THE WATER-ENERGY-FOOD NEXUS ASSESSMENTS OF CARBON NEUTRAL EFFORTS

By

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ABSTRACT

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Efforts toward carbon neutrality are crucial for humans' well-being and the environment. Currently, two main ongoing carbon mitigation efforts are enhancing carbon sequestration and reducing carbon emissions. However, there are debates regarding the tradeoffs of these two efforts' related policies and action plans. This dissertation investigates and assesses the tradeoffs of carbon neutral efforts from a WEF nexus perspective. Three typical efforts were selected as assessment targets to answer the overarching question of how carbon neutral efforts would affect the water-energy-food (WEF) nexus. The Chinese conversion of cropland to forestland program (CCFP) is representative of carbon sequestration. The hydropower development in MRB is an example of the energy transition to reduce emissions. The coal power industry is the coupling effort of energy transition and carbon capture, utilization, and storage (CCUS) applications in reducing carbon emissions.

This dissertation consists of three main chapters, each corresponding to a journal article to address the three assessment targets. In Chapter 2, I evaluated the accomplishment of CCFP in China and its WEF nexus tradeoffs by applying remote sensing images from 2001 to 2019. The WEF assessment includes the transition matrix generation and the water yield calculation of the converted cropland and irrigation land. Indices related to WEF systems are also considered. In Chapter 3, a diagnostic approach with ten indicators was developed to assess the unilateral change's impacts on the WEF nexus. Using the diagnostic method, I provided statistical evidence of the benefits and tradeoffs of water, energy, food, economic prosperity, and the environment

surrounding hydro dams in the Mekong River Basin. In Chapter 4, a scenario-based, life cycle coal power production assessment tool was proposed. By evaluating three portfolios or scenarios, the tradeoffs between reducing coal power production and CCUS application were revealed.

This dissertation has successfully assessed the primary tradeoffs of carbon mitigation efforts from the WEF nexus perspective. The three studies can be wrapped up and come to three major conclusions: 1) The cons of major carbon mitigation efforts on WEF nexus and local sustainability exist, but not as speculated, especially for the CCFP and the hydropower dam construction. 2) The carbon neutral policies in China can accomplish their goals if adequately implemented. 3) The adaptive equilibrium between the CCUS application and coal power production reduction in China is crucial and needs to be better planned.

The dissertation can enrich the carbon neutrality debate and fill gaps in the current literature on WEF nexus tradeoff studies on carbon mitigation by providing a remote-sensing approach and detailed coal modeling tools. The assessment tools proposed in Chapters 3 and 4 can be widely used by policymakers to understand better the tradeoffs regarding sustainability and WEF nexus in carbon neutral efforts.

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1. CHAPTER 1: INTRODUCTION

Global pursuit of carbon neutrality

Climate change and global warming lead to severe environmental and social consequences, including sea-level rise, storms, floods, droughts, extreme weather, etc., threatening humans' survival and well-being, thus attracting the scientific community and the public's attention. Global warming and extreme events have impacted millions of lives. For instance, studies have shown that climate change was likely responsible for more than half of the fatalities during the 2003 Paris heatwave (Mitchell et al., 2016).

The Intergovernmental Panel on Climate Change (IPCC) has announced its sixth assessment report in 2021 with the evidence that the rise in average Earth surface temperature will be 1.5 degrees Celsius in the next 20 years, and 2 degrees Celsius by the middle of the century, without a sharp emission reduction (IPCC 2021). The output has far exceeded government and researchers' expectations. Their original goal was to limit global temperature growth to 1.5 degrees Celsius within this century compared with the pre-industrial level (Edenhofer et al. 2014; Rogelj et al. 2016).

One of the most critical reasons leading to global warming is greenhouse gas emissions, especially the atmosphere's carbon dioxide. Therefore, it is imperative to recognize the importance of carbon neutrality, which refers to achieving net-zero carbon dioxide emissions and developing/ implementing climate policies to mitigate climate change.

Carbon neutrality goals and efforts

To accomplish the carbon neutrality goal and to meet the 2015 Paris Agreement, global greenhouse gas emissions need to be cut by 25– 50% over the next decade. It requires the cooperation of all the countries globally. As of now, there are only two carbon neutral countries, Bhutan and Suriname, but other countries and organizations are at least setting their carbon neutrality goals. China's president Mr. Xi has made a statement in UN 2020 that China pledges to be carbon neutral by 2060 and aims to hit peak carbon emissions before 2030 (McGrath 2020). At the same time, US president Biden announced the new target for the United States to achieve a 50-52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution in 2030. The 27-member bloc of the EU also vowed in 2021 to become carbon neutral by 2050 and reduce its greenhouse gas emissions by at least 55% by 2030 from 1990 levels.

Carbon emissions depend on the amount of carbon escaped from the carbon cycle. Two primary pathways could be made to reduce atmospheric carbon dioxide: 1) reduce carbon emission into the atmosphere and 2) enhance the carbon sequestration through carbon capture, utilization and storage. To achieve these carbon neutrality goals, policymakers have issued various policies and made efforts. Although the two pathways and efforts are working simultaneously, there is a complex relationship between the two. Emission reduction is the primary one, and the most crucial part of it is to increase renewable energy production as the replacement for fossil energy. Conventional fossil energy accounts for the largest share of carbon emissions, especially coal and oil. There are many renewable energy sources too that have been explored. Currently, the dominant renewable energy source around the world is hydropower. It has pros and cons, affecting other natural resources in good and bad ways. There is thus a need to study the sustainability of renewable energy development, especially for hydropower.

Aside from reducing carbon dioxide emissions toward energy production, improving carbon sequestration is also crucial to accomplishing the carbon neutrality goal. Two types of efforts can be made to enhance the carbon sequestration: 1) improve natural carbon sinks in soil, vegetation, and oceans; 2) enhance the capture/sequestration amount of CO_2 emitted during the energy production process. The sustainability within the utilization of carbon mitigation efforts and the interconnections between them needs to be assessed.

Sustainability in carbon neutral efforts

The Sustainability debate includes carbon sequestration efforts. For instance, China's Conversion of Cropland to Forestland Program (CCFP) has been proved to have enhanced the Chinese terrestrial carbon sink significantly. However, various concerns and debates exist regarding the utilization of CCFP for sustainability and the food security issue linked to the reduction in cropland area caused by the slope land conversion into forests and grasslands (Xu et al. 2006; Rodríguez et al. 2016).

The development of renewable energy is recently the main emission reduction effort toward carbon neutrality. However, the sustainability of a couple of categories in green energy is under debate, especially for hydropower, which accounts for the largest share of renewable energy production. Hydropower dam construction has been claimed to lead to various negative impacts on sustainability (Moran et al. 2018), hydrology (Pokhrel et al. 2018), aquaculture production (Stone 2016), greenhouse gas emission (Scherer et al. 2016), and habitat fragmentation (Wu et al. 2003).

On the other hand, one important technology is carbon dioxide capture, utilization and storage (CCUS). It can help improve carbon sequestration within the energy production process but has resulted in more water, energy consumption and sustainability issues that threaten water security (Li et al., 2016).

There is an urgent need to understand the sustainability of carbon neutral efforts in a systematic way. An integrated study that considers reducing carbon emission efforts and enhancing carbon sequestration efforts is needed. Since the carbon neutral efforts are highly correlated to energy, and the crucial resources in its sustainability debates are water and food, the water-energy-food nexus has been recently proposed to be a framework to assess its sustainability.

W-E-F nexus approach

Water-Energy-Food (WEF) nexus is an emerging new framework that has been widely used in sustainable development studies because it attempts to maximize the synergies and minimize trade-offs between these three sectors (Bazilian et al. 2011). Water, energy, and food are inextricably and crucially linked to almost all aspects of human well-being, consumption, and production (Pittock et al., 2015). To increase governance efficiency and enhance water, energy, and food security, interdisciplinary study with a nexus approach is an excellent way to accomplish this goal (Hoff 2011).

Noticing that water, energy, and food are essential to human well-being, scholars and international agencies began to care about studying the interconnection between these three systems. Scholars have developed many conceptual frameworks to link them through the nexus approach (Bazilian et al., 2011, Mohtar & Daher 2012, Scott et al.,2015). The Food and Agriculture Organization of the United Nations (FAO) defines the nexus as "a new approach in support of food security and sustainable agriculture" and "the complex interactions between water, energy, and food" (FAO 2014).

Researchers have applied the WEF nexus to carbon regulation issues, either using the nexus to study carbon dioxide issues (Makgabutlane et al., 2020) or putting the carbon into the WEF nexus to become a water-energy-food-carbon nexus (Chamas et al., 2021). But most of them rarely focus on carbon sequestration pathways, and there is still a lack of systematic, comprehensive study on the sustainability of different carbon neutral pathways. Even the carbon neutral efforts made by different countries, organizations, and individuals are significant and encouraging. The synergies and tradeoffs assessments for sustainability are unignorable. There is an urgent need to develop a comprehensive study focusing on assessing the sustainability of carbon-neutral efforts.

Research objectives and dissertation framework

The overarching research objective of this study is to assess the sustainability of carbon neutral efforts by applying the WEF nexus approach (Figure 1.1). To address this objective, I examined sustainability issues related to the carbon sequestration effort (Land-based carbon sink improvement) and emission mitigation effort (Renewable energy transition and CCUS application). For the carbon sequestration efforts assessment (Chapter 2), I applied a real-world case assessment of the large-scale carbon sequestration efforts through the CCFP in China. I proposed and developed two assessment tools for the carbon emission reduction analysis (Chapters 3 and 4). One is remote sensing based (Chapter 4) on renewable energy transition. The other is life cycle scenario-based (Chapter 4) on the combination of energy transition and CCUS.

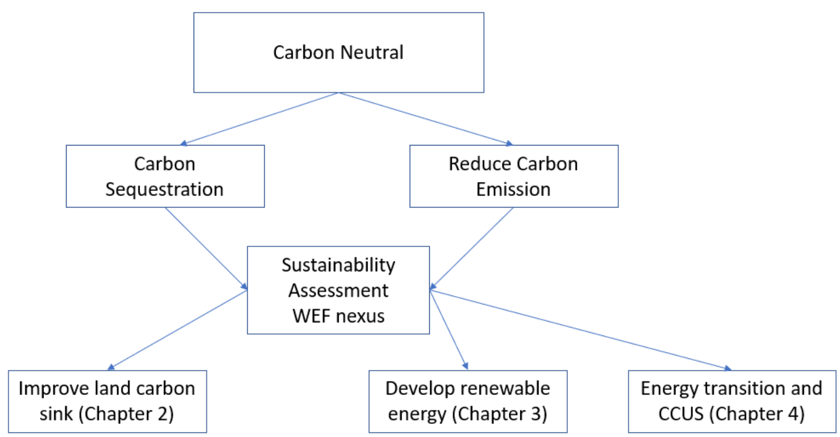

Figure 1.1 Dissertation framework/flowchart

Therefore, this dissertation consists of three assessments of the carbon neutral efforts. Two of them are based on remote sensing observations (Chapters 2 and 3), and one is based on scenario portfolio analysis in predicting the future (Chapter 4). One is to study the improved sequestrations (Chapter 2), and two of them study carbon emission mitigation (Chapters 3 and 4).

For the main purpose, one is to provide the information for evaluation (Chapter 2), two of them deliver assessment tools and can be widely used (Chapters 3 and 4). The study sites also varied. One focuses on a global hydropower hotspot: the Mekong River basin (Chapter 3), and the other two focus on the largest global carbon emission contributor: China (Chapters 2 and 4). Two assessments evaluated one single policy impact (Chapters 2 and 3), and the other one evaluated two policies' coupling effects (Chapter 4). This dissertation aims to help people better understand the sustainability of the carbon neutral efforts by providing observations and assessment tools.

Research questions and dissertation organization

The overarching research question of this dissertation is: "Are the ongoing efforts to achieve a carbon neutral state sustainable from WEF Nexus perspectives?"

Specific research questions are:

1. "How do the carbon sequestration efforts in China impact its WEF system security and WEF nexus?"
2. "How do the carbon emission reduction efforts impact WEF nexus in the way of the energy transition, using an example from the hydropower development effects on MRB's local WEF nexus?"
3. "How to find an equilibrium solution regarding WE nexus and carbon mitigation in China's coal power industry, under the context of CCUS application and renewable energy transition?"

These specific questions from 1 to 3 had been addressed in three separate chapters, from Chapter 2 to Chapter 4, respectively. In Chapter 2, I applied the remote sensing approach to provide evidence for the sustainability assessment from the WEF nexus perspective on the CCFP in China in Chapter 2. In Chapter 3, I proposed a remote sensing-based diagnostic assessment tool with statistical evidence of the benefits and tradeoffs of water, energy, food, economic prosperity, and the environment surrounding hydro dams. I applied it to the dominant source of renewable energy and the MRB's global hotspot of hydropower production. In Chapter 4, I developed a scenario-based life cycle coal power assessment tool with adaptive parameters to study the tradeoffs and synergies between two carbon mitigation policies: renewable energy triggered coal power production reduction and CCUS application. I further utilized the tool on different predicted coal power portfolios in China to seek a sustainable solution. I summarized the critical findings of this research, pointed out the practical implications, specified limitations, and discussed directions for future research in the final chapter.

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2. CHAPTER 2: THE SUSTAINABILITY ASSESSMENT OF CO2 CAPTURE, UTILIZATION AND STORAGE (CCUS) AND THE CONVERSION OF CROPLAND TO FORESTLAND PROGRAM (CCFP) IN THE WATER-ENERGY-FOOD (WEF) FRAMEWORK TOWARDS CHINA'S CARBON NEUTRALITY BY 2060

Abstract

The global warming induced by the emission of greenhouse gases, especially the carbon dioxide has become the global climate and environmental issues. China has been working in the CO_2 emission reduction and carbon sinks with the purpose of becoming the carbon neutral country by 2060. The re-forestation as natural sinks efforts represented by the Conversion of Cropland to Forestland Program (CCFP) and the CO_2 capture, utilization and storage (CCUS) technologies as geological sequestration of CO_2 have great potential. However, the trade-off among CCFP, CCS/CCUS and Water-Energy-Food (WEF) nexus are not well evaluated. In this paper, the remote-sensing data are collected and used to evaluate the sustainability of CCFP by analyzing the variation of land use and land cover (LULC), crop production etc. The results show that 13.29% of the cropland in 2001 vanished and converted to grassland (8.3%), mosaic cropland (3%) and urban land (0.98%) in 2019, demonstrating that the CCFP is successful in both WEF nexus and carbon sink. The total crop production has increased around 50% between 2001 and 2019, implying that the CCFP will not lead to the food risk during the conversion of croplands into other types of land in China. A sustainable implementation of CCFP and other environmental Payments for Ecosystem Services (PES) policies in 2019-2060 could reach an estimated total growth of 7.462 billion m^3 in comparison of that in 2018 and the total plantation forest stock of about 10.852 billion m^3 in 2060, with a corresponding minimum CO_2 sink of 2.90 billion tons in 2060. The estimated peak of net equivalent CO_2 emissions before 2030 is about 11.0 billion tons, could not be reduced to zero by 2060 without the large-scale application of the CCS/CCUS technologies as geological

sequestration of CO_2. Besides, the application of CCS/CCUS can be beneficial for WEF e.g. through replacing the water by CO_2 during energy production, especially in the shale gas production in the regions with high water risks in China. In one word, CCS/CCUS and CCFP are two decided pathways of carbon sequestration and should be systematically applied to achieve China's carbon neutrality by 2060.

