled with a socioeconomic model so that the socioeconomic data of the study area can be dynamically updated.
- The trade-off variables can be introduced into the negotiation process of agents, such as government subsidies and carbon taxes.
- Beyond the energy production system, the power transmission system and power storage technology should also be considered in future energy planning.
- To investigate the impacts of future potential socioeconomic pathways on the energy-mix system, more projection models, which could forecast socioeconomic parameters of the agent-based model, should be coupled in the ABM.

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Appendix

Appendix 1: Literature review results of sustainable indicators

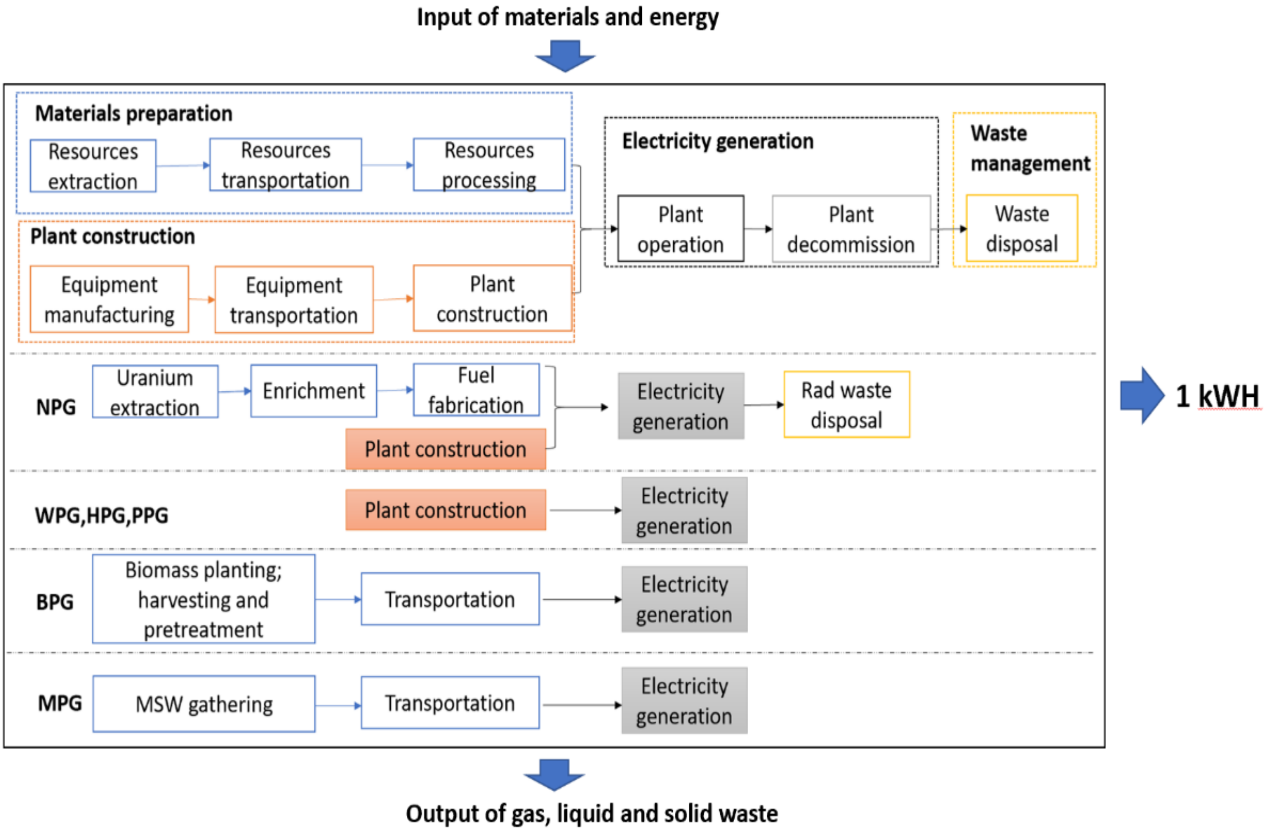
The Scope of the Review

It is necessary to structure a review scope to impose restrictions to the reviewed energy technologies and the methodological approaches used to assess them.

(1) Reviewed energy technology restriction: the individual case studies of mainstream energy power plant technologies (Table 3.1) are considered.

(2) The selected literature should apply life cycle analysis or life cycle cost assessment as a research method. The lifecycle should be restricted to the boundary in Figure A1.1.

Figure A1. 1 The life cycle of different energy power plants



The emissions intensities stated here have been derived from the specific LCA studies and from associated literature reviews of LCA studies conducted internationally. The life cycle includes three life cycle phases: 1) fuel provision (from the extraction of fuel to the gate of the plant), 2) infrastructure (commissioning and decommissioning), and 3) plant operation (operation and maintenance, including residue disposal).

(3) data extraction:

a. Tabulate summary of data extracted from literature.

b. Data examination, clear outliers from the data.

Economic indicators

ECO1: Levelized cost of electricity

The Levelized cost of electricity (LCOE) of a given technology is the ratio of lifetime costs (power plants capital investment; operation and management cost; fuel cost and waste disposal cost) to lifetime electricity production. The method of LCOE makes the comparison of electricity generation technologies with different generating and cost structures possible. The LCOE is highly varied by the regional conditions, particularly for renewables (IRENA, 2019b; Kost et al., 2018; NDRC, 2019). To apply a more real LCOE value, which fits Chinese mainstream electricity generation technologies, the literature selected refers to LCOE following the evaluation constraints in section 2.4. The values applied in this study are shown in Table A1.1 (IRENA, 2019b; Kost et al., 2018; Jinchao Li et al., 2016; NDRC, 2019; C. Peng, 2015; Woon & Lo, 2016).

The global weighted-average LCOE for hydropower, on-shore wind, bioenergy, and solar PV power has reduced and become more competitive with fossil fuels (IRENA, 2019b). Particularly in China, the LCOE for on-shore wind reduces to 0.35-0.5 RMB /kWh in the windiest regions, and solar PV reduces to approximately 0.37-0.51 RMB /kWh (NDRC, 2019). The on-shore wind and solar PV power plants located in the most suitable area have a comparable economic feature to fossil fuel power plants. However, the cost of waste-to-electricity (WTE) technology is still high due to the high cost of waste gathering and transportation.

Table A1.1 Levelized cost of electricity generation technologies

	Unit	**NG**	**Nuclear**	**Wind**	**PV**	**Hydro**	**Biomass**	**MSW**
Levelized cost of energy	USD/kWh	0.0195	0.053	0.069	0.0636	0.0456	0.0763	0.32

ECO2: Energy efficiency

Energy efficiency refers to “ the efficiency of conversion from the energy in the fuel source into electricity” (Evans et al., 2010). The efficiency would influence the electricity generation cost in the long term, which further influences sustainability. Thus, it is an essential indicator for stakeholders to consider. The summarized values are shown in Figure A1.2 (Ardolino et al., 2020; Evans et al., 2010; Fei et al., 2018; Felix & Gheewala, 2014; J. Liu et al., 2009; Meldrum et al., 2013; Pu et al., 2015; World Energy Council, 2004; Q. Yue et al., 2019).

Hydropower has the highest efficiency of 90%. The energy efficiency of on-shore wind power reaches the energy efficiency of natural gas power. Other energy technologies are still incomparable with natural gas power. Energy efficiency might increase with technological innovation in the future.

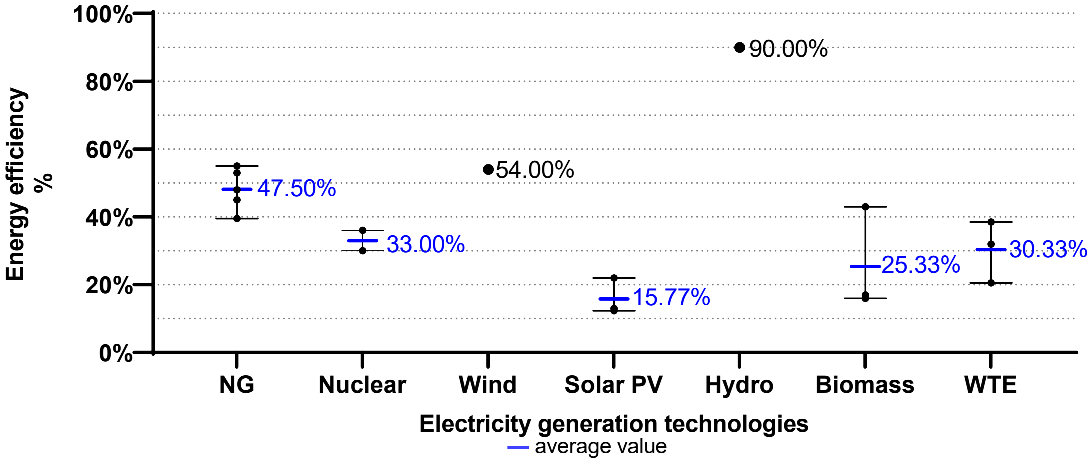


Figure A1.2 Energy efficiency of different electricity generation technologies

ECO3: Energy endowment

The "Energy endowment" is the indicator showing the potential of energy resources in the study area. Energy endowment is the ratio of the total reserves of a specific energy source in YRDR compared with its total national reserves. The energy resources are widely distributed in China and varied by regional geographic characteristics. The stakeholders tend to choose the technologies with higher resource potential in each region. The value of energy endowment is calculated and listed in Table A1.2.

The most impoverished resource in the YRD region is natural gas, which depends on imports from other countries. In contact, the waste resources are the richest due to the high-income level in the YRD region (Cinda Security, 2019). Because of the significant crop production in the Jiangsu and Anhui provinces, biomass resource endowment is very high in the YRD region, with a value of 0.1003.

Table A1.2 Energy resources endowment

	AH b_1	**ZJ** b_2	**JS** b_3	**SH** b_4	**YRDR** $\sum_{n=1}^{n=4} b_n$	**China** B	**Energy endowment** $\sum_{n=1}^{n=4} b_n \;/\; B$	**REF**
NG($10^9 m^3$)	0.25	0	23.31	0	23.56	84000	0.0003	(Q. Yan et al., 2016)
Uranium(t)	0	7320	0	0	7320	366000	0.0200	(China Nuclear Energy Association, 2020; Nuclear Energy Agency; International Atomic Energy Agency, 2016)
Hydro(W)	3.98E+09	6.75E+09	1.99E+09		1.27E+10	4.02E+11	0.0317	(CNC, 2005; Yao & Gao, 2012; D. Yue, 2009; Zongqi, 2005)
Wind(W)	2.51E+09	1.64E+09	2.38E+09		6.52E+09	2.53E+11	0.0258	(Xue et al., 2001)

Solar(kWh)	1.82E+14	1.35E+14	1.56E+14		4.73E+14	1.56E+16	0.0303	(China Meteorological Administration, 2008)
Biomass(MW)	7348.34	2073.9	6373.63	373.5	16169.37	161198.8	0.1003	(Song et al., 2016)
Waste(10^9 kg)	64.61	153.02	180.96	75.06	573.65	2420.62	0.1957	(Anhui statistical bureau, 2020; Jiangsu statistical bureau, 2020; Shanghai statistical bureau, 2020; Zhejiang statistical bureau, 2020)

Environmental indicators

ENV1: CO2 emissions

To achieve an energy transition target, it is needed to assess the life-cycle CO2 emissions of electricity generation. The substantial CO2 emissions generated from upstream equipment manufacturing processes should be considered (Feng et al., 2014). The CO2 emissions values are shown in the Figure A1.3 (Alsema, 2012; Chunjie et al., 2012; Crawford, 2007; Y. Dong et al., 2015; Fan et al., 2016; Fei et al., 2018; Feng et al., 2014; Hailong et al., 2017; Hertwich et al., 2015; Hou et al., 2015; Hu et al., 2013; Ito et al., 2003; Jiang et al., 2018; Jungbluth, 2005; K.Sovacool, 2008; Kannan et al., 2006; Krauter & Rüther, 2004; Lenzen, 2008; X. Li et al., 2019; Z. Li et al., 2017; Longo et al., 2020; Noori et al., 2015; Pearce, 2012; Poinssot et al., 2014; Spath et al., 2004; Turconi et al., 2013; Usapein & Chavalparit, 2017; Warner & Heath, 2012; Weng & Chen, 2017; World Energy Council, 2004; Q. Yue et al., 2019; D. Zhang et al., 2015; Q. Zhang et al., 2007) .

