November 2022

On the Road to Carbon Neutrality: Green Investment Needs in China

An Analysis of the Spatial and Temporal Distribution of Provincial Renewable Electricity Investment

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SCHOOL OF PUBLIC POLICY

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This working paper is prepared based on a previously published working paper Integrating sustainability into climate finance by quantifying the co-benefits and market impact of carbon projects with updates on policy implications.

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LIST OF ACRONYMS

ATB	Annual Technology Baseline
BNEF	BloombergNEF
CBIRC	China Banking and Insurance Regulatory Commission
CCS	Carbon Capture and Storage
CF	Capacity Factors
CO_2	Carbon Dioxide
CoC	Cost of Capital
CPI	Consumer Price Index
CRF	Capital Recovery Factor
CSP	Concentrated Solar Power
DOE	Department of Energy
ETS	Cap and Trade Systems
FITs	Feed-in-tariffs
FYP	Five Year Plan
GDP	Gross Domestic Product
GHG	Green House Gas
GPP	Government Procurement Purchasing
GTAI	Germany Trade & Invest
IEA	International Energy Agency
IGCC	International Green Construction Code
IISD	International Institute for Sustainable Development
IRENA	International Renewable Energy Agency

IRS	Internal Revenue Service
LCOE	Levelized Cost of Energy/Electricity
NDC	Nationally Determined Contribution
NDRC	National Development and Reform Commission
NEA	National Energy Administration
NREL	National Renewable Energy Laboratory
PBoC	People's Bank of China
PPP	Public-Private Partnership
PTC	Production Tax Credits
PV	Photovoltaic
PVd	Present Value of Depreciation
R&D	Research and Development
RE	Renewable Energy
REN21	RENEWABLES 2020 GLOBAL STATUS REPORT. REN21 Secretariat, Paris
RPS	Renewable Portfolio Standards
SSP2	Shared Socioeconomic Pathways “Middle of the Road”
Taxadj	Tax Adjustment
T&D	Transmission & Distribution
TLCC	Total Life Cycle Cost
UNEP	United Nations Environment Programme
USA	United States of America
USD	US Dollar
WACC	Weighted Average Cost of Capital

EXECUTIVE SUMMARY

Since 2013, and coming at a time of increased ambition to expand solar and wind energy production, China has invested more in non-hydro renewable energy sources than any other country by being responsible for 30% of the global investment in renewable capacity. Since then, China has invested approximately $800 billion in non-hydro renewables with a total installed capacity of 536 GW by 2020. Demand for renewable energy investments is likely to continue increasing in the coming decade. China's latest nationally determined contribution (NDC) aims for emissions to peak before 2030 and carbon neutrality to be achieved before 2060. To support these goals, China aims to increase its total installed capacity of wind and solar to 1,200 GW by 2030, up from 621 GW at the end of 2021 (NEA, 2022).

These ambitious targets will require increased investment in renewables. However, traditional government policies and current administrative measures will not be sufficient to support the huge investment needs to achieve this low-carbon transition. Most green industries are still regarded as new products in China, making commercial banks and private investors afraid to invest in the industry. The huge investment needs, potential green market demand, and the insufficiency of traditional government policies have prompted China to accept challenges with a more innovative spirit, focus on internationalization, and seek new mechanisms to solve policy and market insufficiency and motivate investment. To provide a clear understanding of the size and character of the investment needed to navigate and finance this transition smoothly, this working paper identifies China's national and provincial green investment needs to achieve the carbon neutrality target from a comprehensive analytical framework.

Over the past two decades, a rich body of studies has estimated green energy investment needs to meet global climate targets in different sectors and regions of the world. Only two studies specifically estimated the green energy investment needs in China. In addition, most of these studies either lack a comprehensive analytical framework to estimate the implications of market investment conditions (e.g., debt-equity ratio, cost of capital, tax rate, inflation rate) for local and regional investment needs, or they lack an assessment of the distributional and equity implications of different investment strategies. Consequently, they do not offer clear policy guidance on how to navigate the challenges of rapidly expanding renewable electricity investment.

This working paper provides a new analysis of green energy investment needs between 2020 to 2060 in China. It addresses past limitations in three major ways. First, we apply a new methodology for estimating the green investment needs that explicitly considers both national and local market investment conditions. Traditional methods focus on considering investment needs during construction, ignoring the investment market conditions during the entire investment period. Second, we estimate the spatial and temporal distributions of the green investment needs among provinces, exploring distributional and inequality implications and associated needs required to achieve a harmonious development. Third, we provide the policy implications of this working paper with a focus on how to scale up China's national and local renewable electricity investment.

We define green investment needs as the needs of investment activity that focuses on renewable projects, mainly solar and wind projects. Using a state-of-the-art integrated assessment model that includes provincial details of China, GCAM-China, we estimate national and provincial wind and solar investments in a global mitigation scenario that limits global temperature change to 1.5°C. In this scenario, China achieves carbon neutrality and GHG (Green House Gas) neutrality around 2055 and 2065, respectively.

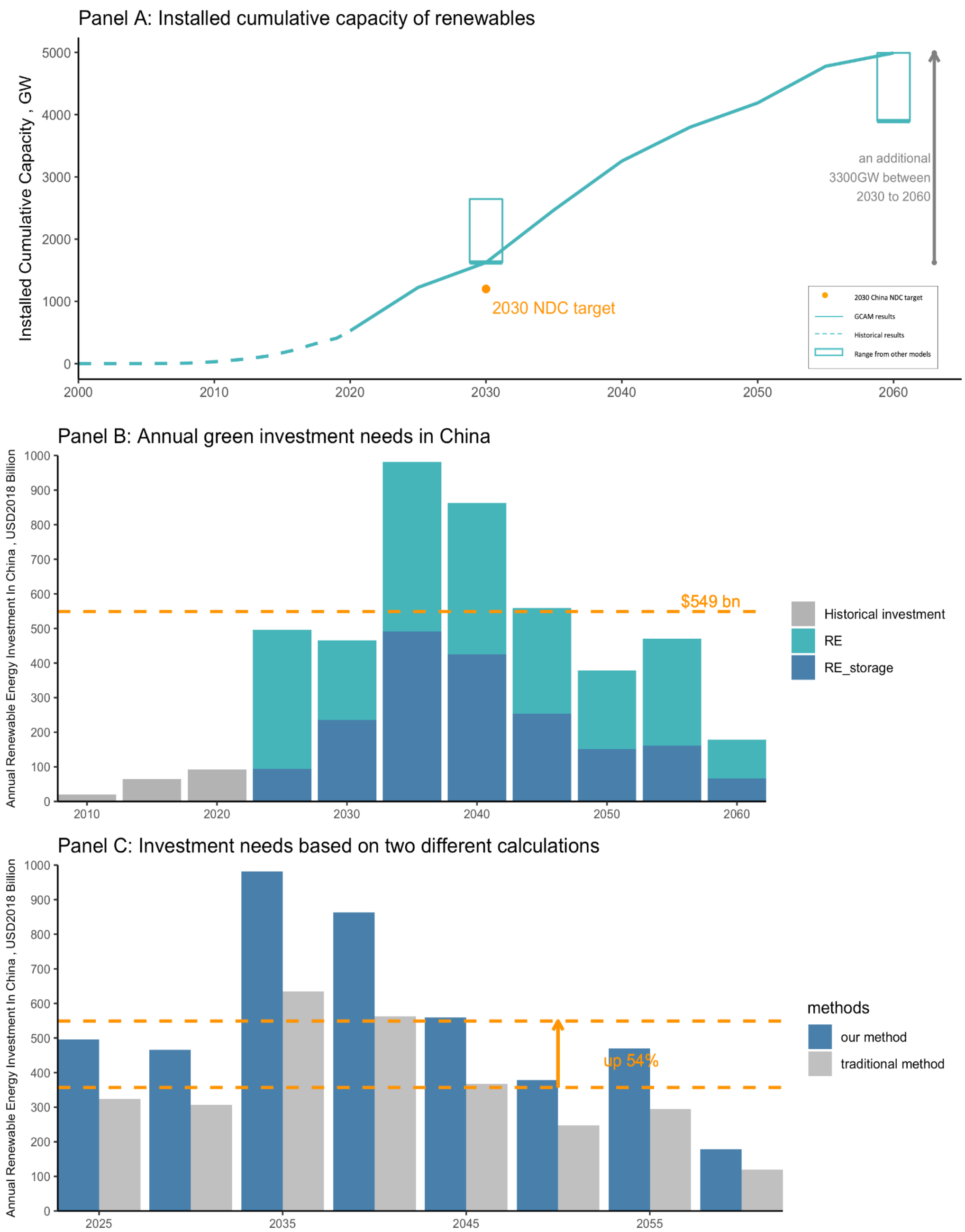
Our results indicate that average annual renewable electricity investment needs between 2020 and 2060 are $549 billion (Figure E1, Panel B) ($709 billion with Carbon Capture and Storage [CCS] technologies), or 3.7 percent of China's annual GDP (Gross Domestic Product) over that period. In comparison, annual renewable energy investment from 2015 to 2020 was roughly $100 billion, counting about 10%[1] of total electricity generation. This means that, to meet the increased electricity demand with mitigation targets simultaneously, investment in renewable energy must be scaled up significantly and urgently, at a rate of three times more than that in the historical period. Our analysis suggests that an additional 4,400 GW of solar and wind capacity must be installed between 2020 and 2060 to meet the goal.

[1] Electricity generation from solar and wind was about 9.5% of the total electricity generation in China between 2015-2020 (IEA, 2021a).

We estimate that the average investment needs, considering the market conditions, are 54% more than the investment needs calculated by traditional methods over the analysis period (Figure E1, Panel C). The traditional method considers only the investment needs that arose during the construction period, whereas our estimates include the investment needs for the entire life cycles of projects by considering investment market conditions. We conclude that the market conditions have a significant impact on estimating green investment. Therefore, a careful design that considers market conditions is needed to help investors understand long-term risks and make better investment decisions.

Figure E1.

Installed Capacity of Renewables and Annual Green Investment Needs in China Between 2020 and 2060 to Fulfill the 2060 Carbon Neutrality Goal

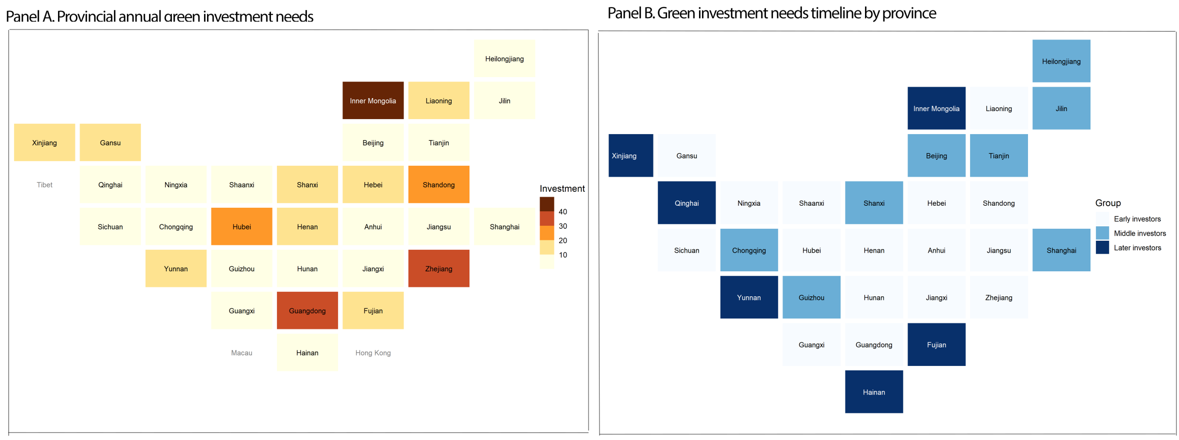


Note: Panel A. Installed cumulative capacity requirements to achieve carbon neutrality and the NDC targets (units: GW). Panel B. Annual national green investment needs in China for 5-year periods from 2020 to 2060 (units: USD 2018 billion). RE (Renewable Energy) storage covers only the cost of battery capacity for wind and PV. Panel C. Investment needs based on two different methods. The traditional method only considers the investment needs that arise during the construction; our method includes the investment needs for the entire life cycle of the project by considering investment market conditions.