Keywords CCUS· CCFP· WEF nexus· Carbon sequestration· Carbon neutrality

2.1 Introduction

Climate change and global warming lead to serious consequences, such as sea level rise, glacier melting, storms, floods, droughts, etc., threatening humans' survival and well-being, thus attracting both the scientific community and the public's attention. One of the critical reasons leading to global warming is greenhouse gas emissions, especially the atmosphere's carbon dioxide. More and more global governments have taken action to reduce carbon dioxide emissions of limiting global temperature growth to 1.5 ^{o}C within this century compared with the pre-industrial level (Edenhofer et al. 2014; Rogelj et al. 2016).

Since carbon dioxide emission depends on the amount of carbon escaped from the carbon cycle, there are mainly two ways to reduce the atmospheric carbon dioxide: 1) reduce carbon emission into the atmosphere and 2) enhance the carbon sequestration. Except for reducing carbon dioxide emission toward energy production, transportation, etc., improving carbon sequestration is also crucial to accomplish the carbon-neutral goal. Two types of efforts can be made to enhance the carbon sequestration: 1) improve the natural carbon sink by soil, vegetation, and ocean; 2) enhance the capture/sequestration amount of CO_2 that are emitted during energy production process.

In terms of efforts to mitigate global warming, China is obviously crucial, and any successful international effort to stabilize greenhouse gas emissions will inevitably include China (Barbi et al. 2016). As China overtakes the US and becomes the world's largest carbon emitter, the Chinese government faces tremendous challenges to reduce carbon dioxide emissions. China first targeted at reducing the carbon intensity by 18% in 2016-2020 (The 13th Five Year Plan 2016). Furthermore, China's president Mr. Xi has made a statement in UN 2020 that China pledges to be carbon neutral by 2060 and aims to hit peak carbon emissions before 2030 (McGrath 2020). Through the afforestation process, Chinese land biosphere sink is equivalent to about 45% of annual anthropogenic carbon emission (Wang et al. 2020), but it is still a long way to go to totally reduce the carbon emissions from energy production. Therefore, China has made great efforts to reduce the CO_2 concentration in the atmosphere through both enhancing terrestrial carbon sink and improve the underground carbon storage by carbon capture, sequestration (CCS) and utilization (CCUS) technologies during the energy production process.

To mitigate the hazard of vast land degradation, China has been implementing various environmental Payments for Ecosystem Services (PES) policies after the Yangtze River flooding in 1998, including the Natural Forest Protection Program (NFPP), the Conversion of Cropland to Forestland Program (CCFP) that is also called Grain for Green (GFG), etc. These policies have been launched to increase natural carbon sink by protesting natural forests and converting some croplands into forests or grasslands, which takes up 56% of the total carbon sink in China during the first decade of the 21st century (Lu et al. 2018).

The CCFP is an extensive public PES program by compensating farmers to convert the ecologically vulnerable croplands or croplands with high slopes to forests or grasslands (Gauvin 2010). The CCFP can reduce soil erosion, sediment transport and flood frequency (Li et al. 2019), thus the carbon sequestration has been strengthened both by vegetation and soil through increasing soil organic carbon (SOC), particulate organic carbon (POC) and light fraction organic carbon (LFOC) (Shi et al. 2020). However, various concerns and debates still exist towards the utilization of CCFP for the sustainability and the food security issue linked to the reduction in cropland area caused by the conversion into forests (Xu et al. 2006; Rodríguez et al. 2016).

Another important carbon emission reduction method is the CCS/CCUS technology, which has been widely used in reducing the CO_2 emission released from large stationary point sources during the energy production process such as thermal power plants, synthetic ammonia industry, iron and steel plants, cement plants etc. (Liu 2015). Globally, the CO_2 usually be injected at deep depth more than 800 m and stored in different geological sites, such as deep saline aquifers, depleted oil and gas reservoirs, deep unmineable coal seams etc. The CCUS technology is much competitive due to the offset of cost by enhancing the recovery of oil (CO_2-EOR), coalbed methane (CO_2-ECBM), natural gas (CO_2-EGR) or geothermal energy. Since the 1970s, the CO_2 has been used in the commercial-scale oil production in the USA (ACCA21 2012). Studies on CO_2-ECBM and CO_2-EGR started in the 1990s (Puri and Yee 1990; van der Burgt et al. 1992), but it is still at the very early test stage of CO_2-enhanced shale gas production (Pei et al. 2015). Besides, the CO_2 is used as the circulation fluid of the geothermal system to extract geothermal energy (Brown 2000). Till the end of 2016, there were 38 large-scale CCS and CCUS projects and about 70 pilot-scale engineering CCUS projects globally and the top three locations are North America, Asia and Europe. Most of these engineering are CO_2-EOR or pure CO_2 capture projects, followed by CO_2-ECBM, and CO_2 sequestration in saline aquifers (Liu et al. 2017).

The CCFP and CCS/CCUS have tremendous success in carbon sinks/sequestration. However, the large PES policy may trigger the variation of land use and land cover (LULC), which can lead to unexpected consequences on local natural resources and cropland production. The CCS and CCUS technologies applied in the energy production process may require much water consumption and cause the security issue of water resources. Therefore, there have been strong debates on the potential food security risk driven by CCFP and water security risk caused by CCS/CCUS.

When evaluating the policy implementation and the government efforts, it is insufficient only to examine the success of the primary goal. The trade-off analysis of policy's impacts on other aspects is also crucial in policy assessment. In order to understand whether these two primary types of carbon sequestration efforts are sustainable, it is urgent to study their trade-offs. The CCFP is the largest and most critical PES policy in China. Still, the decrease in cropland cover area through conversion may reduce crop production and lead to food security issues. The associated LULC change may have further impacts on water resources. The CCS and CCUS technologies applied in power plants can improve water consumption during the carbon capture process and affect energy production.

The trade-offs of CCFP, CCS/CCUS and WEF nexus are mainly between the carbon sequestration itself and food, energy, and water resources. The WEF nexus is a well-known framework that has been widely used in sustainable development because it can maximize the synergies and minimize trade-offs between these three sectors (Bazillian et al. 2011). Food, energy, and water are essential and closely linked to almost all aspects of human well-being (Pittock et al. 2015). Many researchers have applied the WEF nexus in carbon regulation issues. But most of them are theoretical (Daher et al. 2015; Huang et al. 2020; McCarl et al. 2017), but it is rarely focusing on carbon sequestration.

In this paper, the WEF nexus is applied in the sustainability assessment of CCFP and CCS/CCUS without considering other factors (e.g., geological risk by CCUS, policies and economic sustainability etc.) by answering three questions: 1) How important are CCS/CCUS as geological CO_2-sequestration and CCFP as natural carbon sinks for China's carbon neutrality by 2060? 2) How does the implementation of CCFP affect cropland LULC, crop production etc., in the WEF nexus? 3) How does the utilization of CCS/CCUS technologies affect water consumption during energy production in the WEF nexus?

2.2 Methodology

2.2.1 Conceptual framework of WEF nexus

Water, energy, and food securities are of crucial importance for global sustainability. Driven by global population growth, urban sprawl, climate change, and shifting consumption patterns, global demand for these three types of resources is increasing rapidly (Biggs et al. 2015). The Water, Energy and Food (WEF) security nexus–solutions for the green economy has been proposed in 2011, which provides the first platform for consideration water-energy-food into one nexus perspective. The WEF nexus framework is an interdisciplinary structure that can emphasize the WEF sectors separately and their inter connections. It can reflect the status of the fluctuating WEF nexus system, the trade-offs, and synergies caused by changes in different sectors. The WEF nexus framework can help better understand the sustainability considering not only one aspect but also the chain effect caused by the changes of that aspect. Many researchers and institutions have conducted many sustainability studies based on the WEF nexus (Leck et al. 2015; Albrecht et al. 2018).

2.2.2 Data acquisition and workflow for the sustainability of CCFP policy

Both the remote-sensing data and local statistical data are obtained for the sustainability analysis of CCFP. Remote sensing imagery includes LULC, precipitation, net primary production (NPP) and evapotranspiration (ET) between 2001 and 2019. Two sources of LULC data including the LULC product with the spatial resolution of 500 m (MCD12Q1) obtained from Moderate Resolution Imaging Spectroradiometer (MODIS), and the LULC data extracted from the European Space Agency Climate Change Initiative (ESACCI) are used in this paper. The yearly classification imagery of LULC has the 300 m spatial resolution. The yearly LULC classification data with the International Geosphere Biosphere Program (IGBP) schemes is extracted. Precipitation data is from Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) with 0.05 arc degree resolution. The pentad LULC data is combined into yearly LULC data. Yearly NPP data are obtained from MODIS Terra NPP product (MOD17A3HGF) with the 500 m spatial resolution and the evapotranspiration data is also from MODIS (MOD16A2) with the 500 m spatial resolution. The 8-day imagery is combined into yearly time series data. DEM data is obtained from the Shuttle Radar Topography Mission (SRTM). The water surface area classification is from the global yearly surface water classification history dataset, with 30 m spatial resolution, provided by the Joint Research Centre (JRC) of the European Commission (Pekel et al. 2016).

In situ statistical data are extracted from National Bureau of Statistics of China, including marine/freshwater aquatic production, agricultural diesel usage, fertilizer usage, rural hydropower plants, reservoir number and capacity etc.

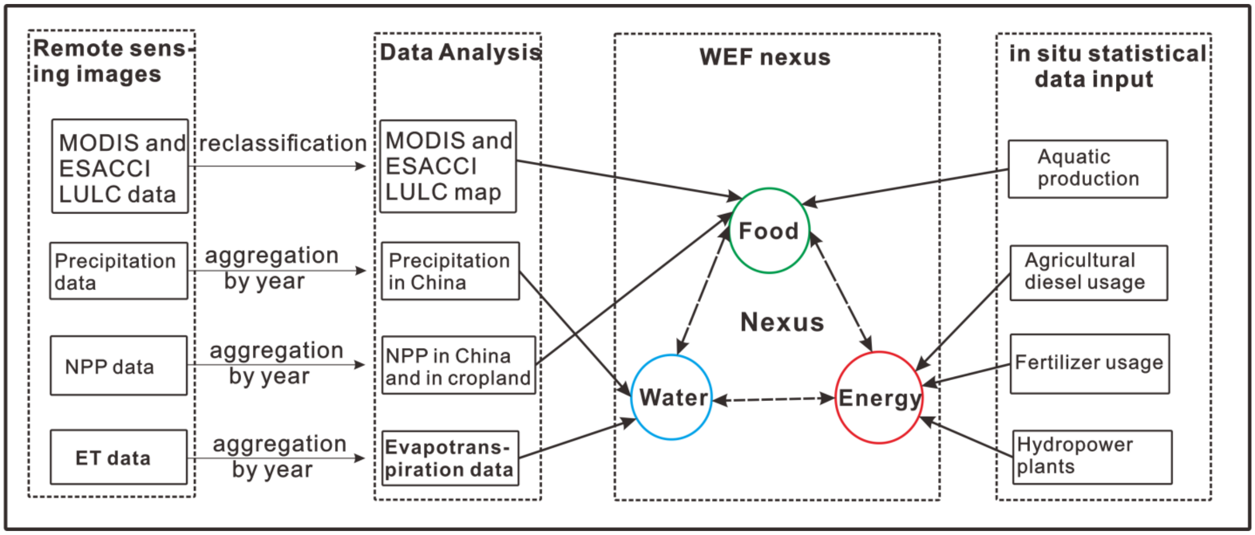

Figure 2.1 Flowchart of the data processing and analysis in WEF nexus

The general framework and overall analytical method for data processing related with CCFP are shown in Fig.2.1. To detect the variation in the LULC map for detailed analysis, the land cover products from MODIS and ESACCI are re-classified. The LULC datasets of MODIS are classified according to the standard of IGBP (Friedl et al. 2002), which has 17 LULC classes and they are grouped into 9 categories in this paper (see Table 2.1). The ESACCI land cover product has 28 LULC types, and they are grouped into 10 LULC types in this paper (see Table 2.2).

Table 2.1 Reclassification of the LULC data obtained from MODIS

Old LULC classes	**New LULC classes**
Evergreen needleleaf forest	Forest
Evergreen broadleaf forest	
Deciduous needleleaf forest	
Deciduous broadleaf forest	
Mixed forest	
Closed shrubland	Other woody
Open shrubland	
Woody savanna	
Savanna	Grassland
Grassland	
Cropland	Cropland
Cropland/Natural vegetation mosaic	Vegetation mosaic cropland
Urban and built-up land	Urban
Barren	Barren
Water body	Wetland and water
Permanent wetland	
Permanent snow and ice	

Table 2.2 Reclassification of LULC data obtained from ESACCI

No.	Old LULC classes	New LULC classes
1	Cropland, rainfed	Rainfed crop (1)
2	Cropland, irrigated or post-flooding	Irrigation (2)
3	Mosaic cropland (>50%)/natural vegetation (tree, shrub, herbaceous cover) (<50%)	Mosaic cropland (3,4)
4	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%)/cropland (<50%)	
5	Tree cover, broad leaved, evergreen, closed to open (>15%)	Forest (5,6,7,8,9,10)
6	Tree cover, broad leaved, deciduous, closed to open (>15%)	
7	Tree cover, needle leaved, evergreen, closed to open (>15%)	
8	Tree cover, needle leaved, deciduous, closed to open (>15%)	
9	Tree cover, mixed leaf type (broad leaved and needle leaved)	
10	Mosaic tree and shrub (>50%)/herbaceous cover (<50%)	
11	Mosaic herbaceous cover (>50%)/tree and shrub (<50%)	Other woody (11,12)
12	Shrub land	
13	Grassland	Grass land (13,14,15)
14	Lichens and mosses	
15	Sparse vegetation (tree, shrub, herbaceous cover)(<15%)	
16	Tree cover, flooded, fresh or brackish water	Wetland water (16,17,18,21,22)
17	Tree cover, flooded, saline water	
18	Shrub or herbaceous cover, flooded, fresh/saline/brackish water	
21	Water body	
22	Permanent snow and ice	
19	Urban areas	Urban (19)
20	Bare areas	Barren (20)

NPP can represent the general carbon sequestration capacity and the productivity of cropland. The total NPP and the NPP in cropland of China are calculated separately. The yearly total precipitation data in China is used to illustrate the change of water resource. Evapotranspiration data is combined with the cropland area to represent the water usage of irrigated agriculture. The difference between precipitation and evapotranspiration can represent the water yield of land (Jia et al. 2014). Besides, the pixel slopes are derived based on SRTM DEM data.