The highest CO2 emission is generated by waste-to-electricity. From Ardolino and Zhao's study, the CO2 from WTE is classified as biological CO2 and CO2 from auxiliary coal(Ardolino et al., 2020; W. Zhao et al., 2016; Y. Zhao et al., 2012). Both types of CO2 emissions are considered in my study and resulted in the highest CO2 emissions of 1112.25 g/kWh. This value is followed by the only fossil-fuel power, natural gas power. Notably, there is one negative value, that CO2 emissions from the biomass power are -240g/kWh, resulting in sequestered CO2 during the biomass plantation period. Instead of producing electricity from fossil fuels, the electricity generated from biomass can effectively reduce carbon emissions from electricity generation. In general, renewables technologies emit very low CO2 emissions and could work as great substitutes for coal power plants considering CO2 emissions, except waste-to-energy power.

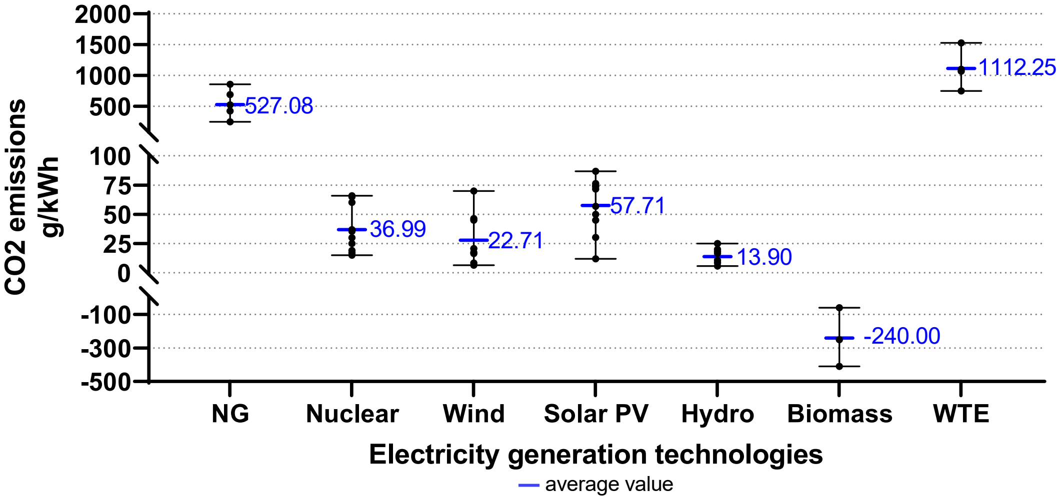


Figure A1.3 CO2 emissions of different electricity generation technologies

ENV2: SO2 emission & NOx emission

Emissions from criteria pollutants are included in this study due to their harm to air quality and human health. The high concentrations of SO2 in the air could be transformed to other sulfur oxides (SOx), which form tiny particles in the air. On the one hand, the tiny particles can be inhaled by humans, and an insufficient quantity can contribute to human respiratory problems. On the other hand, the SO2 increase acidification potential for rainfall, resulting in acid rain harming sensitive ecosystems. The SO2 emissions strongly relate to fuel and material provisions in the manufacturing stage of electricity generation technologies. Thus, the SO2 emissions always varied by the type and quantity of fuel and material consumed through the power plant construction and operation. The value can be found in Figure A1.4 (Ardolino et al., 2020; Buratti et al., 2015; J. Dong et al., 2018; Fei et al., 2018; Hertwich et al., 2015; Longo et al., 2020; Turconi et al., 2013; World Energy Council, 2004; W. Zhao et al., 2016).

The SO2 emission from biomass power rank first and mainly varied due to the different combustion technologies. The PV ranks second due to the high SO2 emissions during the crystalline production stage. For the only fossil fuel energy power, natural gas power shows the same feature. The natural gas provision stage contributes up to 80-90% of the whole life cycle SO2 emissions (Turconi et al., 2013). The SO2 emissions from nuclear power plant also result from the uranium extraction and enrichment energy provision stage.

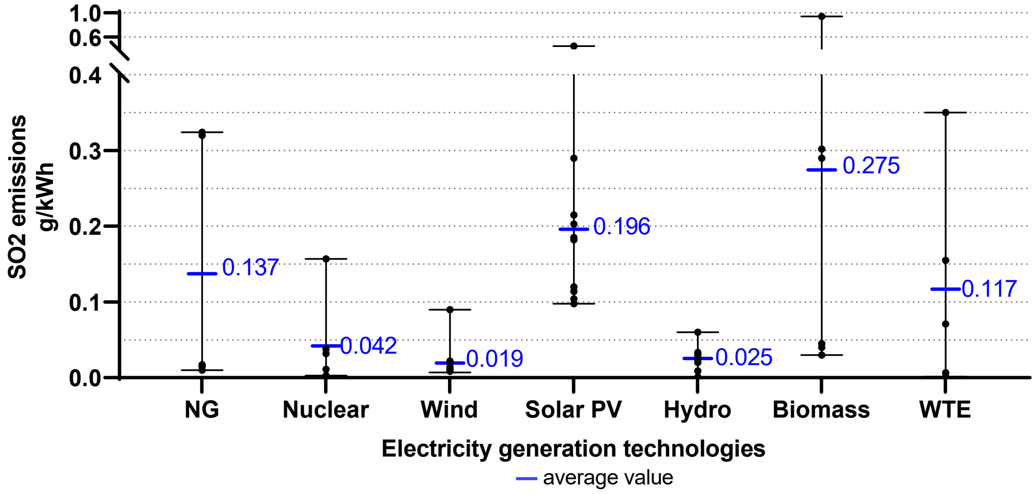


Figure A1.4 SO2 emission of different electricity generation technologies

NOx is composed of nitric oxide (NO) and a smaller percentage of nitrogen dioxide (NO2). Nitrogen oxides directly affect human health and indirectly influence the ecosystem by contributing to acid rain. The NOx value of each type electricity generation technology can be found in Figure A1.5 (Ardolino et al., 2020; Buratti et al., 2015; Fei et al., 2018; Hertwich et al., 2015; Longo et al., 2020; Turconi et al., 2013; World Energy Council, 2004; W. Zhao et al., 2016).

NOx emitted from biomass power is relatively high and varied by the type of biomass used in the power plant. The high nitrogen content of the biomass fuel will result in higher NOx emissions. The high NOx value of the WTE results from the waste provision through transport and waste incineration. The natural gas power plant ranks third in NOx emissions, which is reduced by the denitrification technology implemented in the power plants. For other renewable energy technologies, NOx emissions were mainly associated with the provision of the materials during the construction and electricity input during the manufacturing.

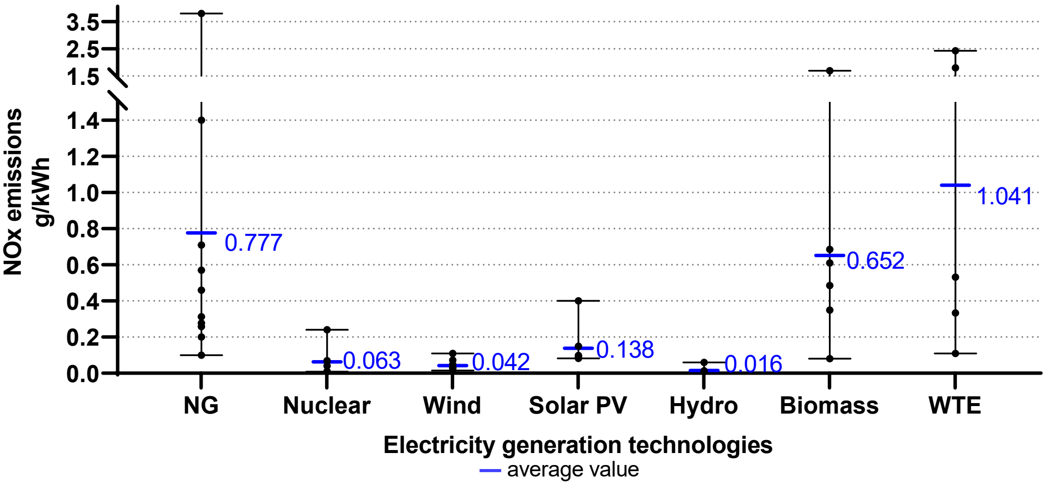


Figure A1.5 NOx emission of different electricity generation technologies

ENV3: Total Particulate Matter

Total particulate matter (TPM) is not often used as a sustainable indicator for energy technologies. However, TPM greatly influent air quality and human health on the local scale. Particularly in the large cities in China, the serve air pollution problem has driven public concern. The local and national institutional developing department has been planned to reduce total particulate matter emissions in future development (NDRC, 2019). In 2018, the State Council issued a three-year air pollution control plan named "New Blue-Sky Action Plan". The plan particularly targets reducing the PM2.5 concentration in the air and improving the air quality in three high developing regions, including the Yangtze River Delta Region (The State Council Issued a Circular on the Three-Year Action Plan for Winning the Battle for Blue Skies, 2018).

In Figure A1.6, the NG electricity generation technologies emit the highest total particulate matter per kWh in the electricity-producing life cycle due to fossil fuel consumption. In addition, the value varied on the efficiency of the electrostatic precipitator installed in the power plants. The biomass and WTE power rank for the second and third position of TPM emission due to the fossil fuel consumption during the material transportation processes. Besides, the relatively high TPM of the hydropower resulted from the construction duration and varied with the size of hydro dams.