The distribution of investment needs across China (Figure E2, Panel A) tends to depend on three factors. First, regions with rich renewable resources, e.g., Inner Mongolia, Xinjiang, and Yunnan, tend to have high investment needs. Second, green investment needs are partially driven by the local electricity demand. Provincial economic development and population play a significant role in determining the total electricity demand. Therefore, provinces ranked as most rapidly developing provinces, such as Guangdong, Zhejiang, and Shandong, are associated with high green investment needs. Third, grid regions have an important influence on demand and supply of electricity in certain provinces. For example, the North China Grid covers Beijing, Tianjin, Hebei, Inner Mongolia, and Shanxi. Within this grid region, Inner Mongolia exports more than half of its electricity to other provinces due to its rich renewable resources. Thus, the increasing electricity needs in other provinces in the region, combined with significantly rich renewable resources in Inner Mongolia, contribute to the high green investment needs in Inner Mongolia. Overall, the top three provinces for green investment during 2020–2060 are Inner Mongolia, Guangdong, and Zhejiang. In addition to the spatial variation in investment needs, the results indicate three different timelines for green investments across provinces (Figure E2, Panel B). All provinces require significant renewable investment before 2035. Some provinces (early investors) will need to invest most heavily before 2035 to reach the goal, while others (later investors) with high potential renewable energy resources, such as Inner Mongolia, Xinjiang, Qinghai, Yunnan, and Hainan, will invest most heavily from 2045 through 2055.

Figure E2.

Provincial Annual Green Investment Needs and Timeline in China, 2020–2060, to Meet the 2060 Carbon Neutrality Goal



Note: Panel A. Average provincial green investment needs in China, 2020–2060 (unit: USD 2018 billion). Panel B. Green investment needs timeline by province. Early-stage investors as those provinces that have their investment needs peak during the period of 2025–2035; middle-stage investors as provinces whose investment needs peak during the period of 2035–2045; and later-stage investors as those with investment needs that peak during the period of 2045–2055. No Tibet, Hong Kong, Macau, and Taiwan due to lack of data availability.

The total annual green investment of $549 billion is a substantial scale-up from previous years. This scale-up will require an enabling environment for promoting renewable energy while engaging private investment. A combination of fiscal, monetary, financial, and energy policy instruments, applied at different stages of renewable energy investment, e.g., technology research and development, technology deployment, manufacturing, and scale-up investment, can attract the investors needed for the low-carbon transition.

Building on the quantitative investment analysis, this working paper identifies and explores the policy instruments needed in each stage of renewable energy investment. We focus on six commonly used policies: production tax credits (PTC), feed-in-tariffs (FITs), renewable portfolio standards (RPS), bidding systems, cap and trade systems (ETS), government procurement purchasing (GPP), and green financial system. We summarize multiple policy approaches that can be used to facilitate the necessary investment for this transition in Table E1.

China's green finance is embracing unprecedented opportunities and challenges from the "dual carbon 30-60 goals." The "dual carbon" has brought a lot of demand for green credit to China and accelerated investment in clean energy projects. However, there is still considerable investment gap to meet the "dual carbon" goals. Future research needs to focus on how to use policy innovations to establish a diversified green credit system, leverage private finance, and scale up green investment in China.

Table E1.

Summarization of Policy Instruments and Recommendations

Policy instruments	Approach	Applied Stage	Current status in China	Recommendation
Production tax credits (PTC)	Tax incentive	Heavily in the stage of R&D, but light in the early deployment stage	PTC was phased out in China.	Used by the government for new technologies to bring the high cost of renewable energy down and make it more competitive in the market in the early stage of renewable energy investment, when the private sector would not adequately fulfill this role.
Government procurement purchasing (GPP)	Direct purchase	Early deployment stage	China enacted GPP with the Government Procurement Law of 2003. Globally, China holds the largest total number of products certified for GPP.	An efficient GPP requires established quantitative GPP targets at the national level and standardized protocol for evaluating and reporting on the success of the GPP program.
Feed-in-tariffs (FIT)	A price-based approach	Early deployment stage	This policy led to remarkable growth in	The FIT encourages earlier investment.

			renewable energy in China, but lacked sufficient flexibility to respond to cost changes, and provided only limited incentives for further cost reduction. Therefore, the National Development and Reform Commission (NDRC) stated that the central government had phased-out wind and solar FITs by 2021.	Starting from 2016, China's development of renewable energy has entered a new period, where the trend of development tends to be stabilized, and the renewable energy industry is mature.
Auctioning or bidding system	A quantity-based approach	Light in the early deployment stage and heavily in mature & investment stages	Since 2004, the Chinese government has had experience with RE tenders, as with FITs. Additionally, the Chinese government took further steps to move from a FIT system to an auction-based system.	It allows for flexibility in its design elements to meet deployment and development objectives and has the ability to cater to different jurisdictions reflecting their economic situation, the structure of their energy sector, and the maturity of their power market.
Renewable portfolio	A quantity-based approach	More towards mature &	In May 2019, China formally	RPS is suitable for the renewable

standards (RPS)		investment stages	released the RPS plan, which mandated renewables consumption in coastal provinces and stimulated the interprovincial power trade.	industry when it is mature. Under RPS, power producers tend to choose renewable energy with relatively mature technology and lower cost to maximize profits. However, the challenge for implementation in China is how to create incentives among provinces due to the misaligned targets.
Cap and trade systems (ETS)	A market-based approach	Both in the early deployment and mature & investment stages	China has one of the world's largest CO_2 emissions trading systems. Currently, it is at the stage of integrating existing Chinese regional ETS pilots gradually into the national ETS.	ETS utilizes the green approach strategy as a market-based solution that reduced greenhouse gas emissions, reduced the need for high-carbon power such as coal, and encouraged the use of more solar and wind power.
A Green Financial system	Finance sector reform	Mature & investment stages	In China, efforts on green finance can be traced back a decade. The green finance definition was officially adopted in 2016 in the	A green financial system allows engaging in large-scale investment in renewable investment by the private sector and realizing sustainable development.

			Guidelines for Establishing the Green Financial System. China's green finance is embracing unprecedente d opportunities and challenges from the "dual carbon 30-60 goals."	

1. Introduction

In October 2021, China stated in its latest nationally determined contribution (NDC) aims for emissions to peak before 2030 and carbon neutrality to be achieved before 2060. To support these goals, China aims to increase its total installed capacity of wind and solar to 1,200 GW by 2030, up from 621 GW at the end of 2021 (NEA, 2022). Thus, the next steps for China during the 14th Five Year Plan (FYP) and beyond are to peak emissions before 2030, increase non-fossil energy to around 25% by 2030, and strictly control coal-fired power plants. In terms of installed capacity, China aims to increase total installed capacity of wind and solar from 415 GW at the end of 2019 (China Energy Portal, 2020) to 1,200 GW by 2030. In the long run, China aims to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060 (NDRC, 2021).

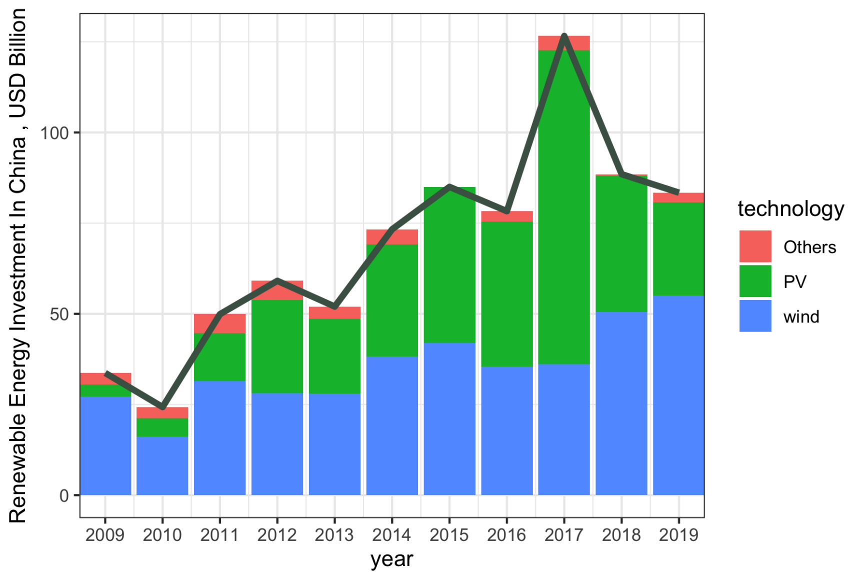
Against this background, accelerating the deployment of renewable energy (RE) in China is inevitable, at both the national and provincial levels, to achieve the 2060 carbon neutrality goal. China is the leading country in renewable energy capacity, with its hydro, solar, and wind capacity surpassing the second-ranking country, the United States (IRENA, 2021a). By the end of 2020, China had a total capacity of 895 GW of renewable generation capacity, with 282 GW wind generation capacity and 254 GW solar generation capacity (IRENA, 2021b). However, compared to China's traditional coal capacity, which is 1050 GW (Cui et al., 2021), the deployment of renewable energy will require a strong commitment from the Chinese central government, along with the actions from the provincial governments.

China also has been the dominant investing nation in non-hydro renewables since 2013, due to raised ambitions in both photovoltaic (PV) and wind energy (Frankfurt School-UNEP Centre/BNEF, 2020). China has invested approximately $800 billion in non-hydro renewables over the past ten years. Figure 1 shows China's capacity investment in non-hydro renewables by technology from 2009 to 2019. We observe a sustained upward investment pattern, where the year 2017, with $143 billion ($2018 dollar), reached the highest investment amount (Bloomberg, 2022; Frankfurt School-UNEP Centre/BNEF, 2020; IEA, 2022). The record high investment in 2017 is mainly driven by the deployment of 53.06 GW of PV capacity during that year, right before the end of solar subsidy in 2018 (Reuters, 2019). The year of 2020, 2021 and 2022 continues to experience the RE capacity expansion, therefore, China's total clean energy investment is expected to increase to 421 $billion in

2022 (IEA, 2022). Given that China is the world's leading green investment market, estimating the investment needs for the carbon neutrality target is therefore essential for policymakers to scale up investment from multiple channels.

Figure 1.

Renewable Energy Investment in China 2009–2019



Source: Frankfurt School-UNEP CentreBNEF, "GLOBAL TRENDS IN RENEWABLE ENERGY INVESTMENT" 2007-2020 reports (Frankfurt School-UNEP Centre/BNEF, 2020; UNEP and Bloomberg New Energy Finance, 2017; United Nations Environment Programme, 2009)

The latest report by the International Energy Agency (IEA, 2021b) estimated that global annual clean energy investment in electricity generation from renewables in the net-zero pathway will be about 1.6 trillion and 1.1 trillion ($2019 dollar) by 2030 and 2050, respectively. An earlier IEA (International Energy Agency) report estimated that global investment in the electricity sector from renewables between 2025 and 2030 will be about 1.3 billion[2] under the net-zero scenario (IEA, 2021c). In addition to projecting the global green investment needs, two studies specifically estimated the green investment in China. McCollum et al. (2018) shows that the annual investment needs of renewables for a 1.5°C scenario by 2050 are $395 billion[3] ($2015 dollar) (McCollum et al., 2018). Zhou et al. (2019) shows an annual investment of $280 billion for the 1.5°C scenario (Zhou et al., 2019).

[2] The definition of renewables in both IEA reports covers bioenergy, geothermal, hydropower, PV, CSP, wind and marine energy for electricity generation purposes.
[3] In both McCollum et al. (2018) and Zhou et al. (2019), the coverage of investment needs includes electricity (non-biomass), electricity T&D (Transmission & Distribution) and storage, and CCS.

During the past two decades, a rich body of studies has documented the estimation and quantification of investment needs among different sectors, regions, and climate targets. The underlying strategies of measuring investment needs from the literature show some consistency with a two-step approach: capacity installation additions, then combined with the unit costs. But the studies vary in the measurement of the unit costs. A growing body of literature, led by IEA, adopted the unit costs of capital to capture the life cycle of a project (IEA, 2021c, 2021b, 2020; McCollum et al., 2018; Zhou et al., 2019). However, the life cycle of a project is limited to the period from the investment decision until the year it becomes operational (IEA, 2020). A body of literature focusing on estimating transportation-related infrastructure investment needs adopted the unit costs of infrastructure, where it covers costs for construction, upgrade, operation, and maintenance (Dulac, 2013; Fisch-Romito & Guivarch, 2019). Instead of having their own methodology to define the unit cost, some studies either adopt a standard unit cost based on international "best practice" norms (Bhattacharyay, 2010; Markaki et al., 2013) or use the unit cost from the integrated assessment models (IAMs) directly (Carraro et al., 2012).