2.2.3 Sustainability evaluation methodology of the CCS/CCUS technology

In order to investigate the sustainability of CCS/CCUS technology by the WEF nexus, the tradeoff energy-water consumption, the water consumption during the process of CCUS are analyzed firstly. After that, a typical coal-based power plant with a capacity of 630 MW in China is used as an example to investigate the overall water consumption of power plant with and without consideration of CCUS. Thus, the water consumption of all coal power plants with the utilization of CCUS in China is estimated. In this work, two different carbon capture technologies (i.e., amine- and oxy-based) are considered. The carbon dioxide captured from the power plant is used as an alternative fluid for fracturing in the petroleum industry.

2.3 Sustainability assessment of CCFP in the WEF nexus and impacts on China's carbon neutrality

2.3.1 Effects of the CCFP implementation on China's carbon neutrality

Benefit from the implementation of PES policies, especially the CCFP policy, China has significantly increased the natural carbon sink, leading the global greening process by the LULC management with the rapid growth in forestland cover area in the 21st century (Chen et al. 2019). The calculated total NPP in China based on MODIS images has significantly increased from 2.74 trillion kgC in 2001 to 3.18 trillion kgC in 2019 (see Fig. 2.2). The forestland cover area based on MODIS LULC products (Fig. 2.2) has increased from 81.3 million Ha in 2001 to 96.6 million Ha in 2019, with the much larger growth rate 11.3% in 2010-2019 compared with that of the first decade in 2001-2010.

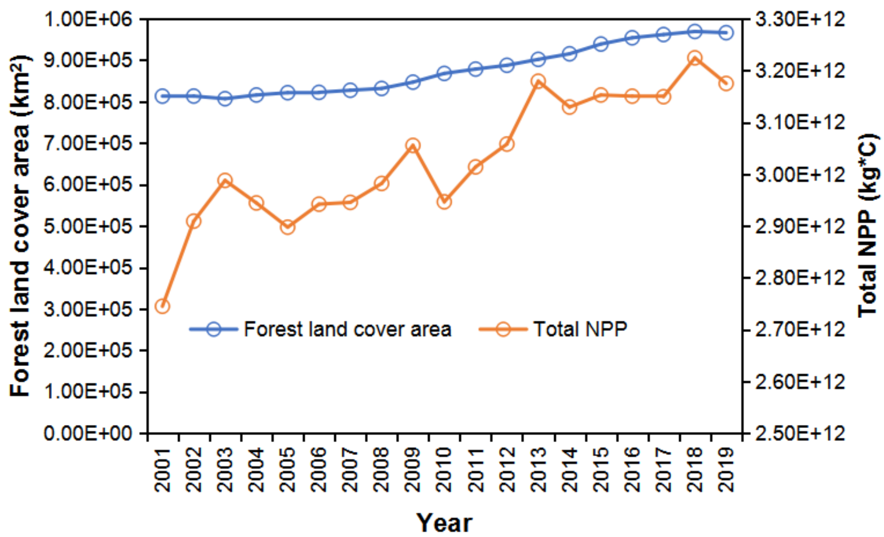

Figure 2.2 The total NPP and forestland cover area in China based on MODIS from 2001 to 2019

Therefore, the implementation of CCFP and other PES policies in China is successful. The forestland including plantation forestland through CCFP and other PES policies in China produces about 4.04 billion tons of CO_2 sink per year during 2010 to 2016, equivalent to about 45% of the estimated annual anthropogenic emissions over that period in China (Wang et al. 2020). Based on the 7th to 9th National Forest Inventory of China's State Forestry Administration, the plantation forest stock in 2008, 2013 and 2018 was 1.96, 2.48 and 3.39 billion m^3 respectively, with a much larger growth of 0.91 billion m^3 in 2013-2018 (annual growth rate of 0.182 billion m^3) compared with 0.53 billion m^3 in 2008-2013 (annual growth rate of 0.106 billion m^3).

Based on the successful experiences of CCFP and PES policies during 2013 and 2018 in China, if we continue with a constant annual growth of 0.182 billion m^3 for the plantation forest stock in 2019-2060, an estimated total growth of 7.462 billion m^3 during these 41 years due to the implementation of CCFP and other PES policies can satisfy the total plantation forest stock of about 10.852 billion m^3 in 2060. We take conservatively the total forest stock of 15.137 billion m^3 and the corresponding CO_2 sink of 4.04 billion tons in 2013 (Wang et al. 2020) as reference, the sustainable implementation of CCFP and other PES policies could contribute a minimum CO_2 sink of 2.90 billion tons in 2060, which makes a great contribution to China's carbon neutrality by 2060.

2.3.2 Impacts of CCFP on cropland cover area and crop production

The CCFP is also called Grain for Green (GFG) program. Thus, a question rises "does the increased green leads to the decline in grain production?" To answer this question, the cropland cover area in China is calculated based on MODIS database, which shows that it firstly increased from 122.5 million Ha in 2001 to 124.8 million Ha in 2004, then it decreased to 122.1 million Ha in 2019 (Fig 2.3), presenting an overall decrease trend. The irrigated cropland cover area also increased up to 66.23 million Ha in 2010, and then it decreased sharply to 64.93 million Ha in 2019.

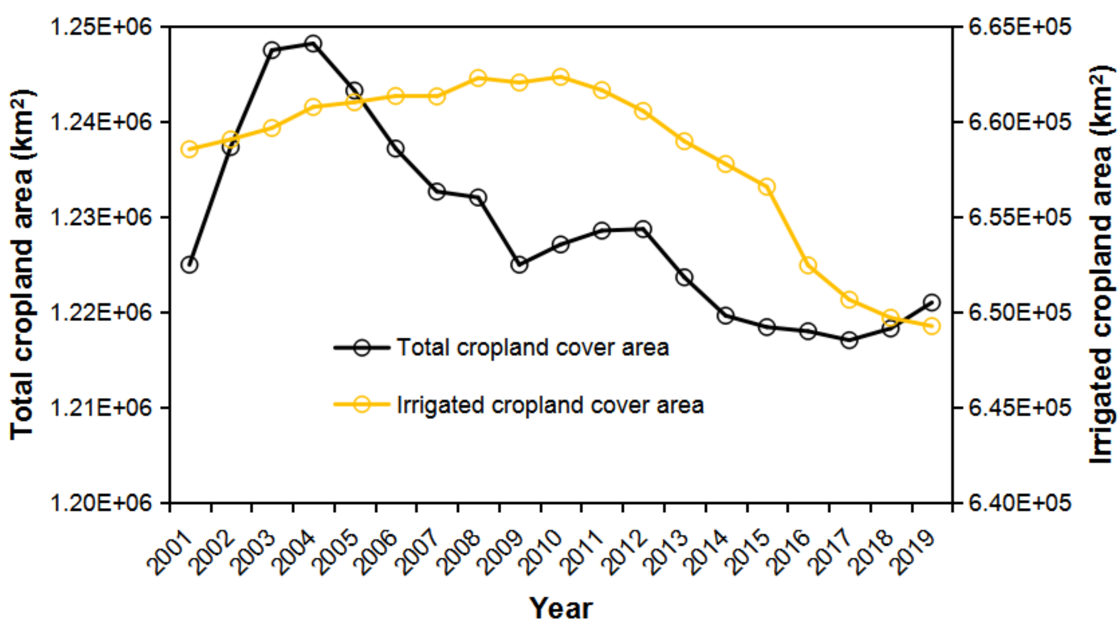

Figure 2.3 The total cropland and irrigated cropland area based on MODIS between 2001 and 2019

The spatial variation of the cropland cover area between 2001 and 2019 can be shown in Fig 2.4, displaying the location of cropland conversion. It demonstrates that the vanished croplands in GFG program are mainly located at the eastern coastal provinces, and large portions of the newly converted croplands are distributed in northwestern provinces. In Hebei, Beijing and

Guangxi provinces, a large amount of croplands are converted into other LULC types, while many newly generated croplands are observed in Shanxi and Xinjiang provinces.

The percentage of different land cover types converted from cropland in past two decades are calculated in a transition matrix (Table 2.3). 13.29% of the cropland in 2001 vanished and converted to other land types in 2019, proving that the implementation of CCFP is successful. More than 68% of the vanished cropland are converted to woody-environmental-friendly land cover and thus greatly enhance the carbon sink in China. Among these 13.29% of vanished croplands, the converted grassland takes the largest percentage (8.3%), followed by mosaic cropland (3%) and urban land (0.98%). The mosaic cropland is defined as the mosaics of small-scale cultivation 40-60% with natural tree, shrub, or herbaceous vegetation. It indicates that some large-scale croplands are shrinkage or separated into small pieces of croplands. The rapid urbanization during 2001 and 2019 occupied some of these vanished croplands, which has no relationship with CCFP.

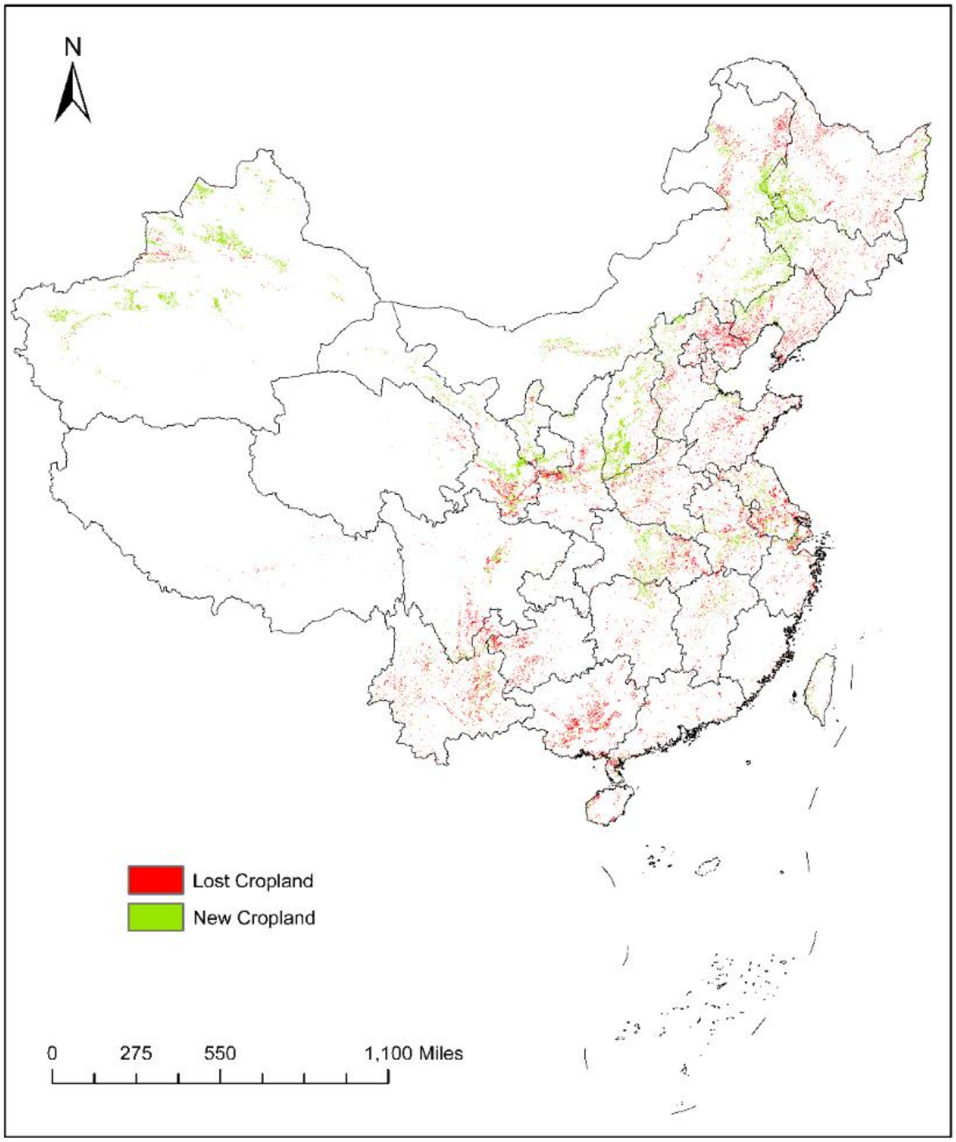

Figure 2.4 The transition of cropland in China between 2001 and 2019

Table 2.3 The percentage of converted and remained croplands in 2019 with the calculated average slope based on the data of 2001

Land types	**Percentage (%)**	**Slope**
Forest	0.25	14.92
Other wood land	0.52	9.81
Grassland	8.30	7.52
Urban land	0.98	2.04
Barren	0.01	2.20
Mosaic cropland	3.00	6.58
Wetland and water	0.13	1.89
Remained croplands	86.81%	3.71

Since one of the goals of the CCFP is to convert cropland on steep slopes and low-production into forest or grassland, the average slope of the vanished and remained croplands are calculated in Table 2.3. The top three highest slopes of converted paths from croplands include forest, other woodland, and grassland. Croplands with medium gradient of slope are not converted. Some croplands with high slope up to 6.58 shrink to small-scale farms. Most flattened cropland pieces converted to urban land with the average slope as low as 2.04.

To better understand the spatial distribution of the cropland conversion combined with the DEM variation, the vanished cropland layer is added to the ESRI Hillshade map (Fig 2.5). It shows that the converted grassland is mostly distributed in the mountainous area with higher elevation in North China. The newly generated urban land is mainly located in Beijing, Tianjin and Shanghai. The converted mosaic croplands are primarily distributed in the South China mountainous area especially in Guangxi and Guizhou provinces.