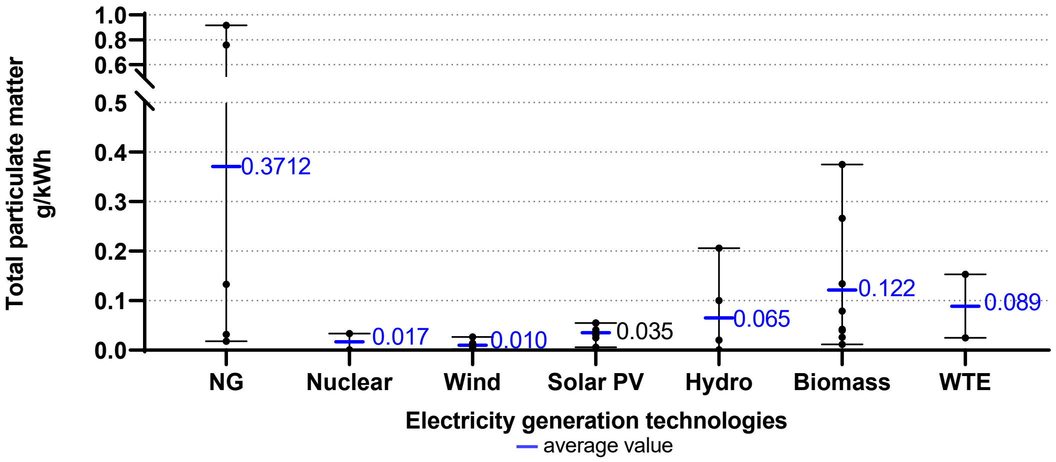


Figure A1.6 Total particulate matter of different electricity generation technologies

Social indicators

SOC1: Human Toxicity Potential

Human toxicity potential (HTP) represents the toxic released from electricity generation power plants to the human environment. SO2 and NOx emissions are all contributed to this indicator (Siddiqui & Dincer, 2017). Badea's research shows how the HTP are calculated from the emissions (equation A1.1) (Badea et al., 2010) :

$$\boldsymbol{HTP = \sum_i \sum_j HTP_i * m_{i,j}}$$ **Equation A1.1**

- i is the type of emissions, including SO2, NOx and so on.
- $m_{i,j}$ is the relative amount of type i emissions.
- HTP_i is the human toxicity potential indices of type i emissions.

According to this method, I have calculated the HTP of energy technologies by utilising the median value of SO2 and NOx emission summarised above.

Table A1.3 Human toxicity potential of different electricity generation technologies

	NG	Nuclear	Wind	PV	Hydro	Biomass	MSW
HTP	0.383141	0.03252	0.039571	0.137424	0.026988	0.75984	0.644016

To validate the calculated HTP value (Table A1.3), I compare it with the HTP value from the literature. It is easily found that there is not much difference between the calculated value and the value from literature. The minor existing differences result from some unincluded toxicity substance in my calculation. To avoid discrepancies resulting from the different components of human toxic substances and keep the value consisting of HTP, I choose the self-calculated HTP value to utilise in this study. The HTP value is limited to exhibit the toxicity potential of SO2 and NOx.

SOC2: Job Creation

The electricity generation technologies' installation brings a positive impact on employment (D. M. . Kammen et al., 2004). These job creation can be classified into two categories: direct employment, including jobs in manufacturing, power plant construction, operation and maintenance; indirect jobs generated in the upstream and downstream suppliers, including fuel production, employee catering and accommodation (Rutovitz et al., 2015). This research only includes direct jobs generated from the energy industry and excludes the indirect jobs generated in the fuel production stage. Figure A1.7 shows the job created by the different technologies (D. Kammen & Kapadia, 2004; Ram et al., 2020; Rutovitz et al., 2015; M. Wei et al., 2010).

Many studies show that renewable electricity generation technologies create more job opportunities. Hydro, solar PV and biomass power plant created significant greater employment than other technologies due to the high job opportunities generated in the plant construction stage (D. Kammen & Kapadia, 2004; M. Wei et al., 2010). Thus, the job creation value highly varied by the power plant scale. The on-shore wind power plant required more employee in the manufacturing stage than other stages of the life cycle. In contrast, the job created by the natural gas, nuclear and waste-to-energy power plant is relatively low than other energy technologies.

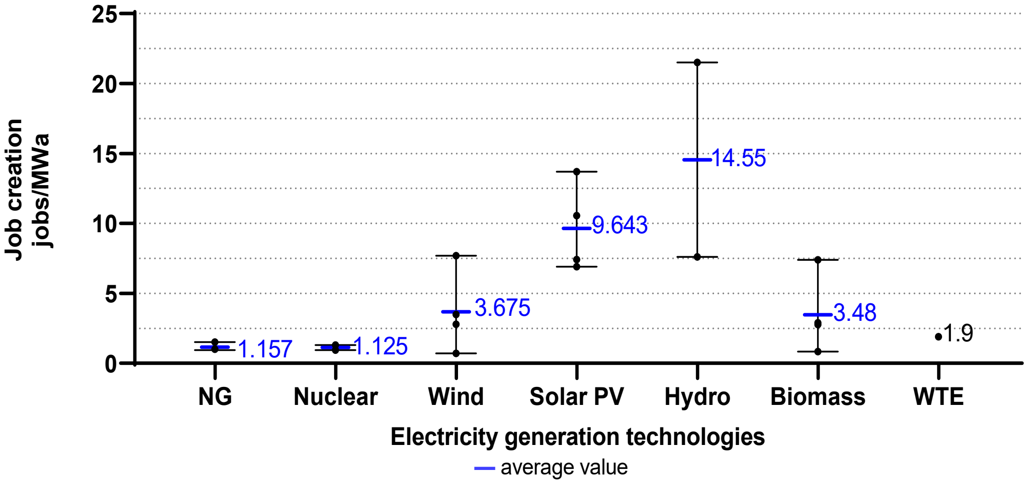


Figure A1.7 Job creation of different electricity generation technologies

SOC3: Social Acceptance

Social acceptance ranks from the random survey data, which refers to the residents' acceptability of the electricity generation technology installations. I apply the social acceptance ranking method from Shaaban's research and design the questionnaire with the four main questions, including Q1 the knowledge background of the response, Q2 the acceptability of the electricity generation technology installation in the YRD region and the nearby area (Q3), and Q4 the preferences ranking of electricity generation technology. The integrated results can rank the social acceptance from Q1 to Q4. The calculation method (equation 5) modified from Shaaban's research (Shaaban et al., 2018) :

$$\textbf{Social acceptance ranking} = Q_1 * (Q_2 + Q_3 + Q_4) \qquad \textbf{Equation A1.2}$$

Table A1.4 shows that on-shore wind and solar power are ranks as the most acceptable electricity generation technologies. In contrast, biomass power and WTE are not welcomed by residents due to their terrible smell, which highly influences the neighbour's daily lives.

Table A1. 4 Social acceptance of different electricity generation technologies

	NG	Nuclear	Wind	Solar PV	Hydro	Biomass	WTE
Q1. Knowledge	2.13	2.34	2.62	2.62	2.72	1.87	2.32
Q2. Installation in YRDR	3.42	2.96	4.04	4.06	3.92	3.96	3.68
Q3. Installation in nearby	2.79	2.25	3.55	3.64	3.53	3.51	2.89
Q4. Technology ranking	3.80	3.63	3.38	3.09	2.71	1.87	1.52
Social acceptance	21.34	20.67	28.76	28.28	27.61	17.46	18.77

Technical indicators

TEC1: Capacity factor & Secured capacity

Flexible electricity generators became critical in the power system due to the variability and uncertainty existing in the power dispatching system (Gonzalez-Salazar et al., 2018). The increasing share of renewables in the power supply system simulates higher uncertainty, promoting the importance of more flexible electricity generation technologies. The technical flexibility of electricity generation technologies is closely related to the physical structure and could be evaluated by minimum load, ramping rate, start-up time and so on (Agora Energiewende, 2017; Gonzalez-Salazar et al., 2018; IRENA, 2019a). In this study, I use the "capacity factor" and "secured capacity" as the technical flexibility indicators, which are shown in figure A1.8.

Capacity factor refers to "a ratio of actual electrical energy output to the maximum possible electrical energy output over a period" (IEA, 2019b). Nuclear energy has the highest capacity factor, and the capacity factor of on-shore wind and solar PV is relatively lower than other electricity generation technologies.

The secured capacity of electricity generation technologies could be counted as securely available capacity at times of peak demand (IEA, 2012). On-shore wind power and solar PV have the lowest secured factor.

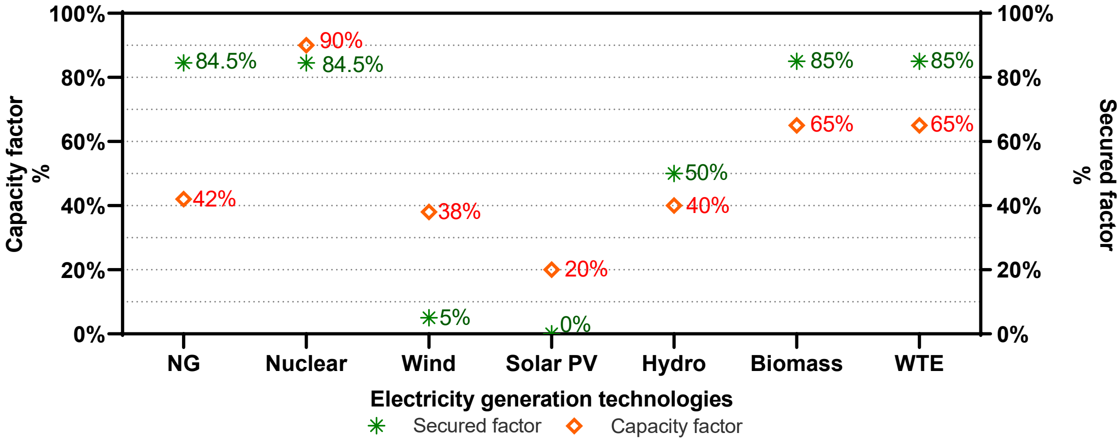


Figure A1.8 Capacity factor & secured factor of different electricity generation technologies

TEC2: Water consumption

In this study, water consumption refers to the net amount of water consumed per kWh electricity production, which is the value of water withdrawal minus water discharge in the production life cycle (Feng et al., 2014; Fthenakis & Kim, 2010). The local water conservation and ecosystem are under pressure from the water consumption of electricity generation. Although the YRD region is rich in water resources, the water consumption of electricity generation is still an important criterion to evaluate and shown in Figure A1.9.

For natural gas and biomass power plant, most water is consumed in the fuel stage. For other powerplants, most water is consumed in the operation stage. The findings show that the biomass power plant ranks first in water consumption, resulting from the considerable water input in crop cultivation (Feng et al., 2014; Yi et al., 2019). Water consumption varied greatly in biomass plantation due to the different water requirements of different energy plants. Hydropower ranks second in terms of total life-cycle water consumption. Reservoirs lose water through evaporation, which changes as a function of the reservoir surface area.