However, most of these studies focus on elaborating the importance of investment needs and using the investment needs to further project their impacts on the society. There is limited research on understanding the impacts of the market investment conditions on the future green investment needs. From the perspective of a meaningful quantitative result of investment needs, a precise representation of the cost of capital (CoC) for these green energy projects is a prerequisite (Steffen, 2020), especially for renewable energy projects that are capital intensive. Egli et al. (2019) considered the differences in the CoC in different countries to calculate the levelized cost of energy/electricity (LCOE) and found that accounting for CoC differences changes the results dramatically (Egli et al., 2019). Many factors actually contribute to the final outcome of CoC, including: investment risks due to technologies and institutional qualities that increase the cost of capital (Iyer et al., 2015); macroeconomic conditions (general interest rate) and experience rate (Egli et al., 2018); and location-specific resources availability (Ondraczek et al., 2015). It is, therefore, essential to include these factors in the projections of the green investment needs.

In China it is also crucial to project the green investment needs at the provincial level, to optimize resources and propose policy for improving local renewable energy development so that all provinces have a better understanding of investment needs over the years. The regional disparity exists in terms of the effect of promoting local renewable energy, which are challenges faced by China towards the carbon neutrality goal. Due to vast regional disparity in China's resource endowments and economic development (Dong et al., 2016; Shen & Lyu, 2019; Wang et al., 2020), there are large variations in renewable energy development among provinces. In addition, regional disparities in local governments' support of policies to promote renewables (Wang et al., 2019), regional technology capacity, renewables management experience (Song et al., 2020), and renewable supply chain disparity (Dong et al., 2016), pose challenges for promoting local renewable energy development across all provinces.

However, while studies have paid much attention to the related drivers and outcomes of regional disparity, few studies discuss one important problem: how regional disparity will affect green investment needs, given that regional differences might shape investors' decisions on renewables location selections (Xia & Song, 2017). This working paper aims to bridge that research gap by demonstrating a method for: 1) taking into account market investment conditions in investment needs consideration; 2) demonstrating how disparities among provincial capacity result in different investment needs.

This working paper provides insights into clean energy investment in China in three ways.

- It is a comprehensive analysis of the renewable energy investment needs. We apply a methodology to estimate the green investment needs by considering market investment conditions and local renewable resources, at both national and provincial levels.
- We identify the spatial and temporal distributions of the green investment needs among provinces with a discussion of the inequality issues that need to be recognized as a challenge to a harmonious development.
- We provide the policy implications described in this working paper with a focus on how to scale up investment in China.

The remainder of the working paper is structured as follows. Section 2 describes the methodology framework, which covers the GCAM-China model, and the procedure and data used to calculate the green investment needs. Section 3 presents the renewable deployment to achieve carbon neutrality from the GCAM-China 1.5°C pathway. Section 4 describes the results and analysis of the modelling with a discussion of the sensitivity analysis. Section 5 is a policy discussion of scaling up green investment in China. The final section summarizes the key findings of this working paper.

2. Methods

2.1 Methodology

2.1.1 GCAM 1.5°C-Carbon Neutrality Pathway

In this working paper, we adopt the mitigation pathway that limits global temperature change to 1.5°C and examine China's transitions to achieving that goal by using the Global Change Analysis Model-China (GCAM-China). Under this modeled pathway, China will achieve carbon neutrality and GHG neutrality around 2055 and 2065 respectively. The 1.5°C-carbon neutrality pathway allows us to identify some key trends, opportunities, and challenges of green investments associated with deep decarbonization in China.

GCAM is an integrated assessment model that examines long-term changes in the coupled socioeconomic, energy, agriculture/land-use, water, and climate systems with technology-rich representations of energy production, transformation, and consumption across 32 geopolitical world regions (Calvin et al., 2019). Built within the GCAM framework, GCAM-China adds layers of 31 regional energy markets for China. Therefore, its ability to take in region-specific socioeconomic data and calibrate technology and resource availability for each province, municipality, and autonomous region (Yu et al., 2019) provides a suitable tool to analyze the investment needs for each province.

Based on the Shared Socioeconomic Pathways "Middle of the Road" (SSP2) scenario with China-specific modifications, the 1.5°C-carbon neutrality pathway from GCAM-China allows global net anthropogenic CO_2 emissions to decline right after 2020 and reach net zero around 2050, while global GHG neutrality is realized around 2055. It also limits global warming to 1.5°C.

2.1.2 Methodology for Calculating Investment Needs

To calculate the renewable energy investment needs, we adopted the total life cycle cost (TLCC), which covers all significant costs over the life of the project (Short et al., 1995) based on equation (1):

$$TLCC_{p,t} = \sum_{n=1}^{N} \frac{C_{p,t,n}}{(1+i_t)^n} \tag{1}$$

Where, C_n is the cost in investment period n, p represents province, and t represents renewable energy technology. N is the total life span of the renewable energy assets, and i_t is the annual discount rate for the technology t.

We then introduce two methodologies to calculate green investment needs based on investor and project perspectives.

Investor's perspective

Here, we introduce another terminology, which is widely used in the field of energy, the LCOE. By definition, the LCOE is the cost assigned to every unit of energy produced by the system over the assets' life spans. Thus, if we discount the TLCC back to the base year, it is equal to the LCOE. Based on equation (1), we then get

$$TLCC_{p,t} = \sum_{n=1}^{N} \frac{Q_{p,t,n} * LCOE_{p,t}}{(1+i_t)^n} \tag{2}$$

where, Q_n is energy/electricity output, and is driven by the capacity factors (CF), since the installed capacity additions won't change. Therefore, $Q_{n,p,t}$ can be interpreted as the electricity generation of province p in investment period n of that year. It is important to mention that if the electricity output, Q_n, is consistent over the time (CF is constant), then equation (5) will be converted to a simplified equation as follows:

$$TLCC_{p,t} = \frac{LCOE_{p,t} * Q_{p,t}}{CRF_t} \tag{3}$$

where, capital recovery factor (CRF) is the ratio of a constant annuity to the present value of receiving that annuity for a given period, which is equal to

$$CRF_t = \frac{A}{P(A)\_n} = \frac{i\,(1+i_t)^n}{(1+i_t)^n - 1} \tag{4}$$

The equations to calculate the LCOE are as follows:

$$LCOE_{p,t} = \frac{CapEx_t * CRF_t * TaxAdj_t + fixed\_O\&M_t}{8760 * CF_{p,t}} + (fuel\ cost_t * heat\ rate_t) + variable\_O\&M_t \tag{5}$$

$$Real\_WACC_t = \frac{1 + norm\_WACC_t}{1 + inflation} - 1 \tag{6}$$

$$CRF_t = \frac{Real\_WACC_t * (1 + Real\_WACC_t)^n}{(1 + Real\_WACC_t)^n - 1} \tag{7}$$

$$Taxadj_t = \frac{1 - TR_t * Pvd_t}{1 - TR} \tag{8}$$

$$PVd_t = \sum_{t=1}^{20} \frac{0.05}{(1+norm\_WACC_t)^t} \quad (9)$$

Based on equations (5) to (9), the LCOE calculation includes the following important parameters:

1) Real weighted average cost of capital (WACC)

In this working paper, we use real WACC instead of the standard discount rate to capture the financing cost in calculating the CRF equation. WACC is a measure to evaluate the weighted cost of capital, where it is calculated based on a combination of historical returns to equity and after-tax interest paid on debt (Short et al., 1995). The discount rate is used to reflect the time value to an investor. Different investors will have different appetites for the time value or cost of money. Even the same investors might have different appetites for different technology investments. Given the ability of WACC to differentiate investors' preferences over the time value or cost of money, using the WACC as the discount rate in the utility industry is a common practice (Short et al., 1995; Vartiainen et al., 2020). Therefore, we adopted the WACC as the annuity factor. The investment cost is spread annually. Since we are interested in fixing the cash flows in 2018 constant dollars, it is suitable to use the real WACC to calculate the present value.

2) Tax and depreciation

For tax purposes, depreciation is a means of recovering, through an income tax deduction, the cost of property used in a trade, business, or property held for the production of income. Also, interest associated with debt financing is tax deductible. We adopted a 20-year straight line for depreciation. 100% of capital costs are assumed depreciable by the IRS (IRS, 2021).

An equally important point is that, for tax calculation purposes, all dollar values should be expressed in nominal values. This is important because taxes are applied to actual dollar values. If an analysis were to apply tax rates to dollar values corrected for inflation, the results would be skewed.

3) Capacity factors

Historical national CFs (2015–2020) of PV and wind are converted from the utilization hours from National Energy Administration (NEA) of China. Capacity factors of wind at the provincial level are also obtained from NEA (2015–2019), while the 2020 CFs are calculated by using 2019 provincial CFs, multiplying a national CF growth rate, because we have only the 2020 national CFs. Because 2017 is the only year we are able to get the utilization rates at the provincial level, capacity factors of PV at the provincial level are computed based on the 2017 provincial utilization hours, multiplied by the national growth rate for every year.

Currently, PV capacity factors in China are low. As technology innovation continues, we assume that capacity factors will increase over the years. Therefore, for PV capacity factors in the future, we assume a linear growing trend between 2020 and 2060. The 2060 CFs come from He and Kammen (2016). Built upon the provincial solar resource potential, the capacity factors from this study are treated as the maximum capacity factors and used as the 2060 CFs. For CSP (Concentrated Solar Power) and CSP storage capacity factors, we adopt the default CFs from GCAM, which is 0.25 and 0.65, respectively, and make them constant over the years. Capacity factors of PV storage technology have the same CFs as the PV.

For wind capacity factors, we also assume a linear growing trend between 2020 and 2060. However, the 2060 CFs use the GCAM default rate directly, which is 0.38 for the national CF. The provincial CFs are calculated by assuming the same growth rate as the national rate. Capacity factors of wind storage technology have the same CFs as the wind.

Project's perspective

In the project's perspective, $C_{p,t,n}$ is decomposed into the following four components by the following equation, where $Initial_{p,t,n}$ is 0 when t>1.

$$C_{p,t,n} = Initial_{p,t,n} + Interest\_charge_{p,t,n} + O\&M_{p,t,n} + fuel\ cost_{p,t,n} \quad (10)$$

To calculate the $Interest\_charge_{p,t,n}$, more steps are needed.

$$Interest\_charge_{p,t,n} = RP_{p,t,n} * i_t \quad (11)$$

$$RP_{p,t,n} = Initial_{p,t,n} * (1 - \frac{CRF_Y - i_t}{CRF_m - i_t}) \quad (12)$$

Where, $RP_{p,t,n}$ is the principal remaining after the m^{th} payment, Y is equal to the term of the loan, and m is equal to the year for which the remaining principal is being calculated.

2.2 Data

Table 1.