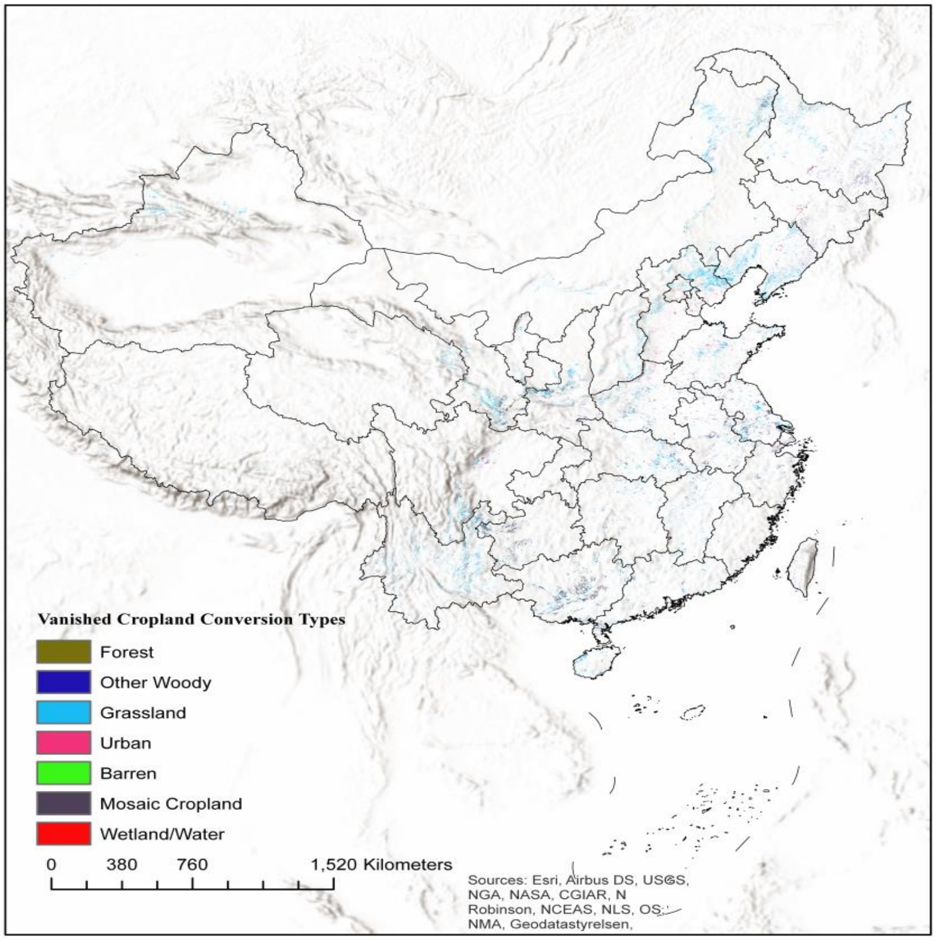

Figure 2.5 The vanished croplands converted to other types of land (e.g., forest, grassland, urban, barren, mosaic cropland etc.) shown in ESRI world Hillshade layer in 2019 compared with that of 2001

The balance between the increased carbon sink benefited from CCFP and food security is the key for the sustainability of CCFP. Food production is determined by the cropland area and cropland productivity. In this paper, the implementation of CCFP has influenced the land cover area of irrigated cropland is studied because the irrigated cropland is the main food production cropland in China. It is proved that CCFP combined with urbanization has reduced the cropland cover area, but their impacts on the irrigated cropland is still unknown. The transition detection on irrigation cropland LULC between 2001 and 2019 based on European Space Agency (ESA) LULC products is carried out and a transition matrix is generated in Table 4. The result shows that CCFP has a small impact on the decrease of irrigated croplands cover area (less than 10%), while urbanization takes about 90% of the decrease in irrigated croplands. Through the implementation of CCFP, most converted croplands are rainfed cropland, rarely irrigated cropland, and thus it has a slight impact on the crop production.

Table 2.4 The conversion of irrigated cropland between 2001 and 2019

Land Types	**Percentage (%)**
Rainfed cropland	0.00
Mosaic cropland	0.00
Forest	0.18
Other wood land	0.01
Grassland	0.18
Wetland and water	0.07
Urban land	3.43
Barren	0.02
Remained croplands	96.10

Based on the national statistics, it is proved that the crop productivity in China has significantly improved within 21 century and leads to an increasing crop production trend even with the declined cropland cover area. Here, we combined the yearly NPP with time series cropland cover area to calculate the yearly average cropland production by remote-sensing assessment in Fig.6. The result shows that the mean NPP significantly increased from 342.8 gC/m^2 in 2001 to 394.2 gC/m^2 in 2019. The same method is applied to evapotranspiration (ET) data as well, and it shows that the yearly mean ET on cropland significantly increased from 293.6 kg/m^2 in 2001 to 347.4 kg/m^2 in 2019 (see Fig.6). The growth in yearly mean NPP and ET on cropland indicates that the crops were more active and denser in agricultural units in 2019 compared with that of 2001.

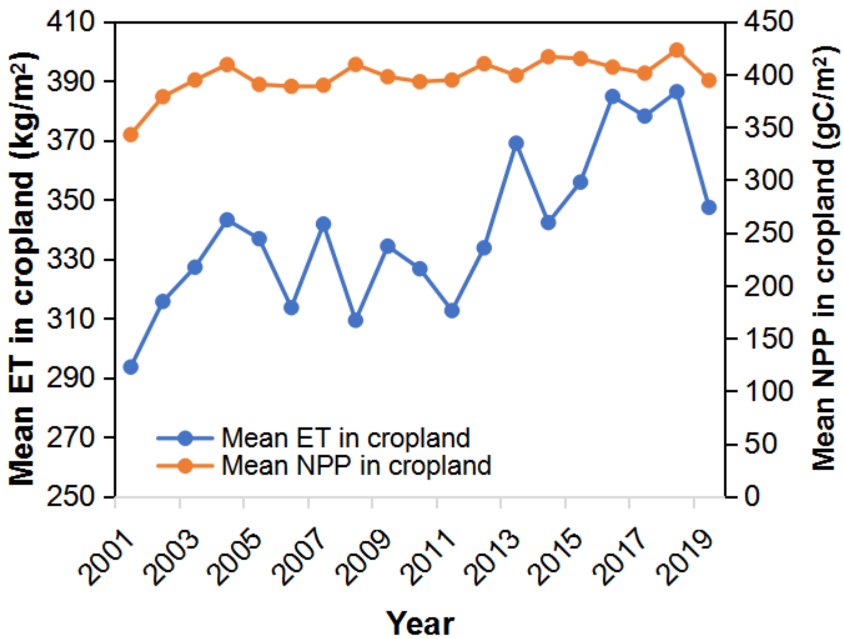

Figure 2.6 Yearly mean NPP and ET in cropland between 2001 and 2019

Therefore, the implementation of CCFP can be proved that it may not lead to food security issue because most of the vanished cropland belongs to rainfed cropland with steep slope, which will not affect the cover area of high-quality cropland like irrigated and low-sloped agricultural lands. Furthermore, based on the report of China, the total crop production has increased around 50% between 2001 and 2019, which is much faster than the population growth rate. It can be concluded that there is no food security risk caused by the CCFP.

2.3.3 Sustainability assessment of CCFP in WEF nexus

The implementation of CCFP will change the LULC that may have great impacts on different types of natural resources, especially the water resources. Except for enhancing carbon sequestration, another goal of CCFP policy is to reduce the soil erosion and improve the water storage. It is crucial to understand how the implementation of CCFP affects the water resources. The variation of cropland cover area driven by CCFP can alter the local water resource. We used the water production indicator (i.e., the precipitation minus evapotranspiration per unit area, representing the water storage capacity in the land) here to measure the trade-offs on water resources of CCFP.

We applied the precipitation and evapotranspiration data onto the converted cropland. To reduce the noise, we calculated the average water yield of 2001 and 2002 as the start point, and the average water yield of 2018 and 2019 as the endpoint. The mean water yield of each conversion land type is shown in Table 2.5. The water yield within the past two decades increased greatly in China, which may be caused by the glaciers melting driven by global warming, the increased number of man-made dams and reservoirs, and the implementation of the CCFP policy. It is found that the most obvious increase in water yield occurred during the conversion of cropland to forest. The converted wood land and grassland also result in a growth in water yield. Therefore, the CCFP can improve water storage in soil and increase the carbon sequestration simultaneously.

Table 2.5 Average annual water yield in different converted croplands

Directions	**Average water yield of 2001 and 2002 (mm)**	**Average water yield of 2018 and 2019 (mm)**
Forest	1930.793925	2552.026424
Other wood lands	590.3889883	648.6419978
Grassland	298.5884448	309.3717871
Urban land	753.9819376	1004.814147
Barren	-210.7836648	-77.0652744
Mosaic cropland	644.1336196	536.8922755
Wetland and water	1673.221434	1898.60465
Remained cropland	351.7852107	440.7938234

Due to the reduced land degradation, soil erosion, and enhanced water yield driven by various PES policies, the water resources in China have increased significantly within the past two decades. The total precipitation has a significant increased trend, see Fig.6. The permanent water surface area has risen considerably based on the analysis of satellite imagery, see Fig. 7. The flood risk is reduced by the CCFP which can stabilize the seasonal water by increasing water production

(Li et al. 2019).

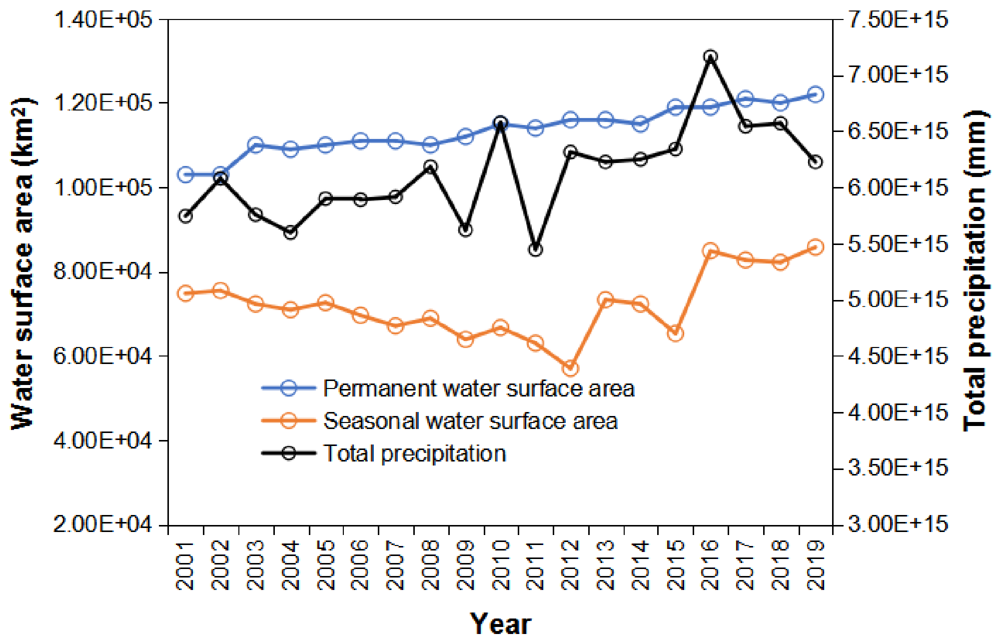

Figure 2.7 Permanent and seasonal water surface area, and total precipitation in China between 2001 and 2019

The vanished cropland by the implementation of CCFP altered the human-made resources input in agriculture at the same time. Energy input is one of the critical inputs in crop production, including the supply of agricultural machine power, fertilizer input, etc. To assess trade-offs of CCFP, it is crucial to understand the variation of energy input in the past two decades. The agricultural diesel usage has increased significantly from 14.85 Mtons in 2000 to 20.03 Mtons in 2018 (Fig 2.8). The fertilizer input in cropland has increased from 42.54 Mtons in 2000 to 54.04 Mtons in 2018 in Fig. 8. The energy input in agriculture increased fast in the past two decades in China, which is partly due to the rapid growth of economics. The converted cropland triggered productivity demand after the implementation of CCFP is another important reason. Fortunately, the dramatic growth of fertilizer input may not lead to a contradiction to carbon sequestration intention, but the manufacturing of fertilizer will release CO_2 into the atmosphere. The N fertilizer has declined significantly after 2014 (Fig 2.8). Therefore, the trade-offs of C-N to greenhouse gases are not required to be considered.

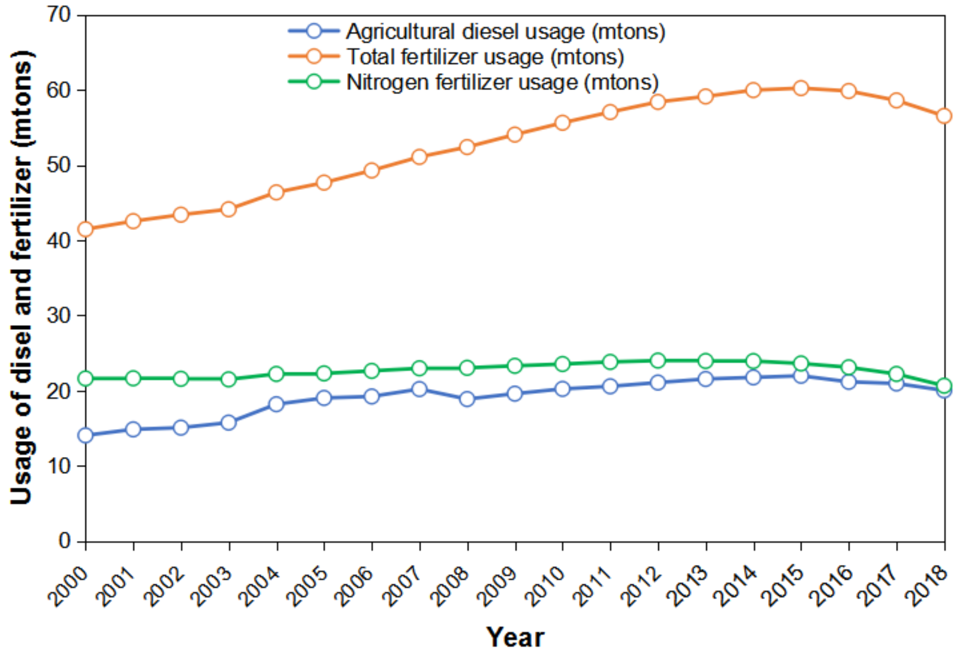

Figure 2.8 The usage of agricultural diesel, total fertilizer, and N fertilizer between 2000 and 2018 in China

The trade-off of CCFP in WEF nexus seems to be clear, showing a strong pro in Water and small cons in Food and Energy. However, the WEF nexus is an integrated resource system, and the chain effect occurs everywhere. For instance, the increased water resource results in more hydropower station in the rural area. The number of hydropower stations with the capacity less than 50,000 kW increased from 44,815 in 2010 to 46,515 in 2018 in the rural areas, and the capacity increased from 59.2 million kW in 2010 to 80.4 million kW in 2018. Increasing water resources can not only boost the generation of electrical energy, but also improve the food production by fishery. The enriched inland freshwater resource results in more aquatic production, which was doubled from 15.6 Mtons in 2001 to 32.0 Mtons in 2019. The freshwater aquatic production increased much more rapidly than the marine aquatic output, which was 22.3 Mtons in 2001 and increased up to 32.8 Mtons in 2019. More water resources can also enhance the irrigation intensity and thus improve the crop productivity. Therefore, it is concluded that the CCFP is sustainable because the pros of water production and carbon sequestration are remarkable and the cons are deductible.