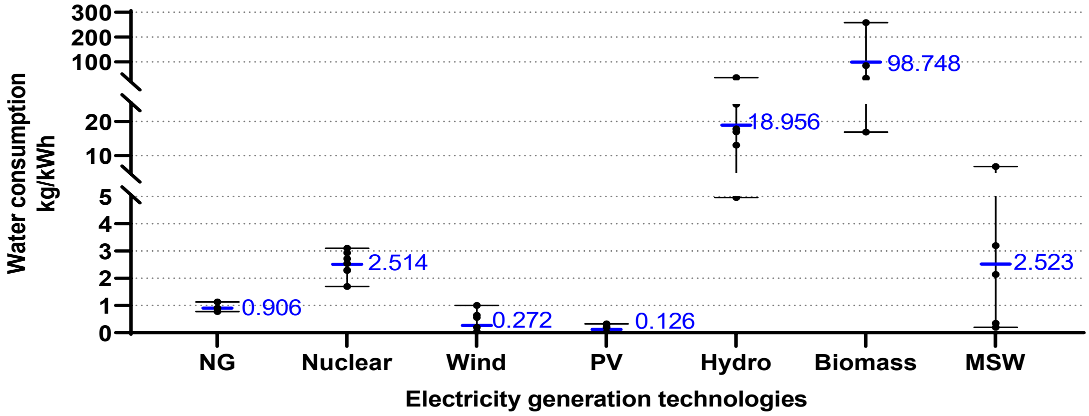


Figure A1.9 Water consumption of different electricity generation technologies

TEC3: Land transformation

This study uses land transformation as the sustainable indicators to rephrase direct land-use change from one land-use type to another due to the input material preparation and power plant construction (Fritsche et al., 2017). For example, land-use change from cultivated land to an energy crop plantation is regarded as direct land transformation. However, the indirect land-use change occurs as a flow-on effect, which is not considered in the land transformation in this research (Fritsche et al., 2017; Mitavachan & Srinivasan, 2012). Figure A1.10 shows the land transformation values.

The most significant land transformation resulted from biomass energy technology. The energy crop caused land-use change accounts for most of its land transformation. The land transformation of hydropower varied in an extensive range due to the hydro dam size. Other energy technologies' land transformation is very low. The land transformation shows a relatively higher value for on-shore wind power because the value represents the entire wind farm. The actual land transformation for an individual wind turbine is very low, and the remaining land area between wind turbine is used for agriculture or recreation (Evans et al., 2010).

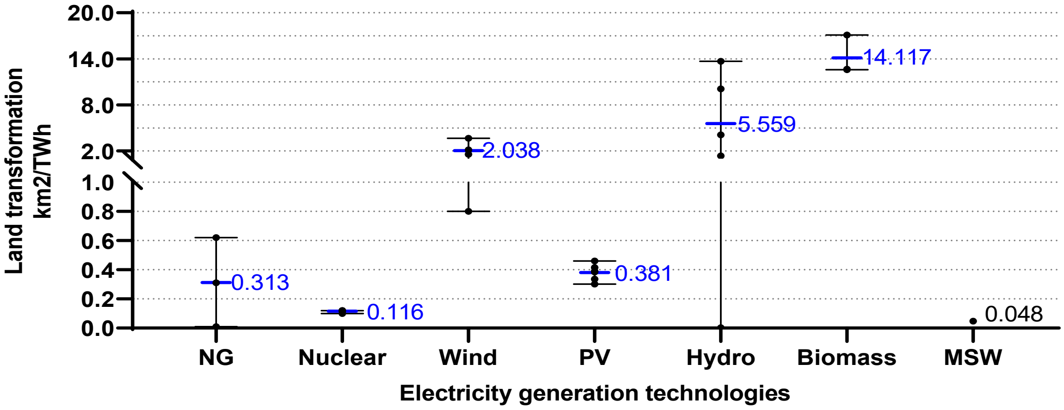


Figure A1.10 Land transformation of different electricity generation technologies

Appendix 2: Figures of modeling environment in Netlogo

The modeling environment of the agent-based model developed in Chapter 4 is initiated by the raster maps output from Chapter 2.

Figures A2.1 and A2.2 respectively present the spatial theoretical energy potential criterion (C1) for each technology and the spatial suitability maps based on other evaluation criteria in NetLogo. The dark color indicates a higher value and the light color indicates a lower value. For instance, in the theoretical energy potential map for nuclear, the dark violet patches are of higher ranking for installation and the lightest violet patches show non-theoretical potential.

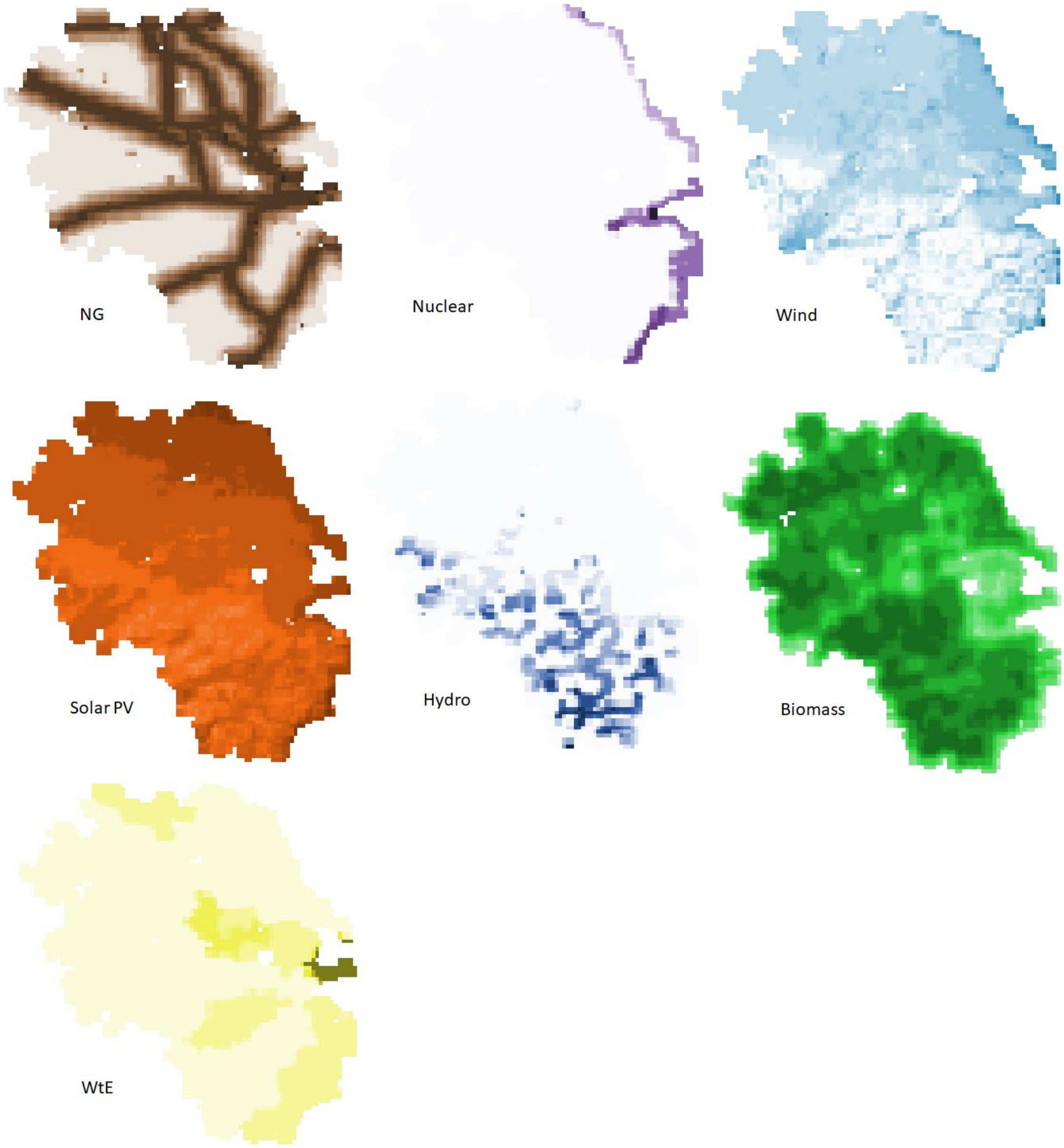


Figure A2.1 Spatial theoretical energy potential (C1) map of alternative power plants in netlogo

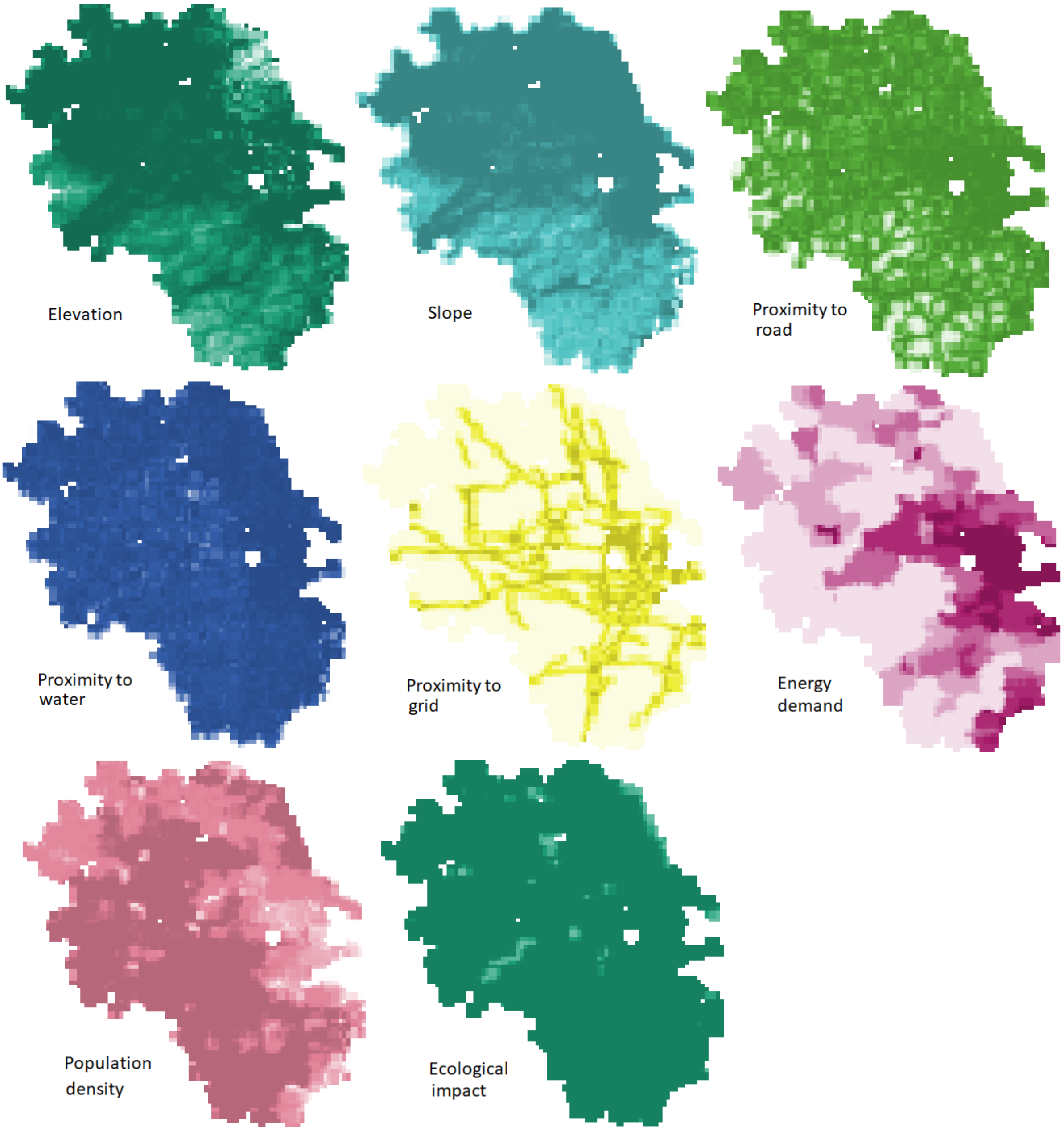
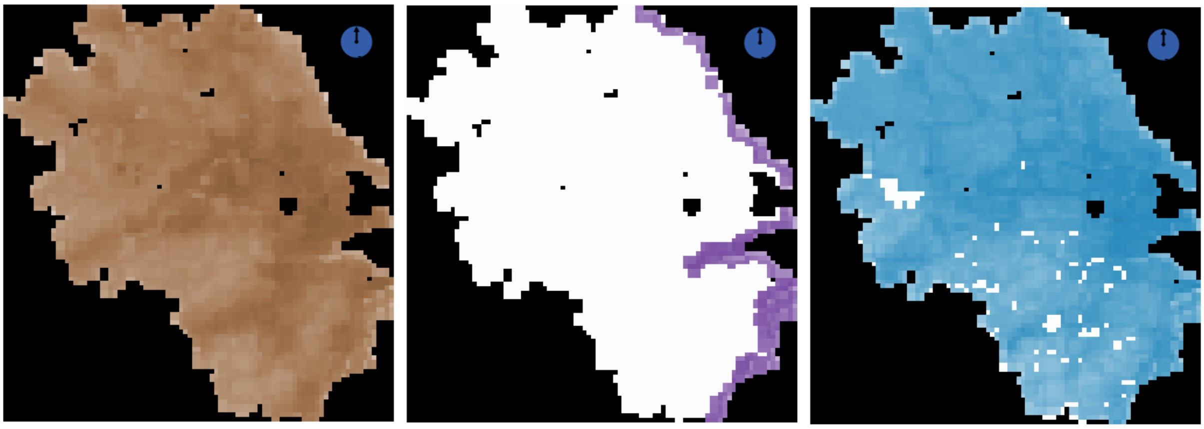
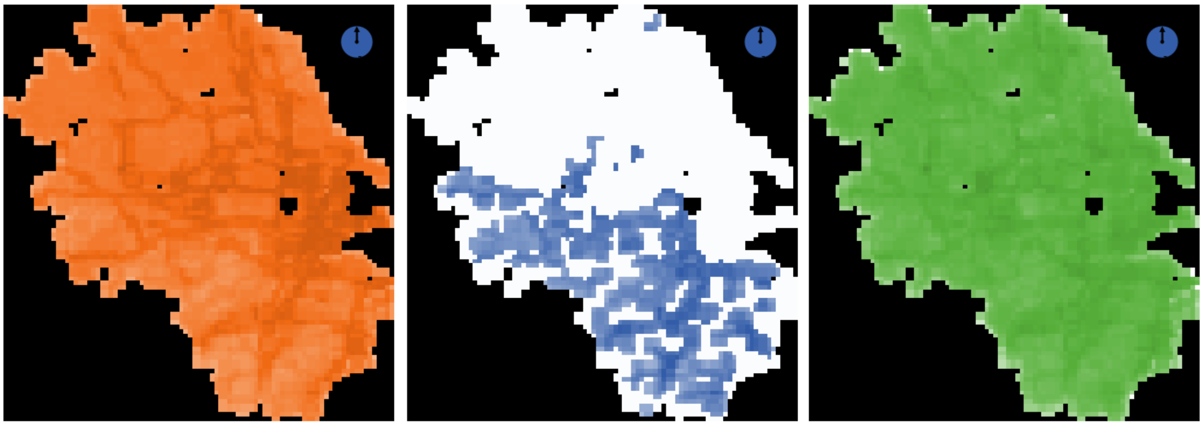