Data and Data Source

Data	Method	Source
Historical Regional capacity factors by technology	Government documents	NEA and China Industrial Association of Power Sources
Future Regional capacity factors by technology	Linear growth between 2020 and 2060 for PV and wind	(He & Kammen, 2016) GCAM results
Useful life	GCAM input	GCAM-China
Depreciation	20 years from IRS	(IRS, 2021)
Inflation rate	Obtained from literature	(Trading Economics, 2021a; World Bank, 2021)
Fixed Operation and Maintenance cost ($/kw)	GCAM input	GCAM-China
Variable Operating and Maintenance Costs ($/kw)	GCAM input	GCAM-China
Fuel costs	No need, since renewable technologies have zero fuel costs	No need
Cost of Capital	The equity and debt ratios for different renewable technologies in China are collected from multiple channels. We also collect data of costs of equity and costs of debt. Given these data, we are able to calculate the nominal WACC. Combined with the inflation, a real WACC was further obtained. A detailed table is provided in Supplemental Table 1[4].	(Anbumozhi and Kalirajan, 2017; IEA, 2015; Ondraczek et al., 2015; Peters et al., 2011; Steffen, 2020; Trading Economics, 2021b; World Government Bonds, 2021)

[4] All supplemental figures and tables are available at: https://cgs.umd.edu/sites/default/files/2022-11/SI_greeninvestment.pdf

Effective Corporate Tax Rate	Obtained from Chinese literature	(PWC, 2021)
Annual capacity additions	Annual capacity additions of electricity generation, at both national and provincial levels, are obtained from the GCAM China carbon neutrality scenario. We further process these GCAM results to get the installed capacity additions.	GCAM-China

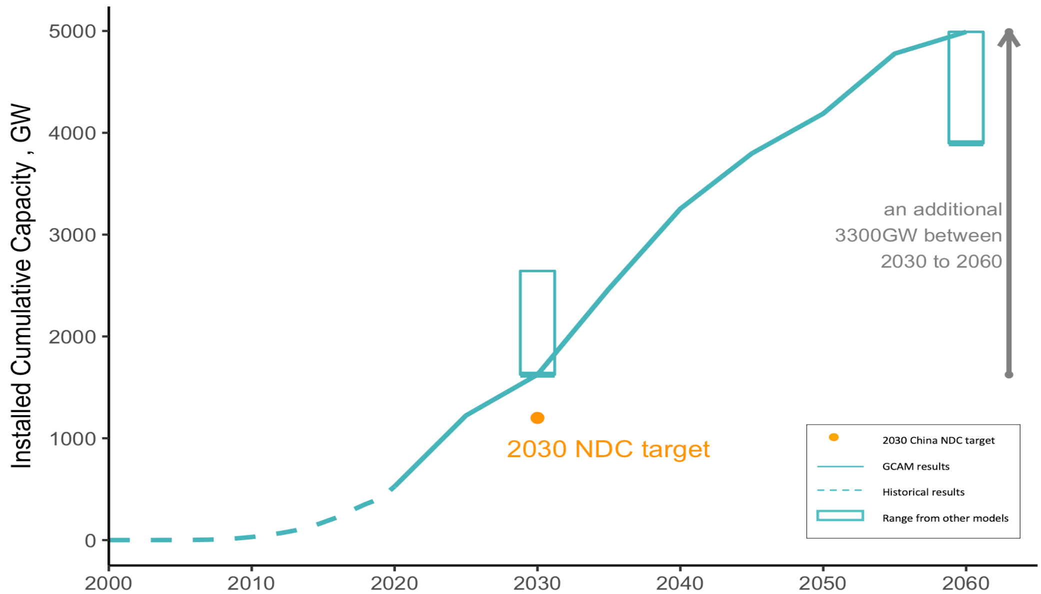
3. Renewable Deployment to Achieve Carbon Neutrality Goal

3.1 The National Renewable Energy Generation Pathway Under the Carbon Neutrality

The GCAM China carbon neutrality scenario, where China will achieve its net-zero target between 2050 and 2055, suggests that an additional 4,400 GW of capacity of solar and wind must be installed between 2020 and 2060. When we compare the carbon neutrality scenario pathway with the NDC target of 1200 GW proposed by China, a shortage of 420 GW between 2020 and 2030 is observed (Figure 2). Also, an additional 3,300 GW solar and wind capacity must be installed between 2030 and 2060.

Figure 2.

Installed Cumulative Capacity Requirement to Achieve Carbon Neutrality from 2020 to 2060 and the NDC Targets



Note: The carbon neutrality scenario indicates that the 2030 NDC target of 1,200 GW total installed capacity from wind and solar is not sufficient to fulfill the carbon neutrality target. The dotted blue line is the historical installed capacity. The solid blue line represents the projection of cumulative capacity from our carbon neutrality scenario. The green boxes represent the range of estimates of 2030 and 2060 installed cumulative capacity from other models[5], respectively. The grey arrow bar represents the additional 3,300 GW capacity to be installed between 2030 to 2060.

Figure 2 also shows the ranges of results from other models[6] in 2030 and 2060. Compared to the other models, the rationale behind our carbon neutrality pathway is as follows. First, while some models are more aggressive towards coal phase-out, our results are based on a more moderate coal phase-out schedule (see Supplemental Figure 1). Therefore, our scenario of installed cumulative capacity from renewables is at the lower boundary among all the models in 2030. Second, under our carbon neutrality pathway, China will peak emission right before 2030 and reach carbon neutrality between 2050 and 2055. Thus,

[5] These models include MESSAGEix-GLOBIOM 1.0, REMIND-MAgPIE 2.1-4.2, and GCAM5.3_NGFS from the NGFS scenarios portal.
[6] These models include MESSAGEix-GLOBIOM 1.0, REMIND-MAgPIE 2.1-4.2, and GCAM5.3_NGFS from the NGFS scenarios portal.

there will be a higher demand for wind and solar capacity between 2020 and 2030 and again between 2050 and 2055 (see Supplemental Figures 2 and 3).

To ensure reaching the 2030 target for non-fossil energy in primary energy consumption (25%), highlighted in the latest NDC, the NEA issued a set of non-hydro renewable obligations, percentage of generation, at the national and provincial levels. The NEA targets are designed to facilitate the acceleration of renewable energy. However, our model indicates that the NEA targets of 18.6% are less than the rate of renewable deployment in the cost-effective carbon neutrality scenario.

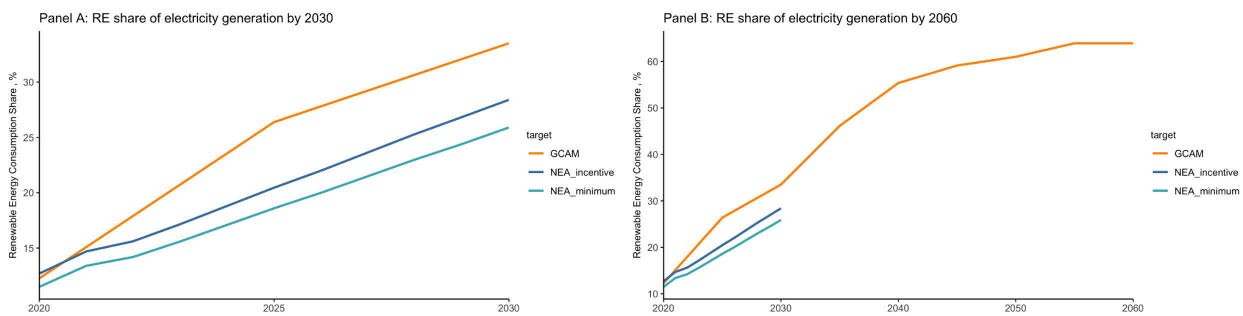
Figure 3 Panel A shows that under the carbon neutrality pathway, the share of electricity generation from non-hydro renewables is 33.5% by 2030. Our model suggests a consistent non-hydro renewable electricity generation share in 2020 (12.3%) with a historical 2020 number of 11.5%. However, it begins to diverge from the near-term targets set by the NEA. A difference of 7.8% is observed between our model projection and the NEA targets by 2030, with the minimum non-hydro renewable obligation. The incentive non-hydro renewable obligation[7], which serves as a political encouragement (NDRC, 2019), reduces the gap to only 5.1%. If properly encouraged with economic incentive, a higher non-hydro renewable obligation might be achieved in 2030, which could further reduce the gap.

Figure 3 Panel B presents the long-term trajectory of the non-hydro renewable electricity generation share to achieve carbon neutrality before 2060. The projected share of 2060 (64%) is almost twice as much as that of the share in 2030 (34%). Therefore, to meet its carbon neutrality target, China needs to develop policies and a regulatory framework to significantly ramp up renewable energy development.

[7] The incentive non-hydro renewable obligation is calculated based on the minimum non-hydro renewable obligation with a 10% float rate.

Figure 3.

Renewable Energy Share *in the Total Electricity Generation in the Short and Long Term*



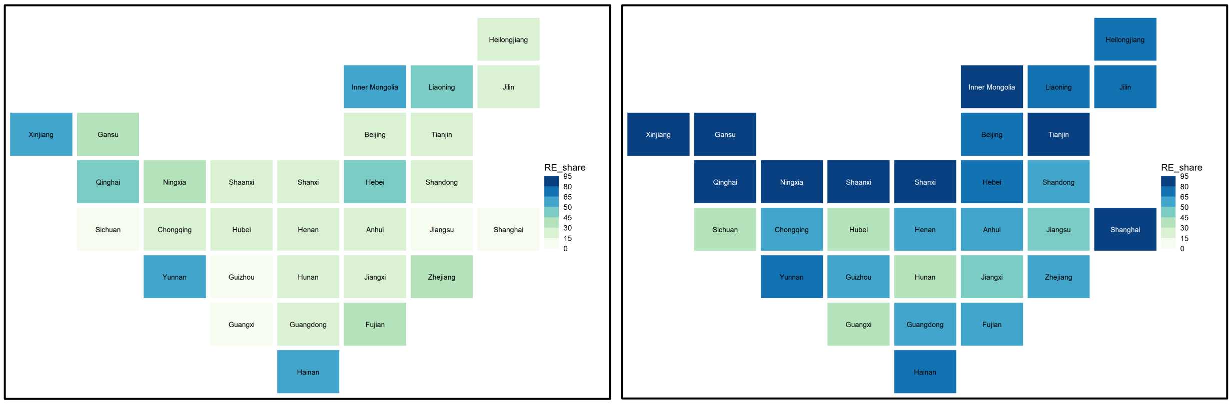
Note: Panel A: 2020–2030. Panel B: 2020–2060. The orange line shows the non-hydro renewable energy share of electricity generation from the GCAM. The light blue line represents the minimum non-hydro renewable obligation (i.e., percentage of generation) set by NEA. The dark blue line represents the incentive obligation set by NEA.

3.2 Sub-national Non-hydro RE Near-term and Long-term Levels

In Figure 4, we present the desired renewable energy share of the total electricity generation under the carbon neutrality scenarios at the provincial level for 2030 and 2060. We observe that provincial variations exhibit a consistent pattern in the near term and the long term. In 2030, the provinces of Yunnan, Hainan, Inner Mongolia, Xinjiang, and Qinghai are ranked as the top five provinces with the highest non-hydro RE share of electricity generation. All of their RE shares are 50% or above. In 2060, Inner Mongolia will lead the trend, followed by Xinjiang and Ningxia.

Figure 4.

Renewable Energy Share (%) of the Total Electricity Generation in 2030 (Panel A) and 2060 (Panel B)



Note: The darker the purple color, the higher the percentage of RE share of the total electricity generation. Tibet is not included, because there is no data.

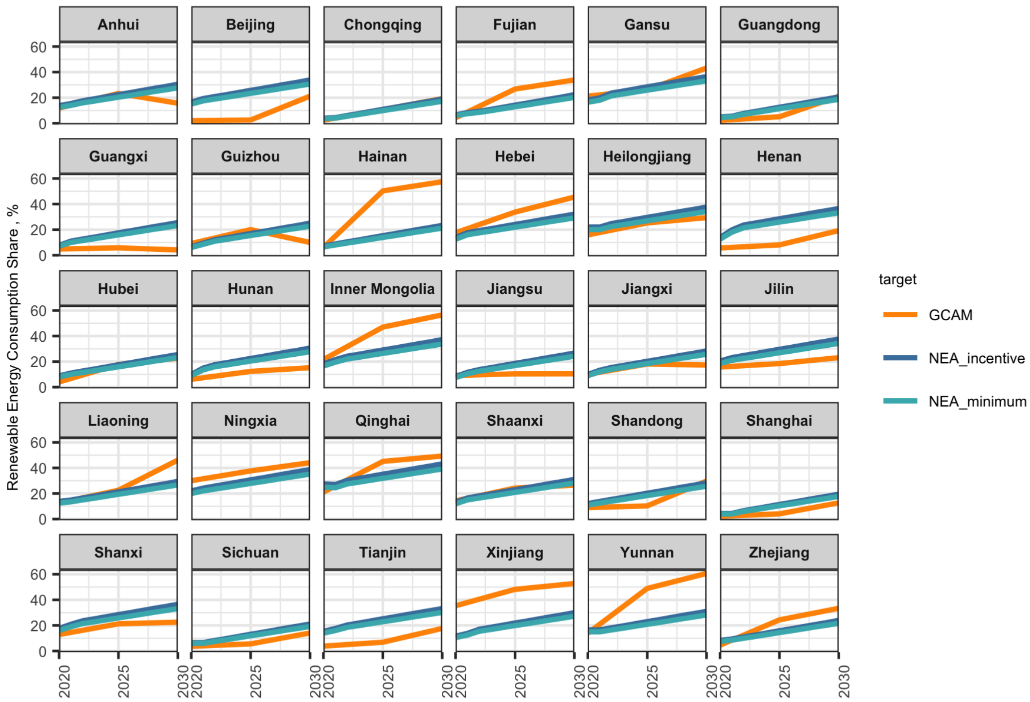
Several factors can help explain the overall trend of provincial variations in RE share of electricity generation. First, the spatial distribution of renewable energy resources in China is diverse. The majority of potential solar energy is in the northern and western parts of China. 80% of China's potential onshore wind energy is distributed in the north, northeast and northwest (IRENA, 2014). That spatial distribution creates a very diversified renewable energy capacity portfolio of the entire nation. For detailed solar and wind resource distribution by province, please refer to Supplemental Figures 4 and 5.