The remote-sensing based assessment in CCFP analysis provides a broader view on the sustainability of CCFP in WEF nexus. Instead of dealing with the statistical numbers, it provides another perspective to evaluate the spatial distribution and slight changes caused by policy implementation. For instance, the results in this paper show that the cropland conversions are distributed at some specific locations but not all over the country. The CCFP policy implementation should be insisted based on the assessment in this paper. However, some issues need to be noticed. Firstly, there is great spatial difference in cropland conversion, showing that some provinces have very limited croplands converted. Secondly, the shrinking of large agricultural land blocks combined with the increase of small land blocks (e.g., mosaic natural vegetation and cropland) may lead to a pseudo increasing of national cropland and the food security issue. Thirdly, more carbon emission may occur when the converted land is cultivated and farmed after the subsidies stop.

2.4 Sustainability assessment of CCS/CCUS technologies in the WEF nexus and impacts on China's carbon neutrality

2.4.1 Application status of CCS/CCUS technologies in China

China started the research on CO_2-EOR technology in the 1960s in Daqing oilfield. Afterward, a series of pilot-scale CO_2-EOR projects can be found in Jilin oilfield, Dagang oilfield, Shengli oilfield and Liaohe oilfield (Liu et al. 2017; Cao et al. 2020), proving that the CO_2-EOR technology has been successful in increasing the oil recovery at different levels. The studies on CO_2-ECBM started at the end of 20th century and there is an important pilot scale project in Qinshui Basin. In 2010, the first full chain (from CO_2 capture of the coal chemical industry to CO_2 sequestration in the saline formations) CCS project with the target of 0.1 Mtons of CO_2 injection was settled in the Ordos Basin in China, and the total CO_2 storage amount was about 0.3 Mtons (Wang et al. 2018). However, the researches in the fields of CO_2-EGR, CO_2 enhanced shale gas recovery (CO_2-ESG) etc., are at the very preliminary stage (Liu et al., 2020). Until the end of 2017, about 26 projects of CCS or CCUS had been carried out in China, including 14 CO_2-EOR projects in oilfields of Daqing, Jilin, Shengli, Zhongyuan, Yanchang etc. There are also some projects related with the industrial conversion of captured CO_2 but not used for underground geological sequestration (Liu et al. 2017). However, the massive water consumption in the carbon capture process together with energy production (Li et al. 2016) sparks the controversy on potential water risk related to CCU/CCUS technologies affiliated with energy production. Therefore, the potential of water resources risks associated with the energy production and the consumption of water during the CCS/CCUS process are discussed to analyze whether the CCS/CCUS is beneficial in the energy production industry in the long term.

2.4.2 Analysis of potential water resources risks in energy production of China

Fig. 2.9 shows the total energy related water consumption mapped over regional water risk in China. Ten sectors are involved in the analysis of water consumption on energy production, including the biofuel feedstock production, energy processing including biofuels and oil, energy production including oil, gas, coal, uranium, and unconventional oil and gas, hydroelectric and thermoelectric power (Tidwell and Moreland 2016). The watershed and energy related water consumption locations have high energy-water risk. It can be seen that the northeastern China has the highest concentration of watersheds at energy-water risk. There are in total 1,630 watersheds in China, 764 of which have water risks. Regarding the energy related water consumption, there are 440 watersheds and 54% of them have energy-water risks (Tidwell and Moreland 2016). Generally, it can be concluded that China has a high risk of water consumption related with energy production. Therefore, it is suggested to mitigate the water risk related with energy production by using the technologies of CCUS, such as utilizing CO_2 for enhancing oil recovery.

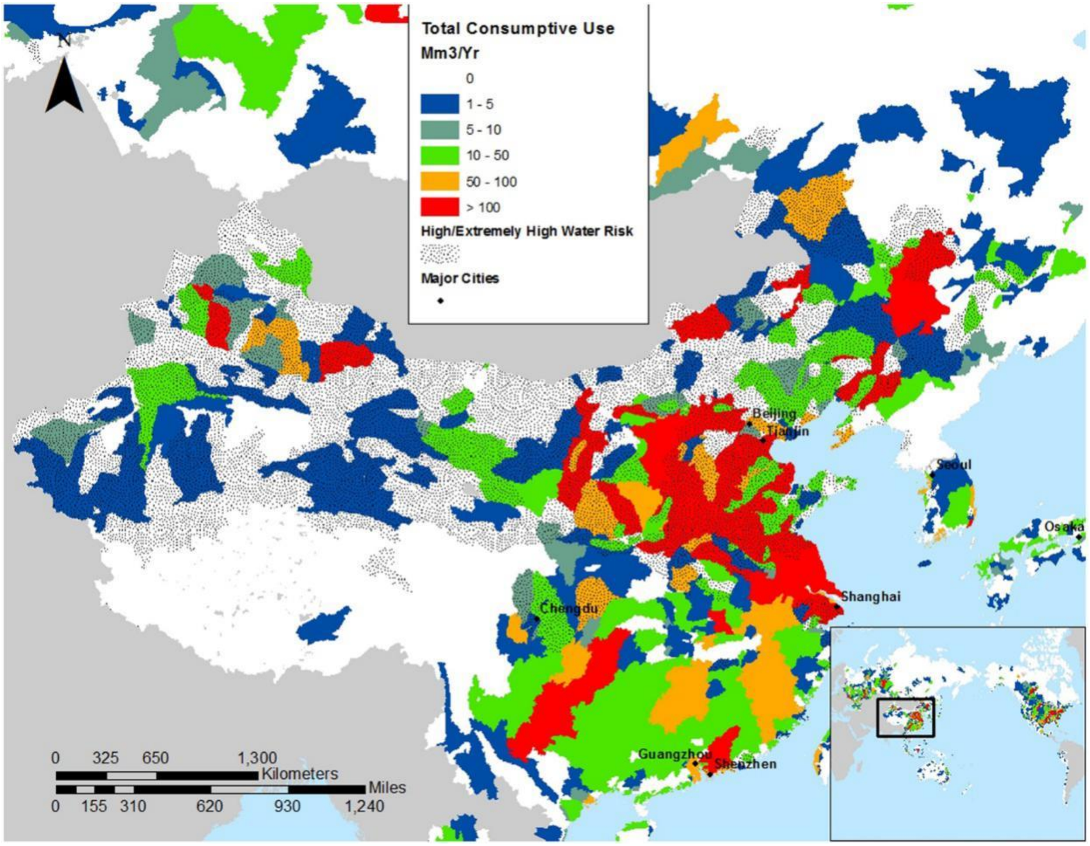

Figure 2.9 Total energy related water consumption mapped over regional water risk in China

2.4.3 Water consumption in CO_2 capture process

The fossil fuel based power plant is a main source of CO_2 emissions. Fig. 2.10 presents the water consumption in four kinds of fossil fuel power plants with and without CO_2 capture process, including subcritical and supercritical pulverized coal-fired (PC) power plants, integrated gasification combined cycle (IGCC), and natural gas fired combined cycle (NGCC). It shows that the water consumption increases 31%~91% when CO_2 capture is implemented. Therefore, the CO_2 capture is the largest contributor to water consumption during the processes of CCS/CCUS. Actually, the cost of CCS technology is also dominated by the process of CO_2 capture and gas separation, which is about \$55 to \$112 per ton of CO_2 (Gislason et al. 2014). In order to decrease the energy and water consumption, it is suggested to make use of the waste heat through heating water. After that, the heated water can be used for power generation. In this way, the emission of water vapor and overall water consumption can be reduced.

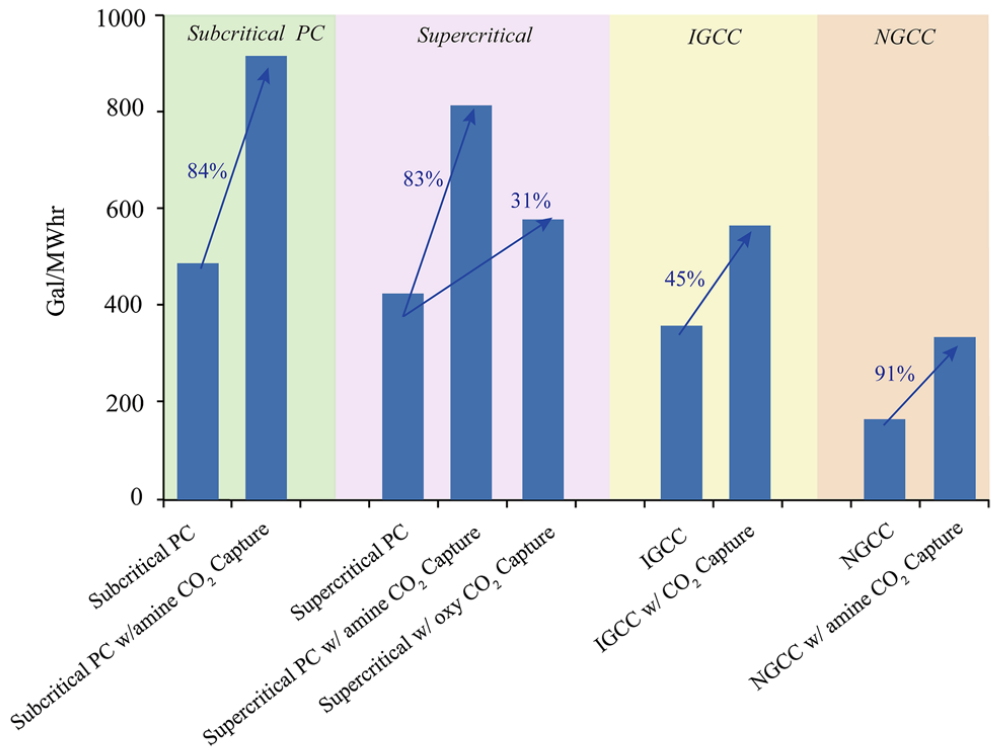

Figure 2.10 Water consumption in fossil fuel based power plants with and without different types of CO2 capture technologies (Li et al. 2016)

2.4.4 Water consumption in CO_2 utilization process

CO_2 can be used to enhance water recovery (CO_2-EWR). The Gorgon CCUS project located in the northwest of Australia is an example to illustrate the water consumption of CO_2-EWR. There are two periods in this project, including the construction period from 2010 to 2015 and the operation period from 2015 to 2050. In the life cycle of the Gorgon project, more than 120 Mtonsof CO_2 will be injected into the Jurassic saline reservoir at a rate of about 3.8 Mtonsper year. Meanwhile, four pumping wells are implemented to manage the formation pressure and produce saline water to meet the demand of water consumption during the life cycle of this project (Flett et al. 2008). The water consumption and supply during the construction and operation phases are shown in Fig. 2.11 (Li et al. 2016). It can be seen that the water consumption is very high at the beginning of construction, and the water supply cannot meet the demand, which is obtained from the treated wastewater and the saline water with a reverse osmosis (RO) process. While the water consumption is decreased and can be meet by water supply during the rest construction and operation periods. For example, the total of potable and service water demand is 960 m^3/d, while the water supply is approximately 1,500 m^3/d in the operation phase. Therefore, it can be calculated that about 6.9 million m^3 of net water can be attained during the 35 years of operation. Generally, it can be concluded that CO_2-EWR is an efficient strategy to produce water and store CO_2 simultaneously.

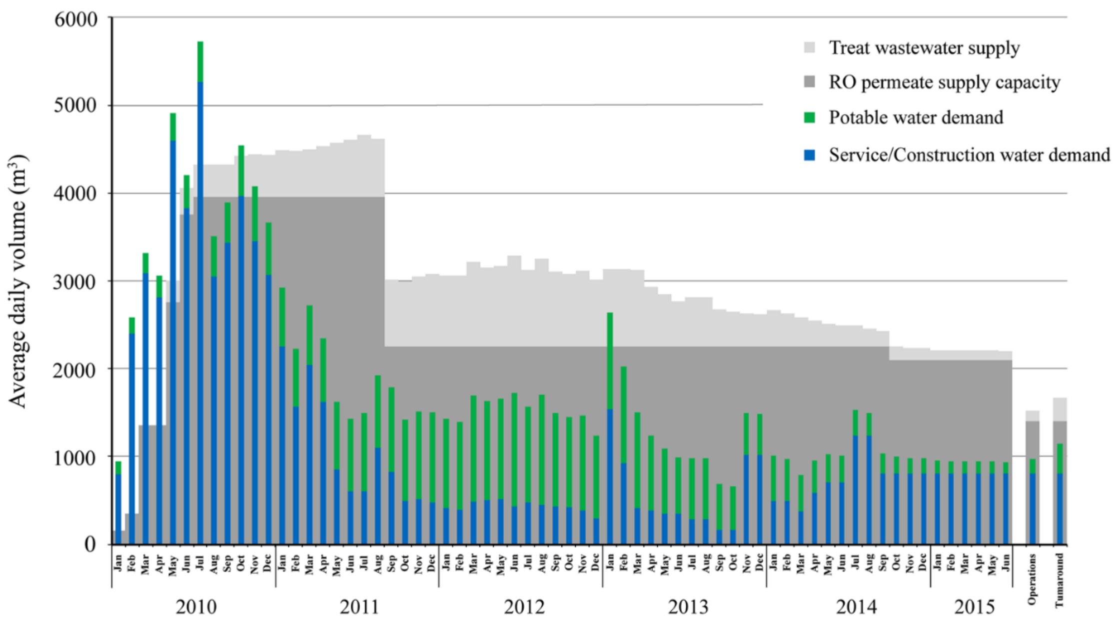

Figure 2.11 Water consumption in Gorgon project (Li et al. 2016)

2.4.5 Water consumption related with energy production and potential application of CCUS

Based on the fuel production categories with water consumption factors estimated by Spang et al. (2014), the water consumption related with the energy production in China can be calculated in Table 2.6. The total water consumption related to energy production in China is 4.93 billion m^3, which is dominated by coal production followed by oil production, with the water consumption of 4.19 billion m^3 and 0.702 billion m^3, respectively. It should be pointed out that the ratio of shale gas production to conventional gas production is 11.6%, while the water consumption of shale gas is about half of the conventional gas, which illustrates that abundant water is consumed during the hydraulic fracturing process in the exploitation of shale gas.