Figure A2.2 Spatial suitability map of evaluation criteria (C2–C9) in NetLogo.

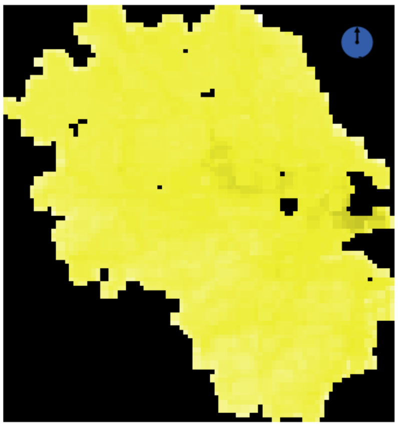
To exclude the possibility of selecting energy technologies with non-theoretical potential in spatial cells, I switch off the cells with non-theoretical potential for each energy technology to obtain the integrated spatial site potential maps in NetLogo shown in Figure A2.3. Figure 2.3 presents the initial spatial environment for the agent-based model.



NG Nuclear Wind



Solar PV Hydro Biomass



WtE

Figure A2.3 Visualization of spatial site potential of technologies in Netlogo

Appendix 3: The simulated values of sustainable indicators under SSPs in 2060

Table A3.1 The simulated values of sustainable indicators under SSPs in 2060

SSP1		**NG**	**Nuclear**	**Wind**	**Solar PV**	**Hydro**	**Biomass**	**WTE**
Levelized cost of energy	USD/kWh	0.123012	0.150081	0.208524	0.179674	0.147741	0.235749	0.431309
Energy efficiency	%	0.475	0.330	0.540	0.158	0.900	0.253	0.303
Energy endowment	%	0.000	0.020	0.032	0.026	0.030	0.100	0.196
CO2 emissions	g/kWh	527.083	36.994	22.705	57.709	13.900	-240.000	1112.250
SO2 emissions	g/kWh	0.137	0.021278	0.009702	0.095714	0.012074	0.137867	0.061261
NOx emissions	g/kWh	0.777	0.030293	0.020928	0.068178	0.007753	0.325221	0.535799
Total particulate matter	g/kWh	0.371	0.008718	5.06E-03	0.01704	0.033245	0.057178	0.044539
Human toxicity potential	kg 1,4DCB‡ eq./kWh	0.383	0.033	0.040	0.137	0.027	0.760	0.644
Job creation	jobs/Mwa	1.157	1.125	3.675	9.643	14.550	3.480	1.900
Social acceptance	ranking	21.338	20.666	28.764	28.284	27.609	17.456	18.772
Secured capacity	%	0.845	1.583659	0.982391	0.191584	0.936861	1.649068	1.653924
Capacity factor	%	0.420	0.900	0.380	0.200	0.400	0.650	0.650
Water consumption	kg/kWh	0.907	2.514	0.272	0.126	18.959	98.748	2.522
Land transformation	km2/TWh	0.313	0.116	2.038	0.381	5.559	14.117	0.048
SSP2		**NG**	**Nuclear**	**Wind**	**Solar PV**	**Hydro**	**Biomass**	**WTE**
Levelized cost of energy	USD/kWh	0.132705	0.197239	0.279096	0.242499	0.206216	0.317069	0.563109
Energy efficiency	%	0.475	0.330	0.540	0.158	0.900	0.253	0.303
Energy endowment	%	0.000	0.020	0.032	0.026	0.030	0.100	0.196
CO2 emissions	g/kWh	527.083	36.994	22.705	57.709	13.900	-240.000	1112.250
SO2 emissions	g/kWh	0.137	0.028988	0.012795	0.1272	0.01623	0.184213	0.074411
NOx emissions	g/kWh	0.777	0.042432	0.027705	0.095167	0.010172	0.429818	0.715015
Total particulate matter	g/kWh	0.371	0.011428	6.58E-03	0.022958	0.044314	0.080529	0.05945
Human toxicity potential	kg 1,4DCB‡ eq./kWh	0.383	0.033	0.040	0.137	0.027	0.760	0.644
Job creation	jobs/Mwa	1.157	1.125	3.675	9.643	14.550	3.480	1.900
Social acceptance	ranking	21.338	20.666	28.764	28.284	27.609	17.456	18.772
Secured capacity	%	0.845	1.229937	0.730117	0.148	0.7205	1.198568	1.288748
Capacity factor	%	0.420	0.900	0.380	0.200	0.400	0.650	0.650
Water consumption	kg/kWh	0.907	2.514	0.272	0.126	18.959	98.748	2.522
Land transformation	km2/TWh	0.313	0.116	2.038	0.381	5.559	14.117	0.048
SSP3		**NG**	**Nuclear**	**Wind**	**Solar PV**	**Hydro**	**Biomass**	**WTE**
Levelized cost of energy	USD/kWh	0.144089	0.257976	0.383162	0.322488	0.274479	0.45961	0.768649
Energy efficiency	%	0.475	0.330	0.540	0.158	0.900	0.253	0.303
Energy endowment	%	0.000	0.020	0.032	0.026	0.030	0.100	0.196
CO2 emissions	g/kWh	527.083	36.994	22.705	57.709	13.900	-240.000	1112.250
SO2 emissions	g/kWh	0.137	0.028988	0.012795	0.1272	0.01623	0.184213	0.074411
NOx emissions	g/kWh	0.777	0.042432	0.027705	0.095167	0.010172	0.429818	0.715015

Total particulate matter	g/kWh	0.371	0.011428	6.58E-03	0.022958	0.044314	0.080529	0.05945
Human toxicity potential	kg 1,4DCB‡ eq./kWh	0.383	0.033	0.040	0.137	0.027	0.760	0.644
Job creation	jobs/Mwa	1.157	1.125	3.675	9.643	14.550	3.480	1.900
Social acceptance	ranking	21.338	20.666	28.764	28.284	27.609	17.456	18.772
Secured capacity	%	0.845	1.229937	0.730117	0.148	0.7205	1.198568	1.288748
Capacity factor	%	0.420	0.900	0.380	0.200	0.400	0.650	0.650
Water consumption	kg/kWh	0.907	2.514	0.272	0.126	18.959	98.748	2.522
Land transformation	km2/TWh	0.313	0.116	2.038	0.381	5.559	14.117	0.048
SSP4		**NG**	**Nuclear**	**Wind**	**Solar PV**	**Hydro**	**Biomass**	**WTE**
Levelized cost of energy	USD/kWh	0.132597	0.144346	0.202692	0.171282	0.155728	0.241091	0.415884
Energy efficiency	%	0.475	0.330	0.540	0.158	0.900	0.253	0.303
Energy endowment	%	0.000	0.020	0.032	0.026	0.030	0.100	0.196
CO2 emissions	g/kWh	527.083	36.994	22.705	57.709	13.900	-240.000	1112.250
SO2 emissions	g/kWh	0.137	0.021787	0.009534	0.097194	0.012441	0.136964	0.059052
NOx emissions	g/kWh	0.777	0.03187	0.021216	0.065426	0.007802	0.332316	0.512508
Total particulate matter	g/kWh	0.371	0.008355	5.11E-03	0.017107	0.032885	0.060028	0.044178
Human toxicity potential	kg 1,4DCB‡ eq./kWh	0.383	0.033	0.040	0.137	0.027	0.760	0.644
Job creation	jobs/Mwa	1.157	1.125	3.675	9.643	14.550	3.480	1.900
Social acceptance	ranking	21.338	20.666	28.764	28.284	27.609	17.456	18.772
Secured capacity	%	0.845	1.642456	0.95448	0.183	0.986368	1.579688	1.610054
Capacity factor	%	0.420	0.900	0.380	0.200	0.400	0.650	0.650
Water consumption	kg/kWh	0.907	2.514	0.272	0.126	18.959	98.748	2.522
Land transformation	km2/TWh	0.313	0.116	2.038	0.381	5.559	14.117	0.048
SSP5		**NG**	**Nuclear**	**Wind**	**Solar PV**	**Hydro**	**Biomass**	**WTE**
Levelized cost of energy	USD/kWh	0.141623	0.268226	0.380892	0.32868	0.255447	0.432549	0.75941
Energy efficiency	%	0.475	0.330	0.540	0.158	0.900	0.253	0.303
Energy endowment	%	0.000	0.020	0.032	0.026	0.030	0.100	0.196
CO2 emissions	g/kWh	527.083	36.994	22.705	57.709	13.900	-240.000	1112.250
SO2 emissions	g/kWh	0.137	0.036044	0.016986	0.169062	0.022854	0.243832	0.103645
NOx emissions	g/kWh	0.777	0.05654	0.036975	0.125255	0.013637	0.591014	0.95844
Total particulate matter	g/kWh	0.371	0.01455	8.89E-03	0.03322	0.057784	0.108098	0.080275
Human toxicity potential	kg 1,4DCB‡ eq./kWh	0.383	0.033	0.040	0.137	0.027	0.760	0.644
Job creation	jobs/Mwa	1.157	1.125	3.675	9.643	14.550	3.480	1.900
Social acceptance	ranking	21.338	20.666	28.764	28.284	27.609	17.456	18.772
Secured capacity	%	0.845	0.905881	0.549925	0.115	0.566463	0.992482	0.94318
Capacity factor	%	0.420	0.900	0.380	0.200	0.400	0.650	0.650
Water consumption	kg/kWh	0.907	2.514	0.272	0.126	18.959	98.748	2.522
Land transformation	km2/TWh	0.313	0.116	2.038	0.381	5.559	14.117	0.048