In addition, the spatial distribution of electricity supply and demand further contributes to provincial variations in RE share of electricity generation. Provinces abundant in renewable energy resources are not corresponding to the patterns of population and economic development (Wang et al., 2020). Thus, a high number of renewable energy shares of the electricity will be exported from those provinces within the internal grid region. We plot the exporter and importer provinces of electricity in Supplemental Figure 6. It confirms the literature and our observation that provinces rich in renewable energy resources are provinces that will export electricity to other provinces in 2030 and 2060. For example, our results show that Inner Mongolia will export 53% and 65% of its electricity generation to other provinces in 2030 and 2060, respectively. Meanwhile, Beijing will import 62% and 73% of its electricity consumption from other provinces.

In Figure 5, we further explore our results of the carbon neutrality scenario with the renewable energy consumption obligation targets between 2021 to 2030 for each province (NEA, 2021). When we compared the share of non-hydro renewable energy generation of the carbon neutrality scenario pathway to the sub-national obligation targets in the near term, we found huge variations among the provinces. We categorize them into three groups: provinces with the same share level between the NEA and our results; provinces with obligation rates higher than the GCAM results, such as Beijing, Tianjin, Hunan, Henan; and provinces whose obligation rates are not sufficient to meet the 1.5°C goal. These provinces are Fujian, Hainan, Hebei, Inner Mongolia, Ningxia, Qinghai, Xinjiang, Yunnan, and Zhejiang. These provinces also have rich renewable resources. Our results indicate that to achieve carbon neutrality, there is a disproportionate RE generation (or capacity) distribution among provinces, leading to some provinces with high RE resources taking more responsibility.

Figure 5.

Provincial Renewable Energy Share in the Total Electricity Generation in the Short Term



Note: The orange line shows the non-hydro renewable energy share of the electricity generation from the GCAM. The light blue line represents the minimum non-hydro renewable obligation (i.e., percentage of generation) set by NEA. The dark blue line represents the incentive obligation set by NEA for individual provinces. Tibet is not included, because there is no NEA data.

4. Renewable Investment Needs

4.1 National Renewable Energy Investment Needs with Uncertainties

With their high upfront investments compared to fossil fuel projects, renewable energy projects are extremely capital-intensive (Egli et al., 2019; Ma & Xu, 2021). Large portions of the investment are incurred at the beginning and need to be financed. Meanwhile, due to variable energy resources, the electricity production of renewable energy projects varies, depending on availability of resources. Thus, project capacity and the financing conditions are the two essential factors that contribute to the investment needs of renewable energy projects. Figure 6 draws on the data we described in the method section to calculate the annual green investment needs, to fulfill the 1.5°C climate targets and carbon neutrality goal in China between 2020 and 2060. We focus on the investment period to 2060 to be consistent with China's carbon neutrality goal. Green investment needs cover costs of grid-connected non-hydro renewable energy, including PV, PV storage, CSP, CSP storage, wind, and wind storage. Supplemental Figure S11 shows another set of calculations that includes the CCS technologies[8] attached to the fossil fuel projects.

The results indicate that average annual green investment needs between 2020 and 2060 are $549 billion ($709 billion with CCS technologies), or 3.7 percent of China's GDP[9]. Given that the annual renewable energy investment over the historical period of 2015–2020 was roughly $100 billion, investment in renewable energy needs to be scaled up significantly and urgently, at a rate of five times more than that in the historical period. The total trend of investment in Figure 6 also illustrates a temporal variation in renewable energy investment, as summarized below. First, extensive renewable energy investments are needed in the near term, which, based on the current investment scale, might pose a huge challenge. Between 2020 and 2025, investment needs are expected to increase from $100 billion per year to $490 billion per year. Second, an investment peak is observed between 2030–2035, when annual investment needs reach nearly $1 trillion. This indicates that the majority of investment needs should be done between 2030 and 2045. Third, investment needs start

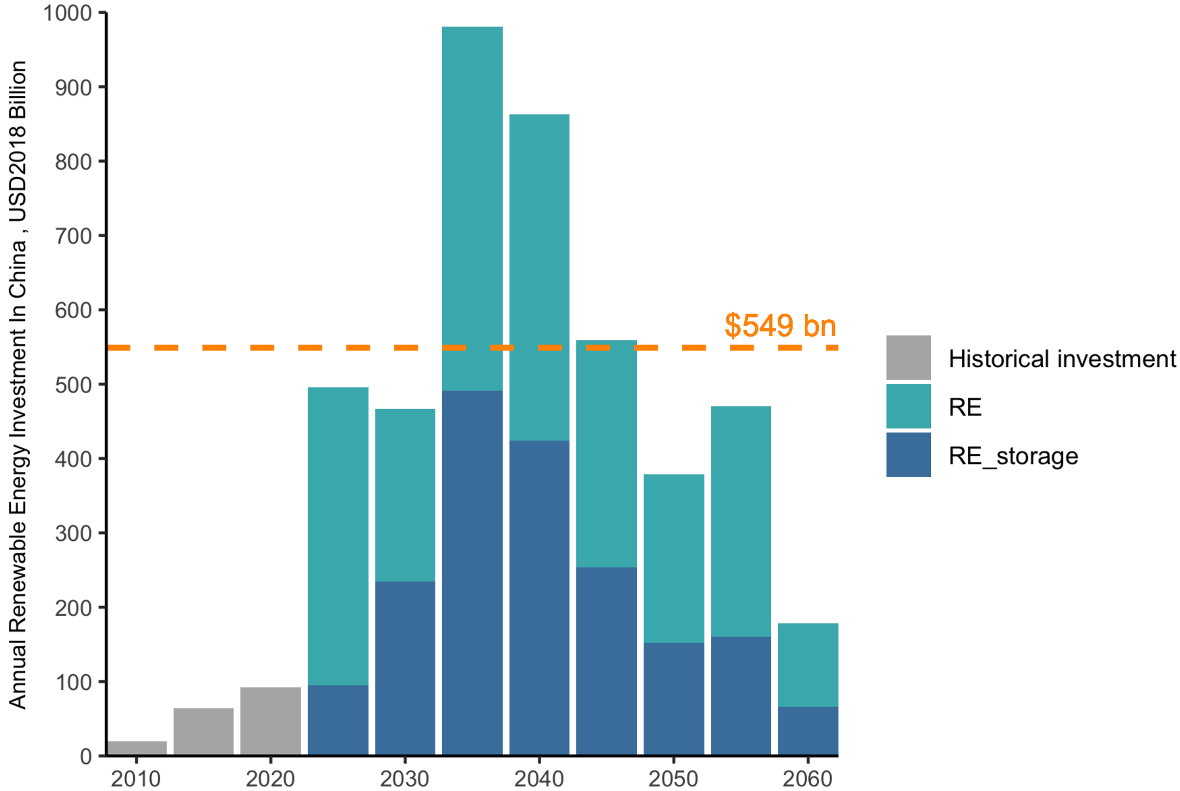
[8] CCS technologies include biomass (IGCC CCS), biomass (conv CCS), coal (IGCC CCS), and coal (conv pul CCS).
[9] In 2020, the Gross Domestic Product (GDP) in China was worth 14722.73 billion US dollars (World Bank, 2020).

to decrease significantly after 2040, declining to $550 billion per year, with a further decrease to $180 billion in 2060.

Figure 6 further illustrates an investment pattern between the conventional renewable technologies and the renewable storage technologies. In the near term, the shift from the investment in renewable energy technologies to investment in renewable storage-based technology demonstrates the role of storage as improving the power quality and balancing the grid in the long term. Due to the early stage of the energy storage technology, the historical investment in grid-scale and behind-the-meter battery storage was low compared to regular renewable technology. The most updated data on battery storage indicates an investment of $5.5 billion in 2020 (IEA, 2021c). Our results show that renewable energy storage investment accounts for 19% of the total RE investment needs between 2020–2025, eventually increasing to 40% in 2060. The general trend of energy storage investment, with an expectation of consistent increase in our 1.5°C scenario, is well within the future projection of energy storage from the literature. Studies estimate that global grid-storage installations would experience a massive sixteen-fold growth rate, from about 10 GWh in 2019 to almost 160 GWh in 2030 (DOE, 2020). For the United States, a ten-fold growth in large-scale battery storage installations between 2019 and the end of 2023 (EIA, 2021), is estimated. A 13-fold growth in Germany between 2021 to 2030 was estimated by research institutes (GTAI, 2019).

Figure 6.

Annual Average Energy Investment Needs for 5-Year Periods in China from 2010 to 2060



Note: Grey bars indicate the historical annual investment from 2010 to 2020. Blue bars indicate projected non-hydro renewable investment to meet China's carbon neutrality goal. The investment needs reported in this working paper are expressed in constant (real) 2018 dollars. (RE storage covers the cost of battery capacity for wind and solar only).

It is noteworthy that these results are subject to some degree of uncertainty, due to the two sets of dimensions used to calculate the investment needs: financial indicators and capacity factors in Table 2 and Table 3. To better illustrate the uncertainties, we conducted a within-model comparison, using inputs listed in both tables and calculating the total investments needs from two dimensions: financial indicators influencing the financial costs and capacity factors influencing the newly installed capacity. In the first set of uncertainties, the China_core scenario is our preferred model with financial data collected by the authors. The ATB scenario adopts the capital costs of each technology and financial data from the National Renewable Energy Laboratory (NREL) Annual Technology Baseline (ATB), which is based on the costs of the United States. The China_ATB scenario adopts the capital costs of technology from China but use financial costs directly from ATB. The Chinese_2.5inflation scenario is based on China_core scenario with an adjustment on the inflation rate. The Financing 20 scenario is also based on China_core scenario with an adjustment on the finance period to 20 years. In the second set of uncertainties, we adjusted capacity factors in each scenario to identify the impact of capacity factors on the investment. Capacity factors in the China_GCAM scenario are constant default rates of 0.38 and 0.24 for wind and PV between 2020 to 2060, respectively. The China_constant_current uses a constant rate over the years but is based on the current capacity factors of wind and solar in China. The China_constant_future uses a constant rate over the years but is based on the potential capacity factors of wind and solar in China from the literature. The results of total investment needs with ranges across the two sets of uncertainties are plotted in Figure 7.

Table 2.

Uncertainties Adopted in the Analysis

Financial sensitivity	Location	Interest rate	E/D ratio	Finance period	Inflation	Tax rate
China_core	China	4%–6.21%	80:20 High equity in China	30	2.0	25%
ATB	USA	4% (5% for coal CCS)	65–75 (E)	30	2.5	26%
China_ATB	China& USA	4% (5% for coal CCS)	65–75 (E)	30	2.0	25%
Chinese_2.5inflation	China	4%–6.21%	80:20	30	2.5	25%
Financing20	China	4%–6.21%	80:20	20	2.0	25%

Table 3.