The exploitation of shale gas usually consumes large amounts of water resources in hydraulic fracturing, which is necessary in the ultra-low permeability of shale reservoir. It is reported that the water consumption in the Marcellus shale gas reservoir is about 20,000 m^3 per well over the whole life cycle, in which 65% of water is consumed at the well site and 35% of water is consumed across the water supply chain (Jiang et al. 2014). The water consumption across the life cycle of a shale well is shown in Fig. 2.12. It can be seen that the water consumption, especially the direct consumption of fracturing fluids is the dominated part in shale gas production.

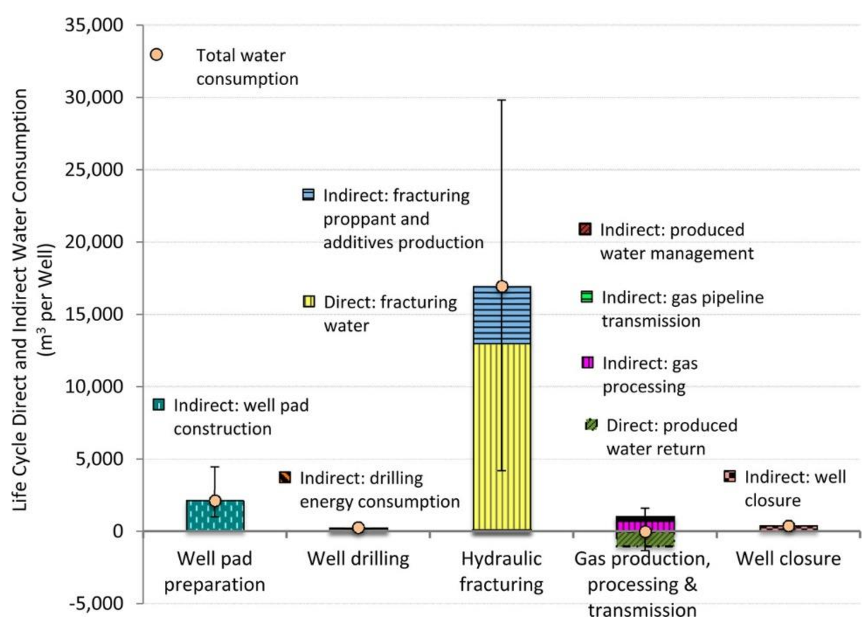

Figure 2.12 Estimated water consumption for a shale gas well. Error bars represent the limit of 90% confidence intervals of water consumption from each life cycle (Jiang et al. 2014)

Table 2.6 Water consumption related with fossil fuel energy production in China

Energy category	Water consumption factor (m^3/GJ)			China output in 2020	Heat values (MJ/kg)	Average water consumption (billion m^3)
	Spang et al. 2014			National Bureau of Statistics 2021	World Nuclear Association 2021	Calculated
	Min	Max	Mean			
Coal	0.006	0.242	0.043	3.9 billion tons	ca. 25 (25)	4.19
Conventional oil	0.036	0.14	0.081	0.195 billion tons	42~47 (44.5)	0.702
Conventional gas	0.001	0.027	0.004	172 billion m^3	42~55 (48.5)	0.0239
Shale gas	0.003	0.221	0.017	20 billion m^3	42~55 (48.5)	0.0118
Total						**4.93**

China has the largest shale gas reserves in the world, with a cumulative proved reserve of more than 6.5 trillion m^3 estimated at the end of 2019. While the exploitation of shale gas in China is still at the primary period, with a production of only 20.04 billion m^3 in 2020, which is far less than that of the USA. Due to the high external dependence of oil and natural gas in China, i.e., 70.8% for oil and 43% for natural gas in 2019, to enhance the domestic oil and gas development is the basic energy strategy in China. Therefore, it can be inferred that the water consumption would increase dramatically with the large-scale exploitation of shale gas in China (Zhou et al., 2019), which may lead to high water risk. To address this problem, it is suggested to use CO_2 as working fluid for hydraulic fracturing in shale gas production. If the CO_2 fracturing technology is implemented, the water consumption will be greatly decreased.

2.4.6 Sustainability of CCUS in coal-based power plants and impacts on WEF system

The water consumption of power plant with and without consideration of CCUS will be investigated based on a typical coal-based power plant in the central of China (Liu and Zhai 2014). The installed capacity of the power plant is 630 MW. In 2013, the standard coal equivalent consumed by the power plant is 1,916,242.87 tons, with the power generation of 4,010.57 million kWh and the CO_2 emission of 3,616,269.76 tons, in which 3,600,333.76 tons of CO_2 is produced during the process of stationary coal combustion and 15,936 tons of CO_2 is produced during the process of desulfurization.

The CO_2 captured from the power plant can be used as an alternative fluid for fracturing. Based on the aforementioned discussion, the water consumption in hydraulic fracturing dominates the overall water consumption in shale gas or unconventional oil or gas production. Regarding the CO_2-based hydraulic fluids, the water is only consumed at the initial compression period, which is much less than that of water-based hydraulic fluids. Generally, compared to conventional water-based hydraulic fracturing, the water consumption can be decreased by 80% per unit energy production when the CO_2-based fracturing is implemented (Wilkins et al. 2016). According to Liao et al. (2020), the permeability of hydraulic fractures generated by water and CO_2 with the same injection mass can be comparable. Thus, 3,600,333.76 tons of water can be saved if the CO_2 captured from the coal power plant is utilized in reservoir stimulation. It should be pointed out that the impact of CO_2 storage on water consumption is negligible, but it can save a large amount of water by replacing the traditional water-based fracturing technology. Generally, the water consumption of the power plant with and without consideration of CCUS is shown in Fig. 2.13.

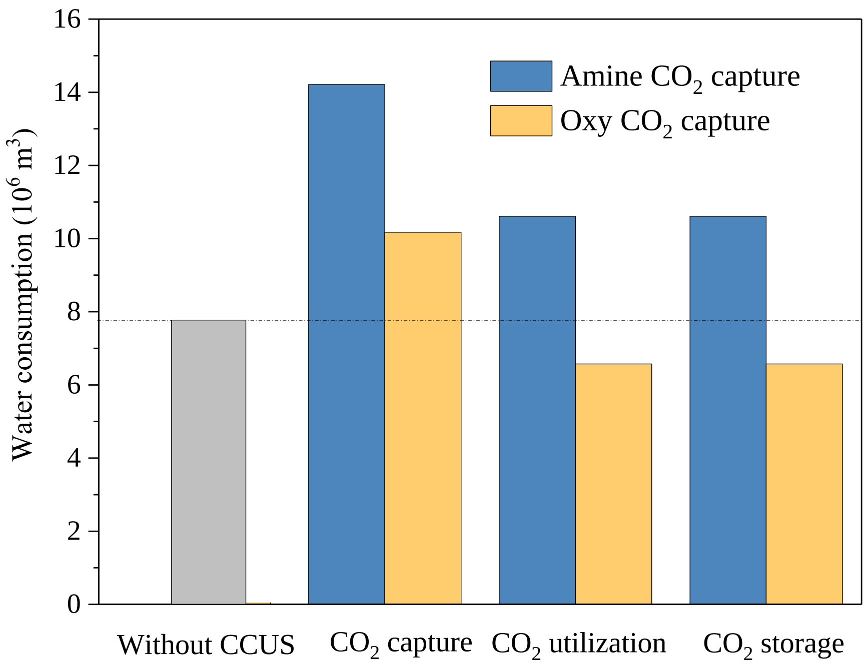

Figure 2.13 Water consumption per year of the 630 MW power plant with and without consideration of CCUS

Different types of CO_2 capture technology have great impacts on the water consumption. It shows that the overall water consumption increases by 2.84 million m^3 per year when the amine-based solvents is applied to separate CO_2. However, the water consumption reduces by 1.19 million m^3 per year when the oxyfuel capture method is used. China has the largest installed capacity of coal-based power stations in the world, which is 1.095 billion kW at the end of 2020, meaning that about 20.73 billion m^3 of water consumption can be reduced per year if the CCUS technologies are implemented for all coal power plants in China. It can be inferred that the energy can be produced in some regions that are lack of water. The CCUS technologies can not only reduce the water consumption but also increase the energy production.

Based on the water consumption factor of oil (Spang et al. 2014), it can be calculated that the saved water due to the utilization of CCUS in the 630 MW power plant per year can generate 330 thousand tons of oil (i.e., equivalent to 14.7 million GJ of energy). Considering that the food can be linked to energy through the utilization of food crops as feedstock for biofuel production, the produced energy caused by the utilization of CCUS can decrease the consumption of food. Furthermore, the water consumption of biofuel production can be saved. For instance, considering that the water consumption for the generation of ethanol is 41.8 ~124.8 m^3/GJ (Rulli et al. 2016), it can be calculated that additional 0.614~1.83 billion m^3 of water can be saved with the utilization of CCUS.

It should be mentioned that the CO_2-based fracturing technology has great advantage than that of water-based case in water saving but requires much more energy consumption (Wilkins et al. 2016). This is caused by the compression and separation of CO_2 in the power plants, and the incremental energy required for CO_2 transportation phase. With the development of CO_2 fracturing technology, it can potentially achieve a lower net energy consumption.

Simultaneously, the injected CO_2 can be sequestrated during the CO_2 fracturing process, which is beneficial for mitigating atmospheric CO_2 emissions and protecting the environment. In comparison with CCUS, the CCS technologies can contribute to much more geological CO_2 sequestration due to the widespread feasibility targeted for China's carbon neutrality by 2060. China has been the largest emitter of CO_2 since 2006, currently responsible for approximately 28% (net equivalent CO_2 emission of 9.8 billion tons = gross equivalent CO_2 emission of 14.2 billion tons – CO_2 sink of 4.4 billion tons) of global CO_2 emissions in 2019. President Xi Jinping stated on 22 September 2020 that China intends to peak equivalent CO_2 emissions before 2030 and then to move to carbon neutrality by 2060. The estimated peak of net equivalent CO_2 emissions before 2030 is about 11.0 billion tons. It is very difficult to achieve the carbon neutrality target by 2060 without widespread application of CCS/CCUS technologies for geological sequestration of CO_2, and the sustainable implementation of CCFP and other PES policies in 2019-2060.

2.5 Conclusions

In this paper, the sustainability of two typical carbon sequestration pathways (CCS/CCUS and CCFP) is analyzed and evaluated by WEF nexus in context of China's carbon neutrality by 2060. Some conclusions can be drawn as follows:

1) The implementation of CCFP policy has led to the decrease in the cropland in China but no food security issue emerges because CCFP has small effect on the decreases of irrigated croplands cover area (less than 10%), while 90% of the decrease in irrigated croplands is induced by urbanization.

2) A sustainable implementation of CCFP and other PES policies in 2019-2060 could reach an estimated total growth of 7.462 billion m^3 in comparison of that in 2018 and the total plantation forest stock of about 10.852 billion m^3 in 2060, with a corresponding minimum CO_2 sink of 2.90 billion tons in 2060.

3) Different types of CO_2 capture methods have significant impacts on the water consumption. The overall water consumption increases by 2.84 million m^3 per year when the amine-based solvents to separate CO_2 method is used. However, the water consumption reduces by 1.19 million m^3 per year when the oxygen-enriched combustion capture method is used in China.

4) More energy may be produced from the shale gas, oil and natural gas reservoirs with the utilization of CCUS when the water is replaced by CO_2, which is especially applicable for the regions facing lack of water resources. Furthermore, the consumption of food can be reduced due to the decreased demand of biofuel production. Overall, the utilization of CCS/CCUS can be beneficial for WEF and China's carbon neutrality by 2060.

5) The integrated impacts of CCFP and CCS/CCUS on water, food and energy resources are understood by WEF nexus assessment, implying that the trade-off is acceptable. The geological

CO_2 sequestration through the large-scale application of the CCS/CCUS technologies CCS/CCUS as well as the CO_2 natural sink through the sustainable implementation of CCFP and other PES policies in 2019-2060 are necessary and play a decided roll for China's carbon neutrality by 2060.

APPENDIX

Summary of the published article for this dissertation

The global warming induced by the emission of greenhouse gases, especially the carbon dioxide, has become the global climate and environmental issues. China has been working in the CO_2 emission reduction and carbon sinks with the purpose of becoming the carbon-neutral country by 2060. The reforestation efforts represented by the Conversion of Cropland to Forestland Program (CCFP) have great potential for sinking CO_2 emission. However, the tradeoffs of CCFP in Water-Energy-Food (WEF) nexus are not well evaluated. In this paper, the remote-sensing data are collected and used to evaluate the sustainability of CCFP by analyzing the variation of land use and land cover (LULC), crop production, etc. The results show that 13.29% of the cropland in 2001 vanished and converted to grassland (8.3%), mosaic cropland (3%) and urban land (0.98%) in 2019. However, the converted cropland parcels have much sharper slope than those remained cropland, and the transition matrix of irrigation cropland shows most of the irrigation lost are related to urbanization. The increasing water resource and related rural hydro power development illustrated by the highly increased water yield in forest and grassland that converted from cropland demonstrating that the CCFP is successful in both WEF nexus and carbon sink. The total crop production has increased around 50% between 2001 and 2019, implying that the CCFP will not lead to the food risk during the conversion of croplands into other types of land in China.

A sustainable implementation of CCFP and other environmental Payments for Ecosystem Services (PES) policies in 2019－2060 could reach an estimated total growth of 7.462 billion m^3 in comparison of that in 2018 and the total plantation forest stock of about 10.852 billion m^3 in 2060, with a corresponding minimum CO_2 sink of 2.90 billion tons in 2060. CCFP are two decided pathways of carbon sequestration and should be systematically applied to achieve China's carbon neutrality by 2060.

Note

The content and information summarized in Chapter 2 have been published in an open-source peer-reviewed journal (i.e., *Environmental Earth Sciences*) in 2021, According to the journal's copyright policy, the publication the publication could be reused and quoted in the dissertation as the author retains the copyright. The article can be found and viewed using the citation below.