Appendix 4: Field trip

The field trip is combined with interviews of stakeholders based on questionnaires, and an online survey for the general public.

There are several difficulties and challenges during the field trip:

1) Difficulties in contact:

The existing contact information on the institute's website is mostly not validated, and there is no direct contact information for the targeted interviewees.

2) Challenges in response:

Without a personal referral from a mutual acquaintance, almost none experts gave a positive response to accept an interviewee.

3) COVID circumstance:

Due to the strict management of entry for individual companies, institutions, and universities, it is not possible to visit any targeting interviewees without previous contact, and some face-to-face interviews are required to transform into online interviewees.

4) The NDRC (institutional sector) will not accept field trips in the short term:

There was one person, who previously joint a research field trip conducted in the Zhejiang NDRC and found out to be recorded in the national spy list. Thus, all the field trip targeting the energy department of NDRC has been rejected since December 2020. This current situation will not last for a too long time, and it is possible to conduct interviewees in the summer of 2021.

To be able to communicate better with stakeholders and not just get answers through questionnaires. Besides the face-to-face interviews, I also had conversations with some stakeholders through online meetings. There are some pictures below:

Figure A4.1 Zhejiang electric power design institute, Zhejiang, China (left)

Figure A4.2 China Datang corporation ltd., Shanghai, China (right)

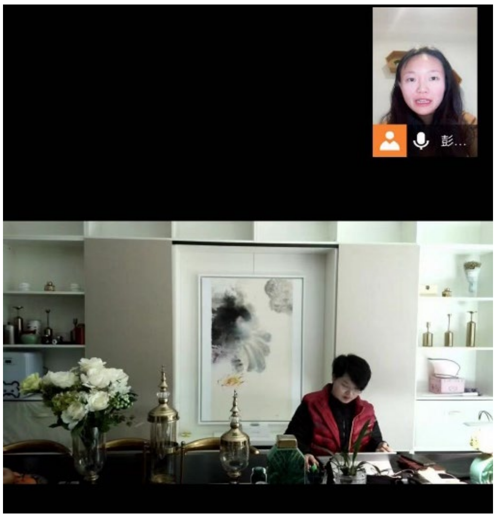


Figure A4.3 Online meeting with Li, the research director from Shanghai University of Electric Power, Shanghai (left)

Figure A4.4 Online meeting with Zhang, the director of Development and reform commission, Shanghai (Right)

Overview of the interviewees:

Table A4.1 Information of the interviewees

Note: due to privacy protection, names are only shown with the interviewees' last names.

ENERGY PLANNERS	NAME	TITLE	INSTITUTES/ ORGANIZATIONS	LOCATION
INSTITUTIONAL SECTORS	Zhang	Director	Development and reform commission, institute of energy and transportation	Shanghai
EXPERTS	Li	Research director	Shanghai University of Electric Power, office of academic research	Shanghai
	Liu	Researcher	Shanghai University of Electric Power, school of engineering economics and management	Shanghai
	Ma	Researcher	Fudan university, school of economic	Shanghai
	Qian	Researcher	Zhejiang electric power design institute	Zhejiang, Hangzhou
INDUSTRIAL SECTORS	Ran	Director	China Datang corporation ltd., investment development department	Shanghai
	Ge	Director	Zhejiang energy, investment development department	Zhejiang, Hangzhou
	Wu	General manager, director	State grid XinYuan international investment co., ltd., engineering department	Zhejiang, Hangzhou
	Song	Engineer-in-chief	Zhejiang electricity power construction co.,ltd.	Zhejiang, Hangzhou
	Yang	Engineer-in-chief	Zhejiang electric power co. Ltd, jinshuitan power station	Zhejiang, Lishui

Questionnaire: Chinese and English

长江三角洲区域应对气候变化的能源转型-公众调查问卷

Energy transition in the Yangtze River Delta to adapt Climate change, China - A public survey

调查执行人 **Investigator**: 彭叶宸楠 （Peng, Yechennan）
调查地点 **Location**: 长江三角洲地区 （The Yangtze River Delta Region）
调查时间 **Time**: 2020年12月-2020年1月 （11.2020-01.2021）
主办方 **Organizer**: 德国汉堡大学地理系，气候变化与安全项目组
Research Group Climate Chang and Security, Institute of Geography
University of Hamburg, Hamburg, Germany
合作方 **Partner**: 上海复旦大学， 环境科学与工程系
Department of Environmental Science & Engineering
Fudan University, Shanghai, China

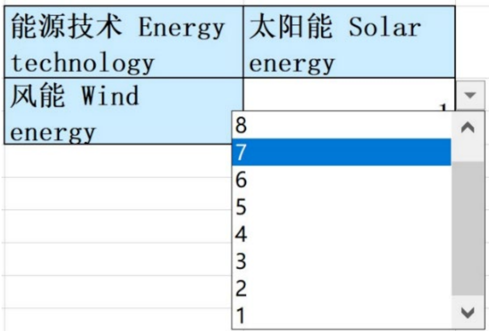
长江三角洲地区作为我国人口最密集、经济发展最活跃、能源消耗最高区域之一，正在经历应对气候与环境变化的快速能源转型。 我们当前正在开展的“长三角地区能源转型的协同效应”科研课题，为了进一步了解能源计划决策者对各个能源科技的偏向性以及在选择能源科技时各影响因素之间相对权重，调查问卷根据层次分析法(AHP)的形式设计。请您花费几分钟时间回答以下问题 （本次调查不记名，所有资讯将仅用于科学研究）。The Yangtze River Delta Region, as China's most densely populated, economically developed and highest energy consuming area, is experiencing rapid energy transition towards the conflict of urban Energy transition in the Yangtze River Delta to adapt Climate change. I am currently carrying out the research project "Dynamic energy landscape adaptation to Climate Change in the Yangtze River Delta Region". In order to further understand the energy planners' priority of energy technology, and measure the importance and the weight of the selected sustainability criteria for future electricity planning, a special questionnaire is designed for this project. Please take a few minutes to answer the following questions. (Your responses will be anonymous and the information obtained will be used only in scientific research).

问卷指南 Instructions on the questionnaire

第一部分运用层次分析法(AHP)对于能源供应技术的偏好进行测量。表格采用两两比较形式。The first part is used to **measures your general preference of the electricity supply technologies.** The analytic hierarchy process (AHP) is a pairwise comparison.

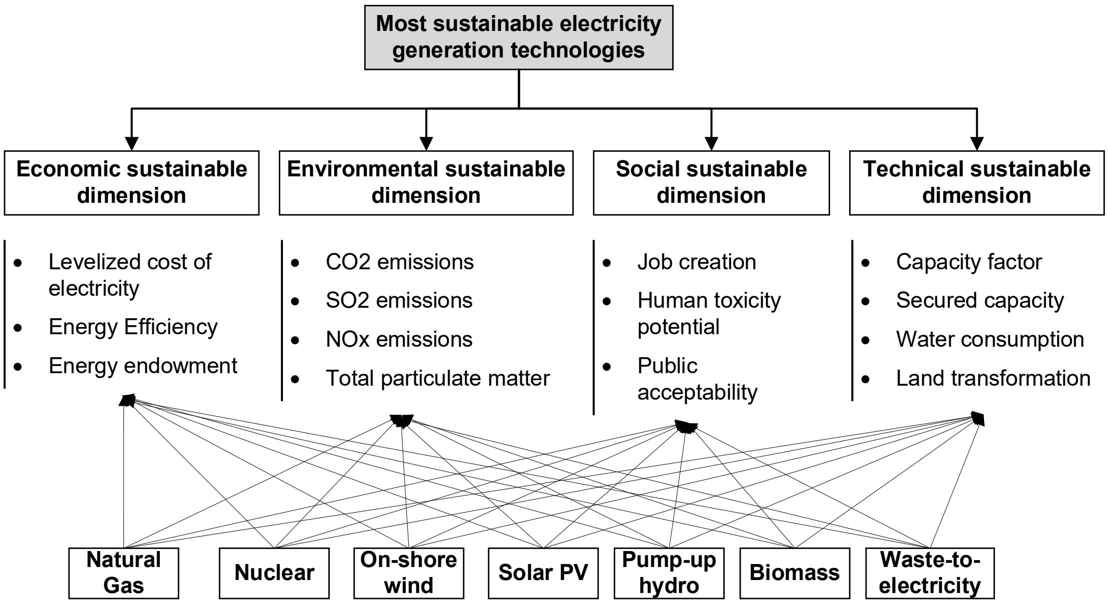
衡量尺度划分为个等级，分别是绝对高于、非常高于、比较高于、稍微高于、同样、稍微低于、比较低于、十分低于、绝对低于、分别对应 9，7，5，3，1，-3，-5，-7， -9 的数值。**请横向填写表格，根据行-列要素重要比选择合适的衡量尺度**。The scale is divided into a scale of absolute high, very high, relatively high, slightly high and equal, corresponding to the values of 9, 7, 5, 3, 1. **Please filling the table horizontally, with the comparison of the criteria of row to the criteria of column, but not vice versa.**

示例：您认为风能相对于太阳能在长江三角洲地区那一项合适？
如果您认为风能供应与太阳能供应相比非常合适，那么请选择 7。
Example: Do you think the wind energy supply is more important than the solar energy supply?
If you think the wind energy supply is very important than the solar energy supply, please select 7.



能源技术 Energy technology	太阳能 Solar energy
风能 Wind energy	1

第二部分运用层次分析法(AHP)对选择能源技术的影响因素重要性进行两两比较。The questionnaire is designed according to the form of analytic hierarchy process (AHP). The analytic hierarchy process (AHP) is a pairwise comparison of the importance of influencing factors of selecting energy technologies at the same level.