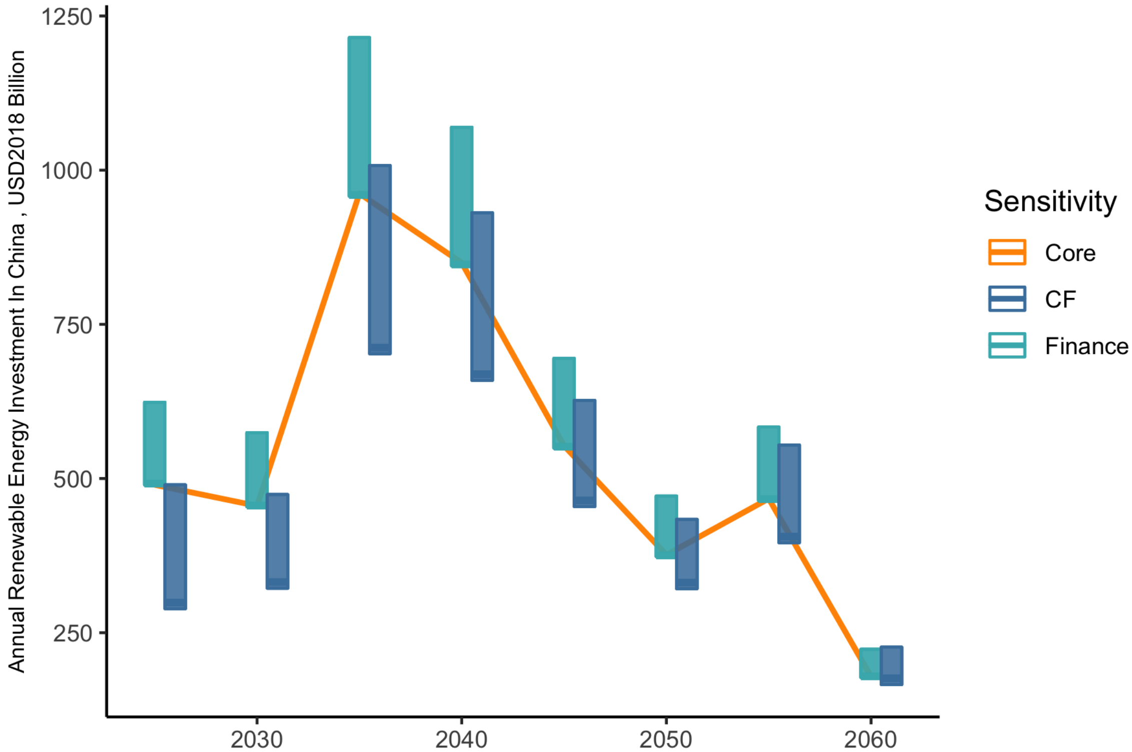
Sensitivities of Capacity Factors

CF sensitivity	CF pathway	Range
China_core	Linear growth	Wind: 0.23–0.38, PV: 0.14–0.19
China_GCAM	GCAM default	Wind: 0.38, PV: 0.24
China_constant_current	Current CF (2020) Constant	Wind: 0.23, PV: 0.14
China_constant_future	Potential CF Constant	Wind: 0.38, PV: 0.19

The results show significant differences between the core scenario, which is our preferred carbon neutrality scenario with Chinese-specific financial indicators, and the other four sets of uncertainties, reflecting the different combinations of financial indicators. In the core scenario, the investment needs are $456 billion in 2030, which appear to be well within the bounds of uncertainty for total investments of $454 to $574 billion from the other four financial sensitivities. Additionally, the results show significant differences between the core scenario and the other three sets of uncertainties based on different capacity factors. The investment needs of 2030 in the core scenario reside in a much wider range of uncertainty for total investments of $322 to $474 billion. The significant differences between the two sets of uncertainties illustrate that both financial and capacity indicators are sensitive to the calculation of the total investment needs.

Figure 7.

Sensitivity Analysis of Annual Average Energy Investments Needs for 5-Year Periods in China from 2025 to 2060, According to Different Financial Indicators and Different Capacity Factors



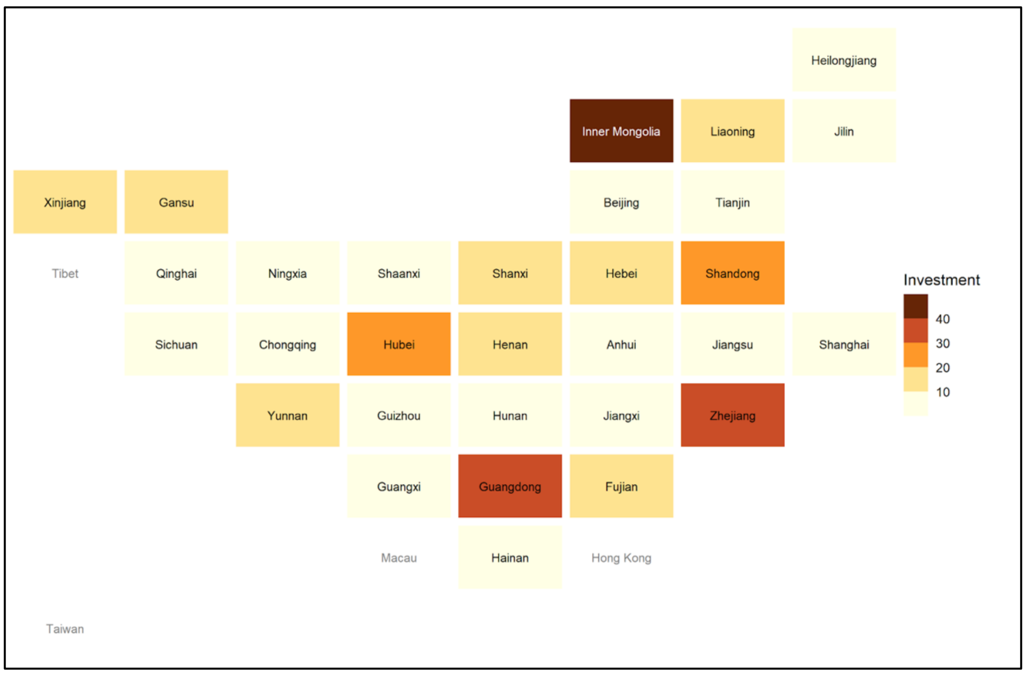
Note: The orange line represents the annual average energy investment needs from our core carbon neutrality scenario. The floating box illustrates the minimum–maximum ranges across the different combinations of the indicators or factors.

4.2 Renewable Energy Solar and Wind Investment Levels at the Provincial Level

Annual green investments show provincial variations in Figure 8, with an overall trend of increased renewable energy investments continuing across all the provinces. Three key trends underpin regional dynamics in solar and wind investment. First, regions with rich renewable resources, e.g., Inner Mongolia, Xinjiang, and Yunnan, tend to have high investment needs. Second, green investment needs are partially driven by the local electricity demand. Provincial economic development and population play a significant role in determining the total electricity demand. Therefore, provinces ranked as fastest economically developed provinces, such as Guangdong, Zhejiang, and Shandong, are associated with high green investment needs. Third, grid regions have an important influence on demand and supply of electricity in certain provinces. For example, the North China Grid covers Beijing, Tianjin, Hebei, Inner Mongolia, and Shanxi. Within this grid region, due to its high renewable resources, Inner Mongolia exports more than half of its electricity to other provinces. Thus, the increasing electricity needs in other provinces, combined with significantly high renewable resources in Inner Mongolia, contribute to the high green investment needs in Inner Mongolia.

Figure 8.

Annual Renewable Investment Needs Between 2025 and 2060

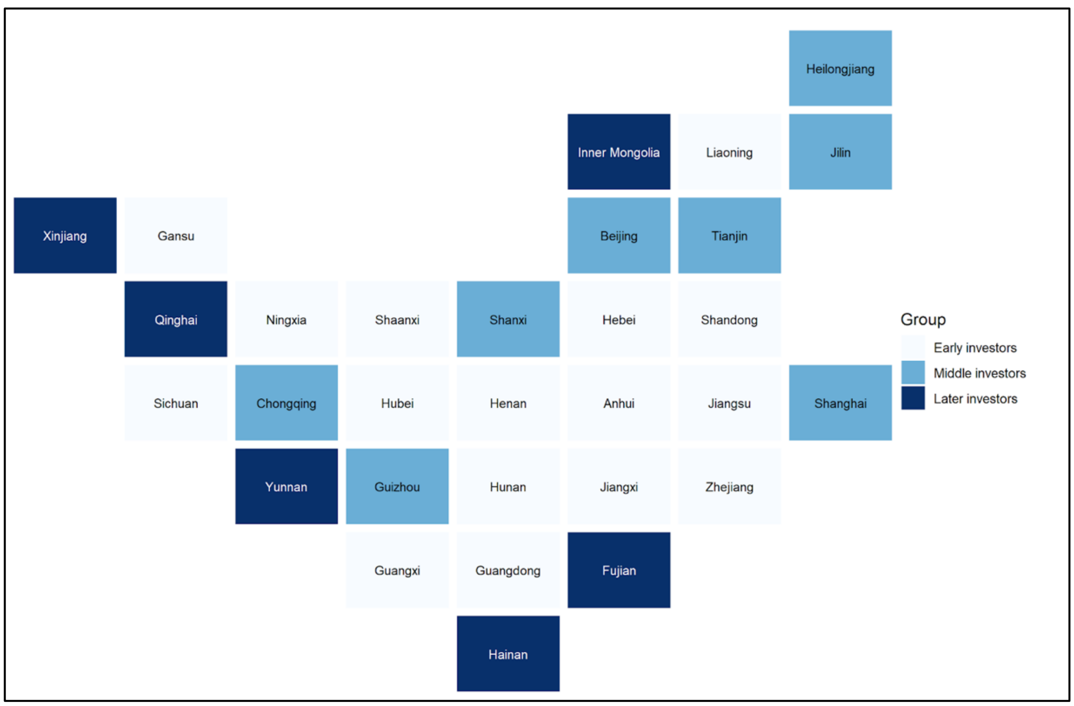


Note: No Tibet, Hong Kong, Macau, and Taiwan due to lack of data availability.

In addition to the spatial variation in investment needs, the results indicate that the investment needs over the next 40 years present three different timelines for these provinces: early investors, middle investors, and later investors, based on their investment peak time. We define early-stage investors as those provinces that have their investment needs peak during the period of 2025–2035; middle-stage investors as provinces whose investment needs peak during the period of 2035–2045; and later-stage investors as those with investment needs that peak during the period of 2045–2055. Figure 9 shows the provincial distribution of the three groups. Several important observations may be drawn from the figure. First, to meet the carbon neutrality goal, China's renewable capacity needs to multiply by three in the next decade, which means the majority of provinces in China need to immediately ramp up their investment in renewable energy. Second, provinces with high potential renewable energy resources, such as Inner Mongolia, Xinjiang, Qinghai, Yunnan, Hainan, will have most of their renewable investment needs occurring in the period of 2045–2055. The increasing renewable energy investment needs in those provinces implies that they need to keep building their capacity to fully utilize the renewable resources. Consequently, they will have to take more responsibility in the later period, when other provinces are constrained by resource availability. However, caution should be taken when interpreting our results for this group of provinces. Large investment needs do not mean they can and will achieve this goal. The vast regional disparity in renewable resource endowments and economic development adds challenges at the provincial level, disproportionately impacting the investment capacity of these provinces. The implications for provinces and how to address the provincial equity issue is another important consideration for China.

Figure 9.

Investment Timeline by Province



Note: The different blue colors represent provinces' different investment peak time. The darker green indicates a later stage. No Tibet and Taiwan due to lack of data availability.

Overall, the spatial and temporal variations among provinces have profound policy implications for renewable investment needs in China, raising the equity issues that need to be addressed. Provinces that lack economic development while embedded with rich renewable resources will require significant support, from both policy and economic dimensions, to meet the high investment needs. Additionally, the spatial distribution of supply and demand creates additional challenges, because it requires significant transmission capacity and grid connection that are not yet in place (IEA, 2021c).

4.3 Taking Financing Costs into Account

The average investment needs over the period of 2025 to 2060 calculated by our methods is 54% more than the investment needs that consider only the overnight capital costs. The cost goes up from $354 billion in the traditional method to $549 billion in our methods. The traditional method considers only the investment needs that occurred during the construction periods, whereas our estimates include the investment needs for the entire life cycle of projects by considering investment market conditions. Overall, different methods that consider the different coverage of investment needs, as well as assumptions about the market conditions, have significant impact on green investment projections. Therefore, from the investors' perspective, a careful design of green investment projection, with all the market conditions considered, helps them understand the long-term risks and make better investment decisions. Additionally, if we take the green investment needs from the project's perspective, there is another 10% increase based on our calculation (see Supplemental Figure 13). Finally, due to its high proportion of the entire investment, we suggest that the non-technical cost[10] be included in the investment calculation. In China, these non-technical costs can reach as much as 20% of the entire investment, with a large share being hidden costs which cannot be evaluated fully by researchers (Li, 2018). As important as it is, the non-technical cost is not covered in this working paper due to lack of data.