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3. CHAPTER 3: A DIAGNOSTIC APPROACH TO ASSESS WATER-ENERGY-FOOD TRADEOFFS OF HYDRO DAMS IN THE MEKONG RIVER BASIN

Abstract

Efforts have been made to develop renewable energies to mitigate climate change, including hydropower dams to generate electricity from potential and kinetic energy in rivers. However, there have been ongoing debates regarding tradeoffs of hydropower dams with other ecosystem services such as water and food security. Yet, it is still unclear how the hydropower dams benefit or impact the water-energy-food systems. In this study, we developed a diagnostic approach to quantitatively assess tradeoffs of hydro dams in the Mekong River Basin, using remotely sensed data and dam construction information. We provided statistical evidence of the benefits and tradeoffs of water, energy, food, economic prosperity, and the environment surrounding hydro dams. It was statistically clear that hydro dams enhanced water resources availability but did not bring obvious benefits to food production. Croplands within watersheds with dams have declined compared to those without dams, and there is little evidence to show a crop yield increase believed to be associated with dam-enabled and -enhanced irrigation. Further, there is no substantial evidence to indicate that the environment, measured by the greenness, within the watersheds with dams were degraded either. The developed approach thus provided quantitative measures of tradeoffs of hydro dams and can be generalized to address similar debates in other watersheds or basins.

Keywords: Hydropower dam; Water-energy-food nexus; Mekong River Basin; Remote sensing

3.1 Introduction

Climate change, particularly global warming, constitutes an unambiguous threat to the planet sustainability (Root et al., 2003; Oouchi et al., 2006), and greenhouse gas (GHG) emissions from the burning of traditional fossil fuels are believed to be one of the underlying causes (Lashof et al., 1990; Meinshausen et al., 2009). Developing renewable energy to reduce GHG emissions and reach carbon neutrality goals is thus an urgent task to mitigate further escalation of climate extremes (Masson-Delmotte et al., 2021; Menanteau et al., 2003). Renewable energy development has consequently been accelerated in the past two decades by expanding green energy resources and introducing technological innovations worldwide (Lund 2007).

Hydropower is one of the most ancient and efficient clean energy resources, playing a vital role in renewable energy innovation. It accounts for 71% of the global renewable electricity supplies (Padilla & Hudson, 2019). Hydropower development has long been framed positively for economic growth, clean energy production, and poverty alleviation (Williams 2020). As a result, more than 9000 large hydropower dams have been constructed worldwide (ICOLD 2021). These dams fulfill the growing energy demands driven by the rapidly increasing global population and energy consumption patterns (Kaygusuz 2004). They also play an essential role in lowering carbon emissions by supplying more than 71% of the global renewable energy as of 2016, which will increase by 2040 (Conti et al., 2016).

Hydropower dams' physical structures and water regulations reduce climate-related hazards by providing flood control (Zsuffa 1999; Sahin et al., 2017) and drought mitigation (Rossi et al., 2005). In addition to these benefits, dams can also benefit water supplies (Kornijów 2009) and regional water resource management (Yang et al., 2015) by reserving freshwater in reservoirs as a hydrological buffer to mitigate floods and droughts (Brown & Lall 2006). Hydropower dams and reservoirs also benefit irrigation by making water available during the low-flow period of the year, especially in monsoon regions of the world (Räsänen et al., 2018; Lacombe et al, 2014). Hydropower dams also synergize with wind and solar energy (Wang et al., 2019; Bhandari et al., 2014; Martínez-Jaramillo et al., 2020) by sharing and transferring water and profits between hydropower and irrigation systems (Tilmant et al., 2009; Zeng et al., 2017; Chatterjee et al., 1998).

The benefits of hydropower dams are unquestionable, but they also have negative impacts from the sustainability perspective (McNally et al. 2009; Liu et al., 2013; Tahseen & Karney 2013; Moran et al., 2018). The reservoirs associated with hydropower dams can produce large amounts of GHG, including methane, carbon dioxide, and nitrous oxide (Räsänen et al., 2018), and quantitative assessments confirm that the environment and ecosystem services suffer the most from hydropower dams (Wang et al., 2010; Briones-Hidrovo et al., 2019; Vogl et al., 2016). Hydropower dams and reservoir constructions subsequently trigger land use and cover changes, including cropland conversion and land degradation, especially forest loss (Zhao et al., 2010; Qi et al., 2012; Guerrero et al., 2020). Intensified water competition between irrigated agriculture and hydropower, both downstream and upstream, can even lead to human-triggered disasters such as the desiccation of the Aral Sea (Cai et al., 2003) and the Usangu basin (Machibya et al., 2003).

Large hydropower dams also alter river flow patterns, stream water quality, and water residence time (Soulsby et al., 2015; Pokhrel et al., 2018; Hecht et al., 2019). These process alterations undermine aquatic biodiversity and fish habitats by disrupting flows, changing sediment loading, and blocking fish migration routes (Golden et al., 2019; Yoshida et al., 2020). Environmental quality, aesthetic values, cultural heritage, and local landscape characteristics are ultimately degraded (Pinho et al., 2007; Botelho et al., 2017; Bakken et al., 2012) as biodiversity and natural habitats are permanently altered (Lees et al., 2016; Lange et al., 2018; O’Hanley et al., 2020).

Acknowledging these adverse environmental impacts, developed nations in Europe and North America stopped building large dams at the end of the last century (Moran et al., 2018). In contrast, hydropower dam constructions increased significantly in Asia and South America, where economic benefits are perceived to outweigh environmental concerns. Nowhere is this trend more evident than in the Mekong River Basin (MRB) (Grumbine et al., 2012), where 177 hydropower dams had been constructed as of 2017 (WLE 2017). Rapidly growing, impoverished communities in this region have traditionally been very vulnerable to natural and ecological disasters (Mainuddin et al., 2010), and dam construction is believed to exacerbate the situation (Vaidyanathan 2011). Debates regarding the benefits and tradeoffs of hydropower dams in the MRB have consequently raged in recent years, involving different sectors, industries, countries, and local and worldwide organizations.

The water, food and energy resources are most crucial to human's wellbeing, and the related issues are important to the sustainability of MRB. Hydropower development is bunded to have implications for water and food systems in the basin, as there is a complex nexus among the water-energy-food (WEF) systems. The WEF Nexus framework (Bazilian et al., 2011) was proposed about ten years ago to suggest that the three are interconnected and must be considered together as a system to avoid tradeoffs and achieve synergies. The framework has thus been considered the most unbiased approach for sustainability assessment and has been applied in various disciplines, including environmental management, economics, social science, geospatial study, hydrological modeling, food, and energy systems (Albrecht et al., 2018).

The Nexus framework was shown to be a practical approach to assessing the impacts of hydropower dam construction in many countries such as Ethiopia (Gebreyes et al., 2020), Nepal (Dhaubanjar et al., 2017), and China (Si et al., 2019). In particular, the framework has been used to examine hydropower development impacts in the Mekong studies (Foran 2015; Räsänen et al., 2015; Zhang et al., 2018). However, these studies in the region, were restricted to either a single aspect of the WEF problems or case studies of one or a few dams (Green et al., 2020; Bussi et al., 2021). Further, most of them focused on transboundary governance issues of the entire dammed basin or some specific sub-watersheds (Piman et al., 2015; Wild et al., 2019). There is a lack of holistic assessment of the benefits and tradeoffs of hydro dams across the entire MRB to discern the impacts of hydro dams from other drivers on WEF sustainability. In this study, we developed a diagnostic approach and used key WEF system indicators (attributes) to quantitatively assess the tradeoffs of hydro dams under the WEF nexus framework within the entire MRB.

3.2 Materials and methods

3.2.1 Study area

The MRB, including the Mekong River mainstream and its tributaries, drains an area of approximately 795,000 km^2 of portions of China, Cambodia, Lao PDR, Myanmar, Thailand, and Vietnam. The river originates in the Qinghai plateau of China, forms the broad Mekong delta in Vietnam, and discharges an annual mean of 14,500 m^3/s water (Want et al., 2017) into the South China Sea. The growing population and increasing human activities within the MRB—especially dam construction (Pokhrel et al., 2018; Endo et al., 2020), combined with the monsoon climate, have raised serious concerns about the WEF sustainability issues (Gallagher et al., 2020; Keskinen et al., 2015).

The entire MRB is further divided into small or sub-watersheds, based on the basin's topography, hydrological and geographical characteristics, without considering the administrative boundaries. Information about these small watersheds (Fig. 3.1) was obtained from the WaterBase project (George et al., 2007) and each small watershed was used as the unit of analysis. There are 199 small watersheds within the MRB, each corresponding to an observation in this study with or without hydro dams.

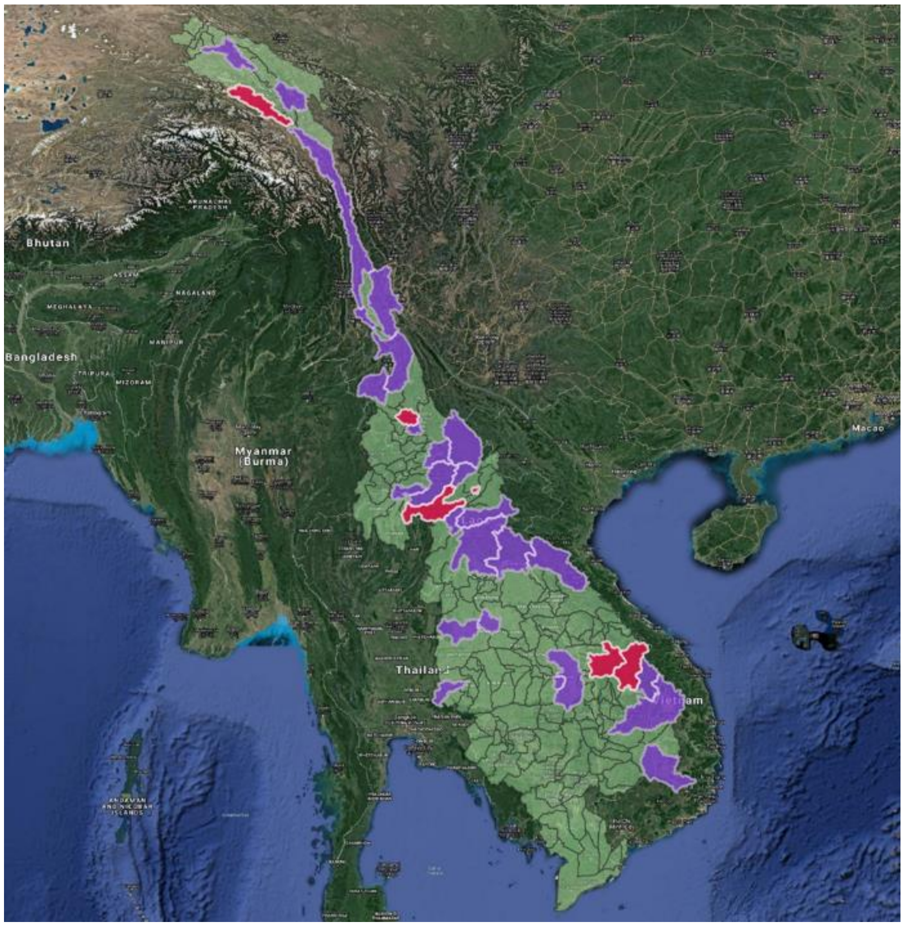

Figure 3.1 The 199 watersheds in MRB. The 32 watersheds with dams are shown in violet and those of the 167 watersheds with no dams are shown in teal. Six watersheds have only one dam constructed between 2001 and 2017 and they are shown in red.

There were 100 hydropower dams in operation in the MRB as of 2017 (WLE 2017) and they are in 32 of the 199 small watersheds. The watersheds within which there are hydro dams are termed the treatment group, whereas those that do not have hydro dams are termed the control group. Therefore, there are 32 watersheds in the treatment group and consequently, there are 167 small watersheds in the control group (Fig. 3.1). Of the 100 hydropower dams, 52 were built after 2001, and only 77 had commission date information. There are six (6) watersheds that contain only one recently built dam (Fig 3.1), which are numbered #13, #31, #60, #61, #110, and #111 and they were built in 2004, 2014, 2014, 2016, 2015, and 2009, respectively.

3.2.2 A diagnostic approach

The WEF-based diagnostic approach (Fig. 3.2) was developed in this study to test the impacts of hydropower dams on key WEF indicators. We first divided the watersheds within the MRB into two groups: 1) watersheds with dams (WWD) and 2) watersheds without dams (WWOD). From the WWD group, we selected six (6) watersheds where dams were built in the middle of our study period, thus allowing us to examine changes in WEF indicators before and after dam construction. This design allowed us to perform two types of diagnostic analyses. The first analytical pathway compares the 32 (WWD) watersheds with and the 167 (WWOD) watersheds without hydropower dams, which can be viewed as an analysis in the spatial domain. The second pathway compares WEF trajectories before and after dam construction for the six (6) watersheds where just one dam was constructed during 2001 to 2017. This analysis can be viewed as a temporal domain assessment. These comparisons facilitate quantitative analysis of the benefits and tradeoffs of hydropower dams within the entire MRB. The watersheds with dams are considered the treatment group, or WWD, and those without dams as the control group, or WWOD.

A set of key WEF, environment and socioeconomic indicators was selected to assess the Local impacts of dam construction on WEF sustainability. Surface water is the most important water resource in the MRB and is critical for human activities (Potsel et al., 1996); permanent and seasonal water surface areas were consequently used as sustainability indicators. Cropland is a straightforward measurement of food production, and the amount of irrigation provides additional information because it usually results in higher crop productivity than rainfed cropland

(Hussain et al., 2006). Net primary productivity (NPP), the accumulation of energy in plant biomass, is a well-known indicator of cropland productivity (Lobell et al., 2002). Since agriculture production has a linear relationship with cropland area and productivity, the percentage of cropland area, irrigated cropland area, and NPP of cropland were consequently used as food sustainability indicators.

We used population density to represent the intensity of human activity, a proxy for economic development and thus the socioeconomic perspective. The percentage of urban land cover and its change rate is included as a second indicator of economic prosperity (Seto et al., 2011). Total precipitation, average temperature, and mean enhanced vegetation index (EVI) were selected as climate and environmental sustainability indicators.