示例：您认为一辆汽车的安全性重要，还是价格重要？
如果您认为一辆汽车的安全性相对于价格十分重要，那么请选择 7。
Example: Do you think the safety of a car is more important than the price?
If you think the safety of a car is very important than the price, please select 7.

指标 Criteria	安全性 Safety	价格 Price
安全性 Safety	1	
价格 Price		

问卷内容 Content

第一部分测量对于能源技术偏好性 Priority of energy technologies

此研究限于陆上发电厂的能源规划

The national plan has specifically noted that only clean energy could be newly added to the whole energy system.

能源技术 Energy technology	天然气发电厂 NG power plant	核电厂 Nuclear power plant	陆上风能发电厂 Off-shore wind power plant	光伏发电厂 PV power plant	抽水蓄能发电厂 Pump storage hydro power plant	生物质能发电厂 Biomass power plant	垃圾焚烧发电厂 WtE power plant
天然气发电厂 NG power plant	1 equal	选择一项。	选择一项。	选择一项。	选择一项。	选择一项。	选择一项。
核电厂 Nuclear power plant		1 equal	选择一项。	选择一项。	选择一项。	选择一项。	选择一项。
陆上风能发电厂 Off-shore wind powerplant			1 equal	选择一项。	选择一项。	选择一项。	选择一项。
光伏发电厂 PV power plant				1 equal	选择一项。	选择一项。	选择一项。
水利发电厂 Hydro power plant					1 equal	选择一项。	选择一项。
生物质能发电厂 Biomass power plant						1 equal	选择一项。
垃圾焚烧发电厂 WtE power plant							1 equal

第二部分测量各个影响因素对于能源技术选择的影响 Weight of sustainable indicators

- **第二层要素**
  - 评估第二层要素对于“能源科技 Energy technology”的相对重要性

影响因素	**说明**
经济 Economic	包括：平准化成本 Levelized cost,能源效率 Energy efficiency，能源禀赋 Energy endowment
环境 Environmental	包括：二氧化碳排放 CO2 emissions, 二氧化硫排放 SO2 emissions, 氮氧化物排放 NOx emissions, 悬浮颗粒 total particulate matter
社会 Social	包括：临近居民接受度 Residents acceptance, 工作机会 Job creation, 工伤 HTP Human toxicity potential
技术 Technical	能源利用系数 Capacity factor, 能源安全利用系数 Secured capacity, 水资源消耗 Water consumption, 占地 Land Transformation

下列各组两两比较要素的相对重要性如何？

指标 Criteria	经济 Economic	环境 Environmental	社会 Social	技术 Technical
经济 Economic	1 equal	选择一项。	选择一项。	选择一项。
环境 Environment		1 equal	选择一项。	选择一项。
社会 Society			1 equal	选择一项。
技术 Technical				1 equal

❖ 第三层要素

➢ 评估第三层中经济要素中各个评估指标对于“能源科技 Energy technology 经济要素”的相对重要性

影响因素	**单位**	**说明**
平准化成本 Levelized cost	$/kWh	The net present value of all costs over the lifetime of the asset divided by an appropriately discounted total of the energy output from the asset over that lifetime.
能源效率 Energy efficiency	%	Energy efficiency refers the efficiency of conversion from the energy in the fuel source into electricity
能源禀赋 Energy endowment	%	The ratio of the total reserves of a certain energy source in YRDR compared with its total national reserves.
经济指标补充		如果您认为有其他更重要的经济指标请进行补充说明

下列各组两两比较要素，对于"经济 Economic"的相对重要性如何？

经济指标 Economic Criteria	平准化成本 Levelized cost	能源效率 Energy efficiency	能源禀赋 Energy endowment
平准化成本 Levelized cost	1 equal	选择一项。	选择一项。
能源效率 Energy efficiency		1 equal	选择一项。
能源禀赋 Energy endowment			1 equal

➢ 评估第三层中环境要素中各个评估指标对于“能源科技 Energy technology 环境要素”的相对重要性

影响因素	**单位**	**说明**
二氧化碳排放 CO2 emissions	g/kWh	CO2 emissions from 1 kWh electricity producing life cycle.
SO2 emission	g/kWh	SO2 emitted from 1 kWh electricity producing life cycle.
NOx emission	g/kWh	NOx emitted from 1 kWh electricity producing life cycle.
TPM	g/kWh	Total particulate matter generated from 1 kWh electricity producing life cycle.
环境指标补充		如果您认为有其他更重要的环境指标请进行补充说明

下列各组两两比较要素的相对重要性如何？

环境指标 Environmental Criteria	二氧化碳 CO2 emissions	二氧化硫 SO2 emission	氮氧化合物 NOx emission	悬浮微粒 TPM
二氧化碳排放 CO2 emissions	1 equal	选择一项。	选择一项。	选择一项。
二氧化硫 SO2 emission		1 equal	选择一项。	选择一项。
氮氧化合物 NOx emission			1 equal	选择一项。
悬浮微粒 TPM				1 equal

- 评估第三层中社会要素中各个评估指标对于“能源科技 Energy technology 社会要素”的相对重要性

影响因素	单位	说明
临近居民接受度 Residents acceptance	Grading	Residents acceptance of nearby electricity generation technologies
工作机会 Job creation	Jobs/MWa	Direct jobs generated from energy industrial and exclude the indirect jobs generated in fuel production stage.
对人体潜在毒害 HTP Human toxicity potential	kg 1,4 DCB‡ eq./kWh	The human toxicity potential refers to the potential human healthy influences resulted by particulate matter, SO2 and NOx emissions generated from electricity production.
社会指标补充		如果您认为有其他更重要的社会指标请进行补充说明

下列各组两两比较要素的相对重要性如何？

社会因素指标 Social Criteria	临近居民接受度 Residents acceptance	工作机会 Job creation	对人体潜在毒害 Human toxicity potential
临近居民接受度 Residents acceptance	1 equal	选择一项。	选择一项。
工作机会 Job creation		1 equal	选择一项。
对人体潜在毒害 Human toxicity potential			1 equal

- 评估第三层中技术要素中各个评估指标对于“能源科技 Energy technology 技术要素”的相对重要性

影响因素	单位	说明
能源利用系数 Capacity factor	%	A ratio of an actual electrical energy output to the maximum possible electrical energy output over a period.
能源安全利用系数 Secured capacity	%	Securely available capacity at times of peak demand

水资源消耗 Water consumption	Liter/ kWh	The net amount of water (i.e. water withdrawal minus water discharge) consumed along the supply chain to produce 1 kWh of electricity.
占地 Land Transformation	km2/ TWh	Direct land use change from one land use type to another due to the energy power plant input material preparation and power plant construction. Indirect land use change that occurs as a flow-on effect is not considered to the land transformation in my study
技术指标补充		如果您认为有其他更重要的技术指标请进行补充说明

下列各组两两比较要素的相对重要性如何？

社会因素指标 Social Criteria	能源利用系数 Capacity factor	能源安全利用系数 Secured capacity	水资源消耗 Water consumption	占地 Land transformation
能源利用系数 Capacity factor	1 equal	选择一项。	选择一项。	选择一项。
能源安全利用系数 Secured capacity,		1 equal	选择一项。	选择一项。
水资源消耗 Water consumption			1 equal	选择一项。
占地 Land transformation				1 equal

最后，欢迎您参与本次调查相关的任何问题，您可以联络本次调查的负责人：彭叶宸楠 Yechennan.Peng @studium-unihamburg.de

At the end, welcome to discuss more about this survey, you can contact the person in charge of this investigation Ms. Yechennan Peng: Yechennan.Peng @studium-unihamburg.de

问卷结束，谢谢您的参与！

Online Survey: Chinese and English

对于发电厂接受度

我们正在开展的“长三角地区动态能源景观”科研课题，为了避免能源转型进程中的社会冲突，我们希望通过本次调查了解您对于各类型能源发电厂的接受度，希望您能抽出几分钟时间，将您的感受告诉我们，期待您的参与！

1.请问您对以下能源技术的认知处于什么阶段?
How much knowledge do you have about the following energy technologies? *

	完全不了解 no idea	从电视网络媒体上听说过 heard from media	了解其基本知识 know basic infomation	拥有较好的知识储备 havegood knowledge	此行业专家 expert
天然气发电站 Natural gas power plant	○	○	○	○	○
核能源发电站 Nuclear power plant	○	○	○	○	○
风力发电站 Wind power plant	○	○	○	○	○
太阳能光伏发电站 Solar PV power plant	○	○	○	○	○
水利发电站 Hydro power palnt	○	○	○	○	○
生物质能发电站 Biomass power plant	○	○	○	○	○
垃圾焚烧发电站 Waste-to-energy power plant	○	○	○	○	○

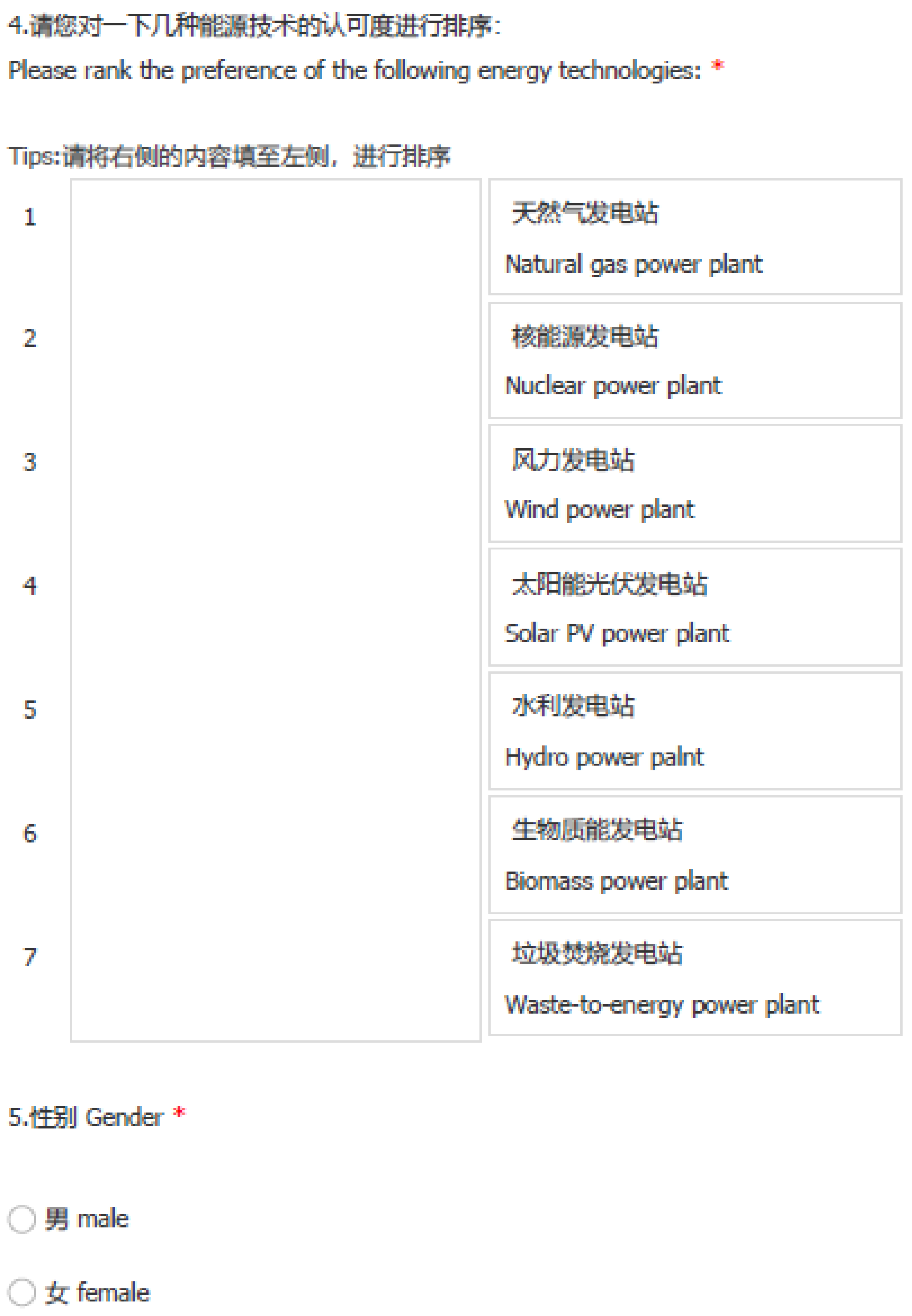
2.您是否支持以下发电站的能源技术在长江三角洲施行?