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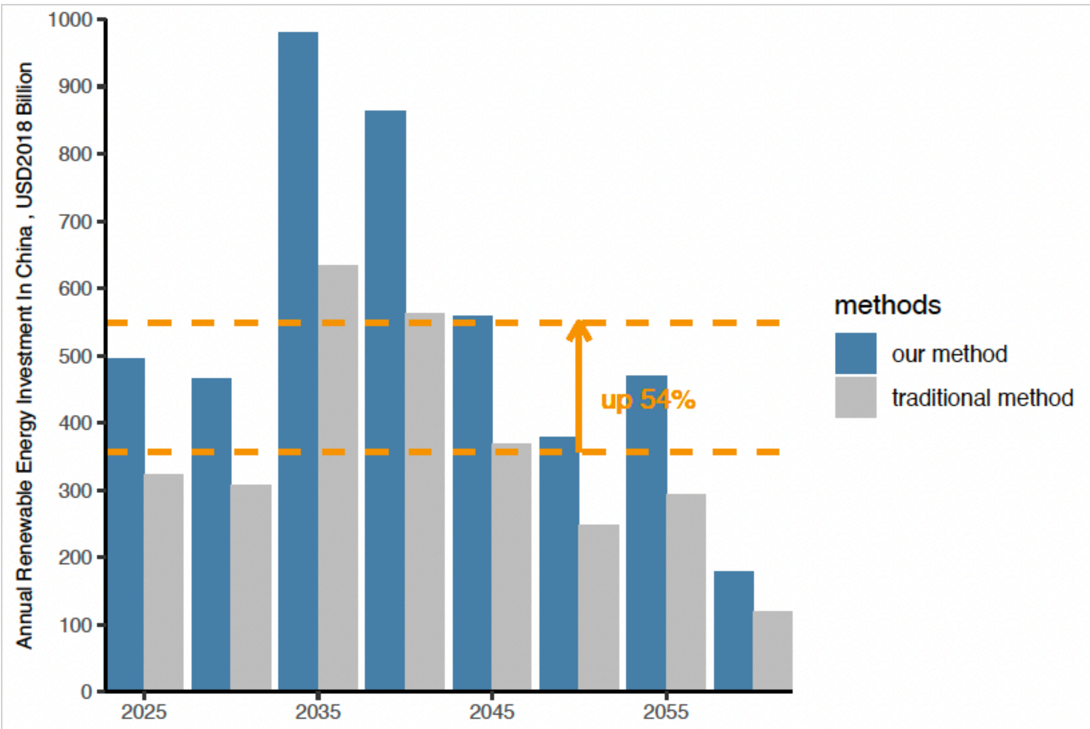
[10] The non-technical costs can be roughly divided into five items: land and tax costs, electricity curtailment costs, financing costs, grid transmission costs, and development costs.

Figure 10.

Investment Needs Based on Two Different Calculations



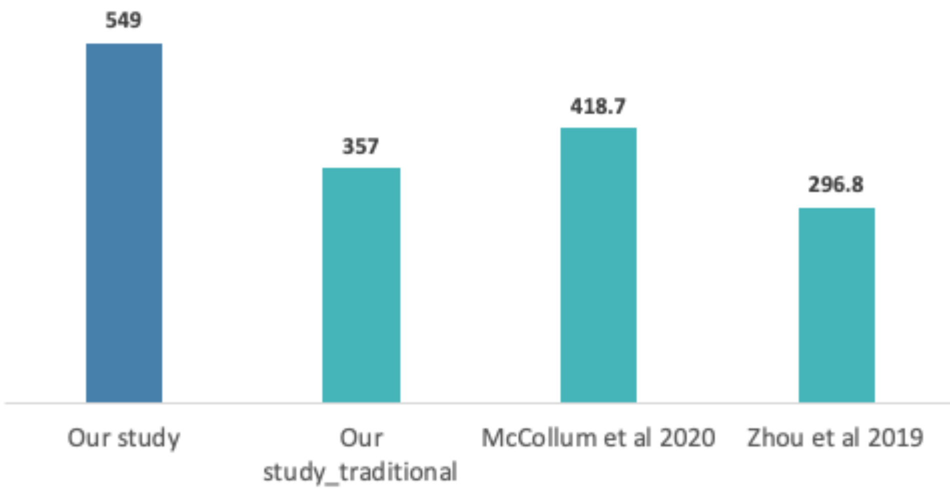
4.4 Robustness Test

We further compare our results with existing literature on the estimation of the investment needs in China. We focus the comparison on the fields of modelling the 1.5°C scenario. The cross-model comparison between our model and the other two models (McCollum et al., 2018; Zhou et al., 2019) specifically estimating the green investment in China is plotted in Figure 11. All investment needs reported in this figure are expressed in constant 2018 dollars. It is instructive to compare our estimates with those from the other two similar studies. Figure 11 shows that although our estimate considering market conditions is the highest, the estimates of the traditional method of our GCAM model is well in range of the McCollum 2018 and Zhou 2019 studies[11]. Therefore, comparison between our estimates and the two studies shows that investment needs followed a similar scale in general, suggesting that green investment needs to increase multiple times to effectively meet the carbon neutrality goal in China.

[11] These two studies cover the investment needs from electricity (non-biomass), electricity T&D and storage. However, our methods do not have the T&D numbers.

Figure 11.

Annual Average Renewable Investment Needs Among Studies (Unit: USD 2018 Billion)



Note: Zhou et al., 2019 and McColumn et al., 2020 estimates from 1.5°C scenarios are based on $2015 dollar. Thus, in order to compare, we convert it to $2018 dollar, with a ratio of 1.06 based on the CPI (Consumer Price Index) Inflation Calculator (https://www.in2013dollars.com/).

5. Policies to Scale up RE Investment

Investment decisions made today will directly impact transition pathways and costs in the future. Our results indicate that a total of $549 billion investment per year in renewable energy infrastructure is needed and will have to be scaled up substantially in the coming years to support broader development and economic transition toward 1.5°C. Given that public budgets are limited, increasing the private investment in renewable energy electricity becomes an urgent matter.

As a result, establishing the enabling environment for promoting renewable energy while engaging private investment through a set of policies should be on the agenda. With a combination of fiscal, monetary, financial, and energy instruments at different stages, these policies should attract investors to support the targets of reducing emissions and deploying renewable energy. Eventually, the policies lay the foundation of the green investment pathway for China. This section covers the supportive policy mechanisms and instruments that will encourage technological innovation and enhance renewable energy deployment in China. We give an overview of policy instruments in each stage of RE investment, followed by a deep dive discussion of key policy instruments and their applications in China.

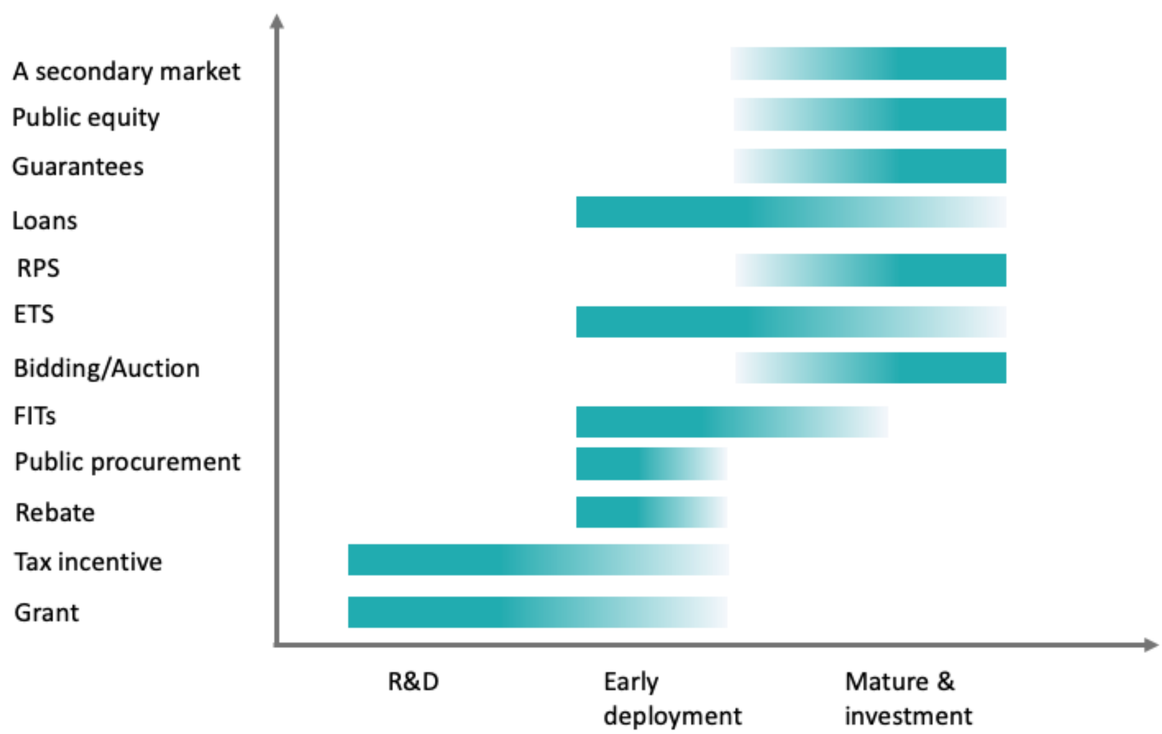
5.1 Policies in Different Stages of Renewable Energy Investment

In general, characteristics of renewable energy (with several uncertain factors) make it a unique investment type, in contrast to conventional energy technologies. First, renewable energy investment involves high stochastic capital costs. Most renewable energy projects are more capital intensive than conventional energy technologies. Using wind projects as an example, 75% of total costs come from capital costs. Thus, capital costs, treated as locked-in investment, constitute an essential source of uncertainty for renewable energy investors. Second, the price of electricity is uncertain, as is unpredictable renewable energy generation on the power grid. Thus, the risk from price uncertainty and unpredictable long-term demand might further prevent renewable energy investments. Third, the positive externalities of renewable energy cannot be internalized by the market itself. Thus, despite all the positive externalities that renewable energy can bring to society, many investors may be reluctant to invest in renewable energy as long as it is still more expensive than fossil fuel. Thus, the profitability of most renewable electricity investments heavily relies on public incentives and, in particular, the support scheme. Meanwhile, to attract more investors to implement new and large renewable energy projects, policies are needed to allocate risk between private and public sectors.

The renewable energy technology cycle includes the following four stages: technology research and development, technology deployment, manufacturing and scale-up, and roll-out (Cumming et al., 2013).To facilitate renewable energy technology's move to the next stage, different sets of policies are required to finance each stage. As illustrated in Figure 12, this working paper focuses mainly on these three stages: the R&D stage, early deployment stage, and the mature & investment stage.

Figure 12.

Policies in Three Different Stages of the Renewable Energy Technology Cycle



5.1.1 R&D Stage

In the R&D stage, government support represents one essential way of correcting renewable energy technology market failures. Given that research and development of renewable energy technology is key to current efforts to meet the decarbonization pathway, continued and broadened support for R&D is needed to realize new technologies and decrease technology costs. Currently, research shows that renewable energy costs were brought down in many countries where new renewables are the source of new electricity (Marcacci, 2017). The formats of policy instruments should focus on grants and tax incentives (such as R&D tax credits) (Bernanke, 2011). The rationale for this set of policies is to increase the supply of new technology that the private sector would not be able to adequately afford (Bernanke, 2011; Bürer & Wüstenhagen, 2009).

5.1.2 Early Deployment Stage

In the stage of early deployment, several prominent policy instruments include: 1) tax incentives, such as FITs, tax credit/deduction; 2) public spending, such as public procurement, loans, and grants; 3) regulatory instruments, such as cap-and-trade policy/emissions trading scheme (ETS), and bidding and auctions. The primary rationale for the government intervention at this stage is to increase the demand for new technologies through a set of policy instruments provided to both the private sector and consumers. The policies ensure that technologies and projects will be financially viable to attract private investors and encourage consumers' adoption of new technologies.

Tax incentives, such as tax credits and tax reductions, in this stage can be applied for the production and investment and the consumption dimensions of renewable energy technologies. On the production and investment side, tax incentives allow private investors to enjoy tax benefits from investment in RE technologies. On the consumption side, tax incentives encourage renewable energy consumption to purchase and install renewable energy equipment. As a result, tax incentives effectively facilitate the penetration of renewable energy deployment into the market. Overall, the tax incentive is an effective tool to bring down the high cost of renewable energy and make it more competitive in the market in the early stage of renewable energy investment. When renewable energy costs reach cost parity with fossil fuel generations, the government should consider gradually phasing out the incentive.

As a price-driven policy, FITs, especially the fixed one, remove the electricity market price risk. The results show that FITs successfully encourage individuals to use renewable energy sources. However, FITs do not have enough capability to create a liberalized, single electricity market (Abolhosseini & Heshmati, 2014). As a result, the FIT encourages earlier investment (Boomsma et al., 2012).

5.1.3 Mature Technology and Large-scale Investment Stage

In the final stage of mature technology and large-scale investment, policy instruments should focus on risk mitigation and supportive framework design to mobilize sizable private investment that could bring in significant sources of capital. Some final stage policies overlap with policies used in the previous stage. Policy instruments include:1) regulatory instruments, such as renewable energy certificate trading/RPS, cap-and-trade policy/emissions trading scheme (ETS), and bidding/auction; 2) public finance, such as public equity/investment, loans, and guarantees; 3) market enabling instruments, such as creating a secondary market for long-term infrastructure assets to create an investment community which comprises funds managing private wealth, insurance funds, pension funds, and sovereign wealth funds (Hall et al., 2017).