Do you support the installation of the following energy technologies in the Yangtze River Delta? *

	极度反对 strongly against	反对 against	无所谓 neutral	支持 support	非常支持 strongly support
天然气发电站 Natural gas power plant	○	○	○	○	○
核能源发电站 Nuclear power plant	○	○	○	○	○
风力发电站 Wind power plant	○	○	○	○	○
太阳能光伏发电站 Solar PV power plant	○	○	○	○	○
水利发电站 Hydro power palnt	○	○	○	○	○
生物质能发电站 Biomass power plant	○	○	○	○	○
垃圾焚烧发电站 Waste-to-energy power plant	○	○	○	○	○

3.您是否支持以下发电站建立在您的居住生活区域附近?
Do you support the following energy technology power stations to be built near your living area? *

	非常反对 strongly against	反对 sgainst	无所谓 neutral	支持 support	非常支持 strongly support
天然气发电站 Natural gas power plant	○	○	○	○	○
核能源发电站 Nuclear power plant	○	○	○	○	○
风力发电站 Wind power plant	○	○	○	○	○
太阳能光伏发电站 Solar PV power plant	○	○	○	○	○
水利发电站 Hydro power plant	○	○	○	○	○
生物质能发电站 Biomass power plant	○	○	○	○	○
垃圾焚烧发电站 Waste-to-energy power plant	○	○	○	○	○



4.请您对一下几种能源技术的认可度进行排序：
Please rank the preference of the following energy technologies: *

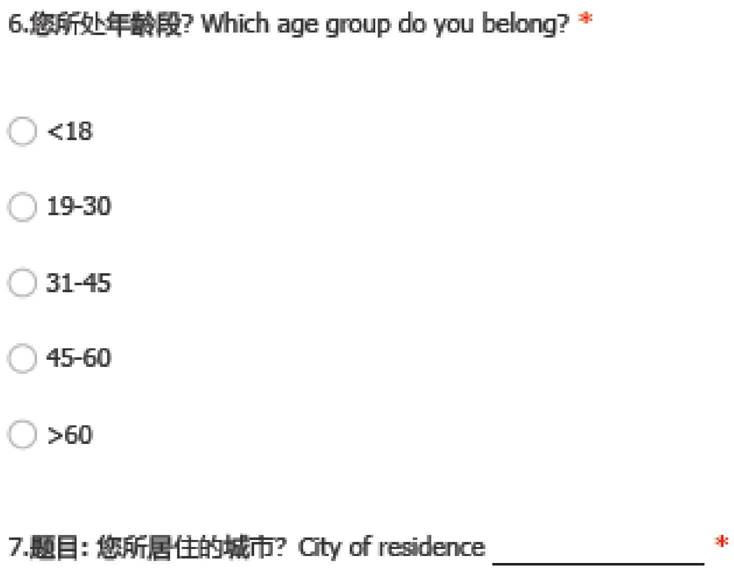
Tips:请将右侧的内容填至左侧，进行排序

1		天然气发电站 Natural gas power plant
2		核能源发电站 Nuclear power plant
3		风力发电站 Wind power plant
4		太阳能光伏发电站 Solar PV power plant
5		水利发电站 Hydro power palnt
6		生物质能发电站 Biomass power plant
7		垃圾焚烧发电站 Waste-to-energy power plant

5.性别 Gender *

○ 男 male

○ 女 female



6.您所处年龄段? Which age group do you belong? *

○ <18

○ 19-30

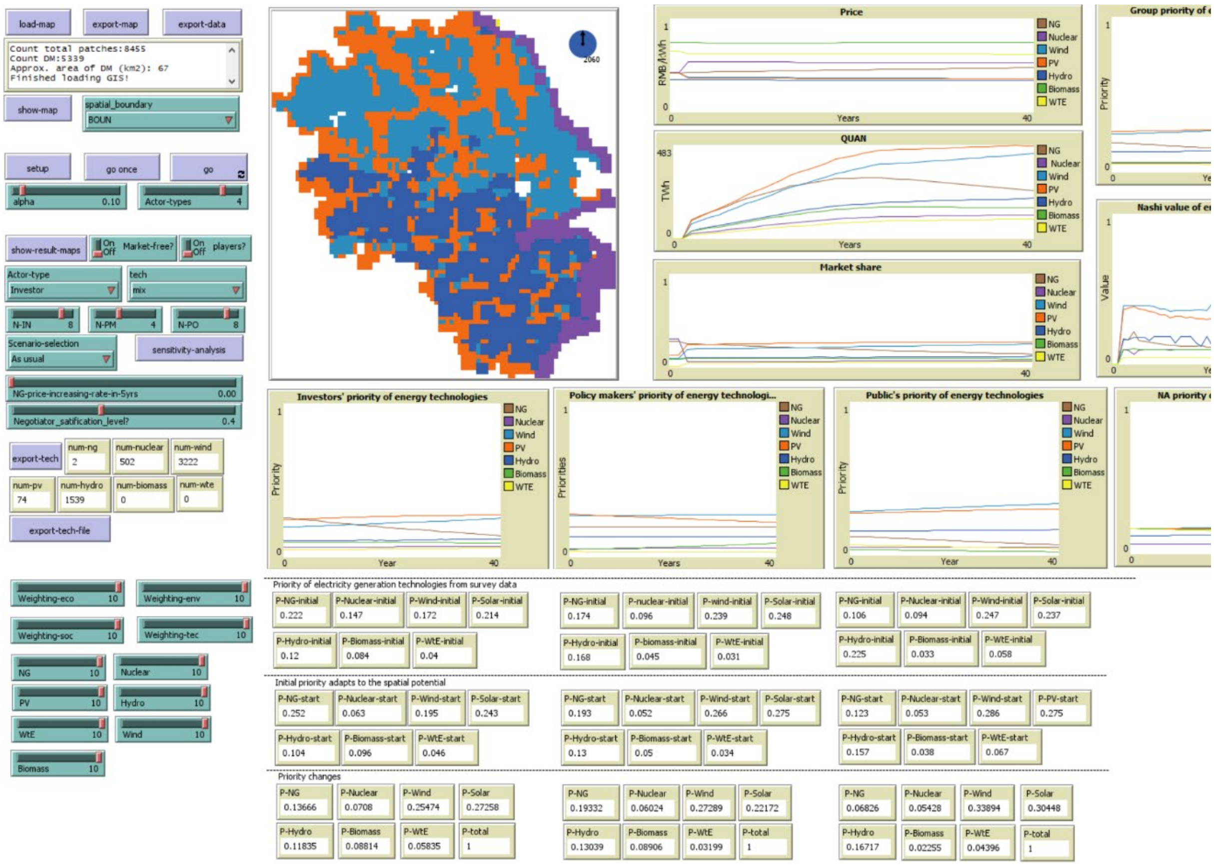
○ 31-45

○ 45-60

○ >60

7.题目: 您所居住的城市? City of residence ________________ *

Appendix 5: Supplementary infomation of the agent-based model



```
Count total patches:8455
Count DM:5339
Approx. area of DM (km2): 67
Finished loading GIS!
```

spatial_boundary: BOUN

alpha 0.10

Actor-types 4

Market-free? On/Off

players? On/Off

Actor-type: Investor

tech: mix

N-IN 8

N-PM 4

N-PO 8

Scenario-selection: As usual

NG-price-increasing-rate-in-5yrs 0.00

Negotiator_satification_level? 0.4

num-ng	num-nuclear	num-wind	num-pv	num-hydro	num-biomass	num-wte
2	502	3222	74	1539	0	0

Weighting-eco 10

Weighting-env 10

Weighting-soc 10

Weighting-tec 10

NG 10

Nuclear 10

PV 10

Hydro 10

WtE 10

Wind 10

Biomass 10

Priority of electricity generation technologies from survey data

P-NG-initial	P-Nuclear-initial	P-Wind-initial	P-Solar-initial	P-Hydro-initial	P-Biomass-initial	P-WtE-initial
0.222	0.147	0.172	0.214	0.12	0.084	0.04

P-NG-initial	P-nuclear-initial	P-wind-initial	P-Solar-initial	P-Hydro-initial	P-biomass-initial	P-WtE-initial
0.174	0.096	0.239	0.248	0.168	0.045	0.031

P-NG-initial	P-Nuclear-initial	P-Wind-initial	P-Solar-initial	P-Hydro-initial	P-Biomass-initial	P-WtE-initial
0.106	0.094	0.247	0.237	0.225	0.033	0.058

Initial priority adapts to the spatial potential

P-NG-start	P-Nuclear-start	P-Wind-start	P-Solar-start	P-Hydro-start	P-Biomass-start	P-WtE-start
0.252	0.063	0.195	0.243	0.104	0.096	0.046

P-NG-start	P-Nuclear-start	P-Wind-start	P-Solar-start	P-Hydro-start	P-Biomass-start	P-WtE-start
0.193	0.052	0.266	0.275	0.13	0.05	0.034

P-NG-start	P-Nuclear-start	P-Wind-start	P-PV-start	P-Hydro-start	P-Biomass-start	P-WtE-start
0.123	0.053	0.286	0.275	0.157	0.038	0.067

Priority changes

P-NG	P-Nuclear	P-Wind	P-Solar	P-Hydro	P-Biomass	P-WtE	P-total
0.13666	0.0708	0.25474	0.27258	0.11835	0.08814	0.05835	1

P-NG	P-Nuclear	P-Wind	P-Solar	P-Hydro	P-Biomass	P-WtE	P-total
0.19332	0.06024	0.27289	0.22172	0.13039	0.08906	0.03199	1

P-NG	P-Nuclear	P-Wind	P-Solar	P-Hydro	P-Biomass	P-WtE	P-total
0.06826	0.05428	0.33894	0.30448	0.16717	0.02255	0.04396	1

Figure A5.1 Screenshot of the agent-based model with the Netlogo platform.

The model data and code is uploaded to the GitHub: https://github.com/Chennan-05/ABM-Energy-planning-multiple-agents-interact

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