Policy instruments in the RE certificate trading/RPS family include renewable energy certificates and portfolio standards (as in the US) or tradable green certificates and quota obligations. RE certificate trading creates an incentive for larger projects. Unlike the FITs, the RPS will not alter electricity or certificate prices as long as the investment is sufficiently small. Thus, profit for the renewable power producer depends on both the electricity spot price and certificate price. A study in the EU found that many member states tried to shift from a feed-in system to green certificates while experiencing both systems (Abolhosseini and Heshmati, 2014). The result showed that FITs could be used for emerging technologies, and RPS should be used to enhance near-market renewable energy technologies.

The other two quantity-driven policy instruments, EST and auction/bidding, can be used in both the second and third stages, but more towards the third stage, since their goal is to create the least expensive project (Frisari & Stadelmann, 2015) by using the market mechanism. Hence, we observe that the current trend is a continued shift away from feed-in policies and towards mechanisms such as auctions and tenders (REN21, 2020). They further contribute to the acceleration of green energy by encouraging increased competition among bidders, cheap electricity prices for consumers, and reduced costs and scale-up deployment on the supply side (Wiser et al., 2003).

5.2 Policy Deep Dive

Here we focus on six commonly used policies to promote renewable energy generation and discuss their roles in promoting renewable energy in China. Those policies are production tax credit, government procurement purchasing, feed-in-tariffs, renewable portfolio standards (renewable energy targets), bidding system, and cap and trade. In the current development stage, China is moving towards market-based policies, such as cap and trade and auctioning bidding systems that provide incentives, such as cost reduction to reduce gas emissions, generate government revenue, and stimulate competition and technological innovation.

We have summarized multiple policy approaches that can facilitate the necessary investment for this transition in Table 4. For a detailed analysis for each policy, please refer to Supplemental Note 1 Renewables Policy deep dive.

Table 4.

Summarization of Policy Instruments and Recommendations

Policy instruments	Approach	Applied Stage	Current status in China	Recommendation
Production tax credits (PTC)	Tax incentive	Heavily in the stage of R&D, but light in the early deployment stage	PTC was phased out in China.	Used by the government for new technologies to bring the high cost of renewable energy down and make it more competitive in the market in the early stage of renewable energy investment, when the private sector would not adequately fulfill this role.
Government procurement purchasing (GPP)	Direct purchase	Early deployment stage	China enacted GPP with the Government Procurement Law of 2003. Globally, China	An efficient GPP requires established quantitative GPP targets at the national level and standardized

			holds the largest total number of products certified for GPP.	protocol for evaluating and reporting on the success of the GPP program.
Feed-in-tariffs (FIT)	A price-based approach	Early deployment stage	This policy led to remarkable growth in renewable energy in China, but lacked sufficient flexibility to respond to cost changes, and provided only limited incentives for further cost reduction. Therefore, the National Development and Reform Commission (NDRC) stated that the central government had phased-out wind and solar FITs by 2021.	The FIT encourages earlier investment. Starting from 2016, China's development of renewable energy has entered a new period, where the trend of development tends to be stabilized, and the renewable energy industry is mature.
Auctioning or bidding system	A quantity-based approach	Light in the early deployment stage and heavily in mature & investment stages	Since 2004, the Chinese government has had experience with RE tenders, as with FITs. Additionally, the Chinese government took further steps to move from a FIT system to an auction-based system.	It allows for flexibility in its design elements to meet deployment and development objectives and has the ability to cater to different jurisdictions reflecting their economic situation, the structure of their energy sector, and the maturity of their power market.
Renewable portfolio standards (RPS)	A quantity-based approach	More towards mature & investment stages	In May 2019, China formally released the RPS plan, which mandated renewables consumption in coastal provinces and stimulated the interprovincial power trade.	RPS is suitable for the renewable industry when it is mature. Under RPS, power producers tend to choose renewable energy with relatively mature technology and lower cost to maximize profits. However, the challenge for implementation in China is how to create incentives among provinces due to the misaligned targets.

Cap and trade systems (ETS)	A market-based approach	Both in the early deployment and mature & investment stages	China has one of the world's largest CO_2 emissions trading systems. Currently, it is at the stage of integrating existing Chinese regional ETS pilots gradually into the national ETS.	ETS utilizes the green approach strategy as a market-based solution that reduced greenhouse gas emissions, reduced the need for high-carbon power such as coal, and encouraged the use of more solar and wind power.
A Green Financial system	Finance sector reform	Mature & investment stages	In China, efforts on green finance can be traced back a decade. The green finance definition was officially adopted in 2016 in the Guidelines for Establishing the Green Financial System.	A green financial system allows engaging in large-scale investment in renewable investment by the private sector and realizing sustainable development.

5.3 A Green Financial System

Achieving deep decarbonization, engaging in large-scale investment in renewable investment from the private sector, and realizing sustainable development depend on a greening financial system. In China, the banking system dominated China's financial system by providing about three fifths of total credit to the market (IISD, 2015a). Thus, to speed the transition to green development in China, the finance sector reform, as a strategic priority (IISD, 2015a), is an indispensable part of the Chinese commitment to achieving its primary targets on fighting climate change.

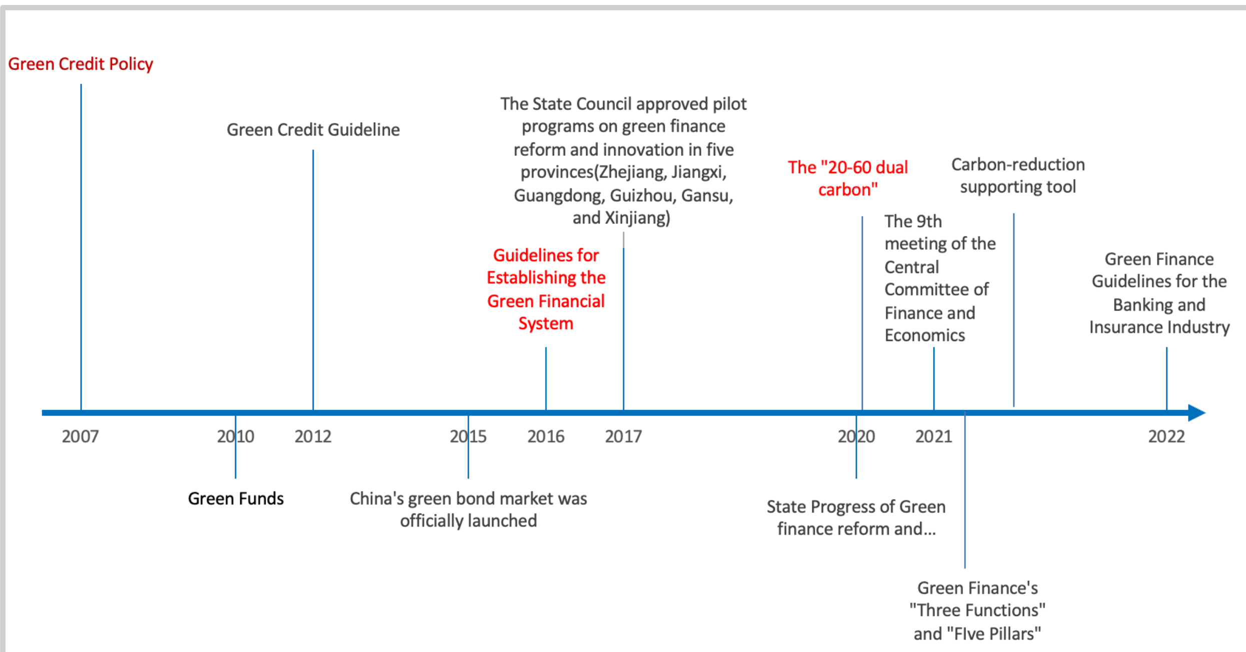
In China, efforts on green finance can be traced back a decade. Green finance has been gaining rapid growth in China since the government issued its Green Credit Policy in 2007 (Figure 13). This Policy aimed to support green development by offering green credits for environmentally friendly industries (Cui et al., 2018). To further support the transformation to a greener economy, China joined the green bond market in late 2015. With its strong market potential, China has overtaken the rest of the world within a year, becoming the largest source of labeled green bonds (IISD, 2015b). During 2016–2019, the green bond market in China gains tremendous growth. Up to 2020, the green bond market in China achieved tremendous progress, where we see a steady annual growth rate[12], a more diversified issuer structure[13], and a decentralized trend[14] (Climate Bonds Initiative, 2020). During the same period, the People's Bank of China (PBoC), in conjunction with seven ministries and commissions, issued the " Guidelines for Establishing the Green Financial System" in 2016, establishing the top-level structure of China's green financial system. It has become an essential milestone in constructing the country's green financial system, which indicates that green finance has entered a stage of rapid development. More importantly, the guidance clearly stated that “the establishment of a green development fund, through the public-private partnership (PPP) model social capital.” With all the efforts, China has made some progress in exploring green finance. However, some financial institutions are still concerned about green industries' risks. Therefore, in 2017, the Green Finance Reform and Innovation Pilot Zone were launched in five provinces and eight cities as a new attempt to promote green finance and facilitate green transformation. By 2020, all these regions and cities have achieved great success, where the green credit balance in the above regions reached US$ 35.11 billion, representing 15.1% of the total loan balance. The green bond balance reached US$ 22.02 billion, which increased 66% between 2019 and 2020 (People’s Bank of China, 2021). After years of development, China's green finance has a solid foundation. In 2020, China made climate pledges of peaking CO_2 emissions before 2030 and reaching carbon neutrality before 2060 (Xi, 2020). The role of green finance has become an important boost to realizing the "dual carbon" goal. Against this background, the PBoC has established the "three functions" and "five pillars" of green finance development strategies to adapt to the profound changes in the country's industrial structure, energy structure, investment structure, and people's way of life (Chen, 2021). Later that year, the PBoC issued two monetary policy tools. One of the two policy tools, the Carbon-reduction Supporting Tool, is essential in lowering loan interest rates for carbon-reduction projects. On top of that, the China Banking and Insurance Regulatory Commission (CBIRC) issued the "Green Finance Guidelines for the Banking and Insurance Industry," with a focus mainly on green banking (e.g., green loans and green credit) and green insurance (The State Council, The people’s Republic of China, 2022).

[12] In 2019, China issued $55.8 billion green bonds, representing a 33% increase from 2018 (Climate Bonds Initiative, 2020).
[13] There is a huge difference in the issuer types between 2016 and 2019. In 2016, Financial Corporates represented roughly 80% of the total volume of issuance, while in 2019, they only represented a third of the total volumes of issuance (Climate Bonds Initiative, 2020).
[14] 2019 sees the first municipal green bond in China. It is a signal of local governments’ ambitions to address climate change (Climate Bonds Initiative, 2020).

China's green finance is embracing unprecedented opportunities and challenges from the "dual carbon 30-60 goals." The "dual carbon" has brought a lot of demand for green credit to China and accelerated investment in clean energy projects. However, there is still considerable investment gap to meet the "dual carbon" goals. Future research needs to focus on how to use policy innovations to establish a diversified green credit system, leverage private finance, and scale up green investment in China.

Figure 13.

Timeline and Milestones of Green Finance Development in China



Conclusions

This working paper is intended to serve as a basis for the estimation of green investment in China in order to achieve the 1.5°C and carbon neutrality goals. In particular, we discuss variations of investment needs among different provinces. In this working paper, we utilize an integrated assessment model, GCAM, along with a set of investment market conditions, to build a methodology to estimate the investment needs of renewable energy in China. We find that annual investment needs for solar and wind generation are $549 billion to fulfill the 1.5°C climate targets and carbon neutrality goals in China between 2020 to 2060. That amount is 54% greater than the investment needs calculated when not considering the investment market conditions.

We also identify the spatial and temporal distributions of the green investment needs among provinces and discuss inequality issues that must be considered to achieve a harmonious development. On the spatial variations side, we observe two trends. First, provinces with strong economic development and large populations tend to have higher green investment needs. Second, because of China's grid connection, provinces with rich renewable energy resources also have high green investment needs. On the temporal variations side, the majority of provinces in China require significant investment in renewables before 2035. However, provinces with high potential renewable energy resources, such as Inner Mongolia, Xinjiang, Qinghai, Yunnan, Hainan, may continue and expand their investment in renewable energy, since most of their green investment needs will occur between 2045 and 2055.

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