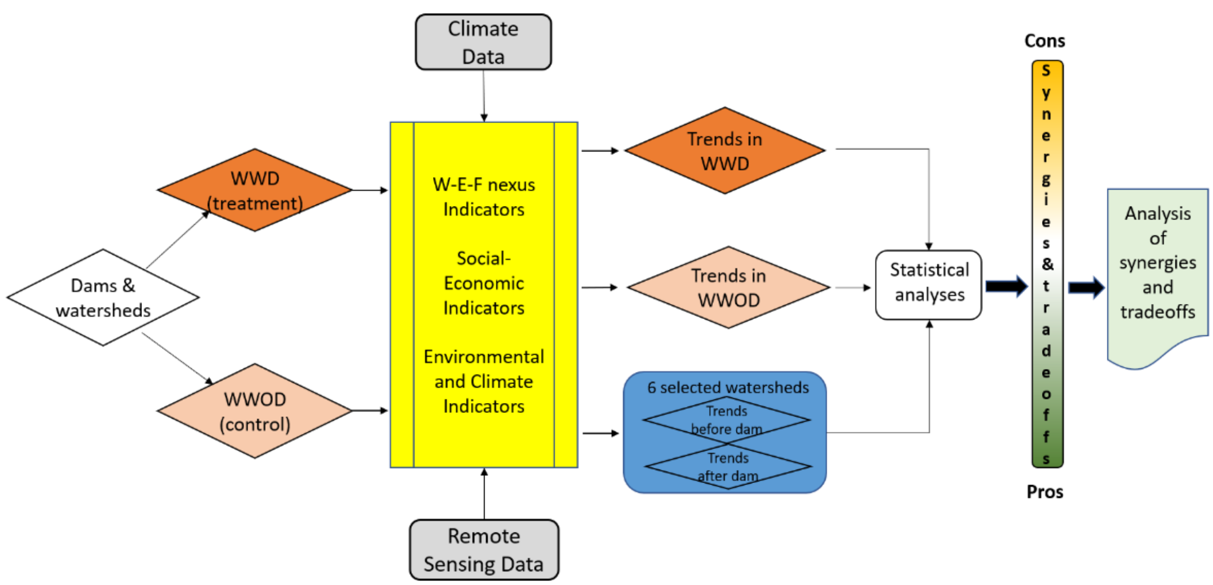

Figure 3.2 Flow chart of the WEF-based diagnostic approach used to assess the synergies and tradeoffs of hydropower dams in the Mekong River Basin.

3.2.3 Data sources

The key WEF indicators were derived from remotely sensed data and products used in this study. To better observe the long-term impact on a large scale, this study utilized global data covering the last two decades. Annual cropland and urban land percentages were derived from the yearly land use and land cover (LULC) classification product of the MODIS dataset (Friedl & Sulla-Menashe 2021). The cropland NPP data (Running and Zhao 2021) were extracted from MODIS products first and then masked by the cropland layer information to obtain agricultural productivity. The MODIS 16-day EVI products were used to calculate the average EVI each year as an indicator of the environmental conditions in the region. Similarly, annual mean temperature values were calculated from the average of 8-day global land surface temperature and emissivity data (MOD11A2) for any given year (Wan et al., 2021). Irrigated land information was extracted from the European Space Agency Climate Change Initiative (ESACCI) product (Defourny et al., 2012), and permanent and seasonal water surface area was extracted from the Joint Research Center (JRC) yearly water classification data (Pekel et al., 2016). Precipitation data were derived from Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data with a 0.05 arc degree spatial resolution (Funk et al., 2015), from which an annual precipitation time series dataset was generated. The LandScan population data (Dobson et al., 2000) were used to calculate the population density.

3.2.4 Statistical analysis

There are multiple methods for time series analysis, but many of them are based on parametric assumptions. Most of the time-series data obtained from satellite imagery are nevertheless non-parametric (Alcaraz - Segura et al., 2010), and thus the Mann-Kendall (MK) trend test and Sen’s slope (Hamed & Rao 1998) have been widely used as a powerful analytical tool for trend detection in time series data in sustainability and hydrology studies (Mondal & Kunku 2012). The MK test was used to measure the monotonic change tendency for each WEF indicator in all watersheds and adopted a “no change” in a time series as the null hypothesis.

Tests were first applied to all watersheds for all indicators. Further tests were applied to detect trend changes before and after the dam commission date for all six (6) watersheds where there was only one newly built dam within each watershed.

The p-value and the tau (t) test statistics are tabulated for further analyses. The Kendall's tau (t) value ranges in theory from -1 to 1 and its direction and magnitude are analogous to the trend coefficient in traditional regression analysis (Sen 1968). Positive and negative values of tau (t) indicate increasing and decreasing trends, respectively, and the magnitude values in either direction indicate the strength of the trend. We used the mean value to represent an indicator's change direction and magnitude for treatment and control group watersheds.

Examination of differences in these statistics between the WWOD control group and the WWD treatment group was necessary to ensure no bias in the groupings. Two-sample tests for different means were consequently applied to test two hypotheses: (i) temporally, there are no significant differences in the average values and distributions of indicators in the WEF system in the study area between WWD and WWOD watersheds, and (ii) there are no significant differences in monotonic trends between treatment and control groups. Two non-parametric tests, the Kolmogorov-Smirnov test (Skakun et al., 2014) and Mann-Whitney test (Berryman et al., 1998), and one parametric test, the student T-test (Kim 2015), were employed to test the difference in means and distributions between two groups.

The MK trend test was applied to all watershed's WEF indicators to determine their temporal trends. For each specific indicator in each watershed, a tau (t) value and a p-value were tabulated for analysis. Watersheds with a p-value greater than or equal to a significance level of 0.05 were considered no change, whereas those with p-values smaller than 0.05 were considered to have had changed. The numbers of watersheds with an increasing or decreasing trend from both groups were counted and their percentages within each group were calculated. The mean value of tau (t) represents the average trend magnitude. These tests were also applied to the six (6) watersheds with only one dam built within the study period to test the trends before and after the dam commission dates.

3.3 Results

3.3.1 Water implications

The construction of hydropower dams and the associated land-use changes significantly impacted the local water resources. The statistical significance test results (Table 3.1) suggest that the watersheds with hydropower dams have a smaller percentage of permanent and seasonal water surface area than those without hydropower dams. However, the monotonic trend results indicated a rapid, time-dependent increase in permanent and seasonal water surface areas following the construction of dams. Dams consequently increased the availability of water resources in the basins where they are located. This is understandable because as dams are constructed, water accumulates to form reservoirs, thus increasing water surface areas and volumes.

Table 3.1 Significance test results in permanent water surface area and seasonal water surface area percentages between WWD and WWOD groups.

Significance test	**Mean**	**Kolmogorov-Smirnov test p**	**t-test p**	**Mann-Whitney test p**
Permanent water surface area in WWD	0.6%	*0.437*	0.130	0.752
Permanent water surface area in WWOD	1.4%			
Tau of Permanent water surface area change in WWD	0.433	<0.001*	<0.001*	<0.001*
Tau of Permanent water surface area change in WWOD	0.175			
Seasonal water surface area in WWD	0.5%	0.028*	0.012*	0.041*
Seasonal water surface area in WWOD	3.6%			
Tau of Seasonal water surface area change WWD	0.363	0.015*	0.001*	0.001*
Tau of Seasonal water surface area change in WWOD	0.164			

Nearly two-thirds of the watersheds with hydropower dams had a growing trend in permanent water surface areas, but this was true for fewer than half of the watersheds without hydropower dams (Table 3.2). Moreover, there is a decreasing trend in 10% of the watersheds without hydropower dams. Similar patterns were observed in seasonal water surface areas, where 60% of the watersheds with hydropower dams, but only 29% of those without dams had an increasing trend. Further, 6% of the watersheds without hydropower dams experienced a seasonal water surface area decline. In contrast, the watersheds with hydropower dams had a higher increase rate in permanent and seasonal water surface areas than those without hydropower dams. A combination matrix between two indicators was conducted. Between permanent and seasonal water surface areas, the majority among nine possible directions is the 47% of the joint increasing of watersheds in WWD and the 35% of the joint unchanging watersheds in WWOD.

Table 3.2 Significance test results in permanent water surface area (%) and seasonal water surface area (%) within WWD and WWOD watersheds.

Change in Water Surface Area	**WWD**			**WWOD**		
	No.	Percent	Tau	No.	Percent	Tau
Permanent increase	20	63%	0.66	64	44%	0.55
Permanent decrease	0			16	16%	-0.45
Seasonal increase	19	60%	0.57	49	29%	0.51
Seasonal decrease	0			6	10%	-0.43

Water surface areas in most of the six watersheds with recent dams changed little (Table 3.3), which indicates that dam construction has minimal short-term impacts on local water resources. Overall distinctions between the two types of watersheds are consequently clear.

Table 3.3 The change of permanent and seasonal water surface area percentage before and after dam construction within the selected six (6) watersheds where dams were constructed during the 2001-2017 period.

Watersheds ID	**Dam Year**	**Permanent water surface area change**		**Seasonal water surface area change**	
		Before	**After**	**Before**	**After**
#13	2004	No change	No change	No change	No change
#31	2014	p<0.01, Tau=0.91	No change	No change	No change
#60	2014	No change	No change	No change	No change
#61	2016	No change	No change	No change	No change
#110	2015	No change	No change	No change	No change
#111	2009	No change	No change	No change	p<0.01, Tau=0.69

The spatial distribution of the changing trend as measured by Sen's slope is shown in Figure 3.3. The watersheds with increasing permanent and seasonal water surface areas tend to be located north and east of the MRB. These areas generally correspond to where most dams have been built (Fig. 3.3). The watersheds with decreasing permanent and seasonal water trends tend to be in the central part of the MRB and farther downstream areas. The overall spatial patterns indicate that the dams have increased the local water storage surrounding the hydropower dams but may have reduced water resources in downstream areas. In addition, such patterns triggered by hydropower dams' construction led to asymmetrical power relationships between upstream and downstream countries in MRB (Ogden 2022).

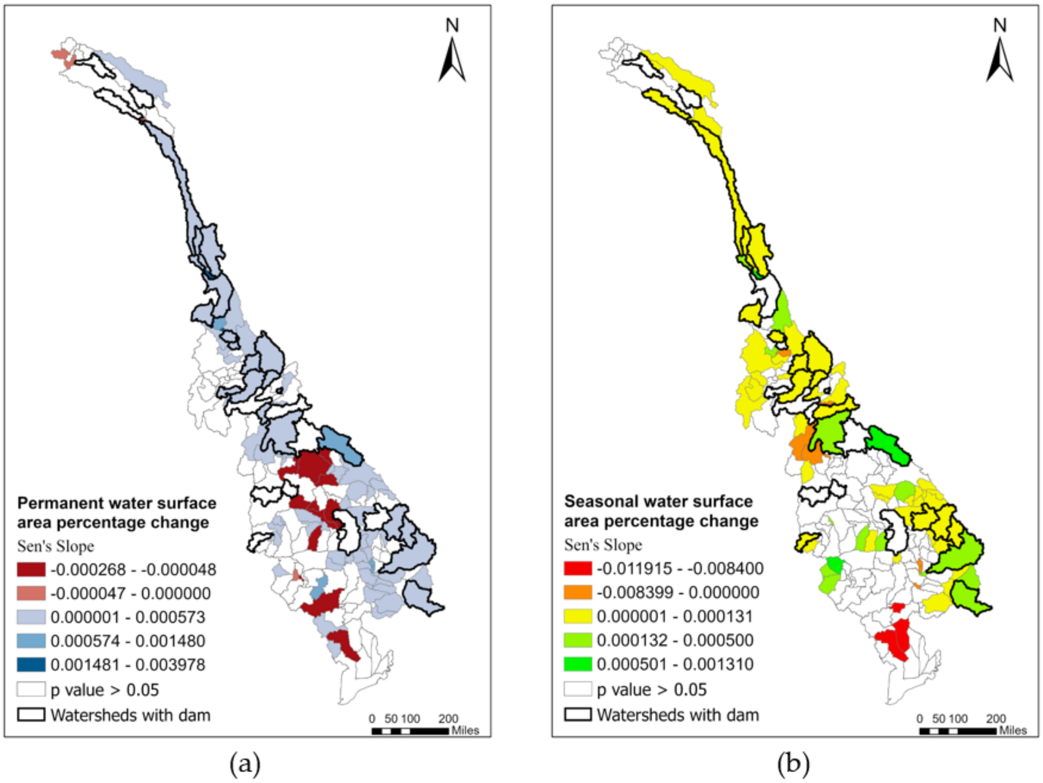

Figure 3.3 Spatial patterns of trends in (a) permanent water surface area percentage and (b) seasonal water surface area percentage (Sen's slope) for both WWD and WWOD groups.

3.3.2 Implications for land-based food production

We evaluated three indicators of food production on land: cropland area percentage, irrigated land area percentage, and average NPP of croplands to assess if there is any difference between WWD and WWOD groups. The statistical significance test results (Table 3.4) suggest that the percentage of cropland area and irrigated land within the WWOD group was higher than in the WWD group, indicating that increased water availability in the dammed watersheds did not necessarily promote agricultural production. On the contrary, there is a declining trend in cropland area in watersheds with hydropower dams but an increasing trend in those without dams.

Table 3.4 Significance test results in cropland, irrigated cropland and NPP for WWD and WWOD groups.

Significance test	Mean	Kolmogorov-Smirnov test P	t-test P	Mann-Whitney test P
Cropland LC in WWD	13.3%	0.017*	0.045*	0.166
Cropland LC in WWOD	26.2%			
Tau of cropland changes in WWD	-0.117	0.009*	0.008*	0.021*
Tau of cropland LC change in WWOD	0.210			
Irrigated land in WWD	1.5%	0.077	0.114	0.185
Irrigated land in WWOD	4.9%			
Tau of irrigated land in WWD	-0.153	0.990	0.875	0.899
Tau of irrigated land in WWOD	-0.173			
Cropland NPP in WWD	702	<0.001*	<0.001*	<0.001*
Cropland NPP in WWOD	525			
Tau of cropland NPP in WWD	0.158	0.424	0.977	0.690
Tau of cropland NPP in WWOD	0.157			

An overall declining trend in irrigated cropland areas was observed in MRB. In contrast with cropland area, the average cropland NPP is higher in watersheds with hydropower dams. A similar trend in NPP was observed for the watersheds without dams, suggesting that the overall NPP trends observed were probably due to factors other than dam impacts. The trends of cropland NPP in the two groups of watersheds were similar, both experiencing a 17-22% increase and a 2-3% decrease.

The rate of change or trend in cropland percentage differed between the two WWD and WWOD groups (Table 3.5). About 50% of watersheds with hydropower dams experienced a decreasing trend and 34% experienced an increase for the data in the WWD group. The corresponding data for the WWOD group showed a 23% of watersheds had experienced a decrease but 50% an increasing trend. These results may reflect that some wetlands within the

WWOD group were converted to croplands resulting from reduced water availability, as shown in the previous section. A combination matrix between two key indicators was conducted. Between cropland land cover and irrigation land covers, the majority among nine possible directions is the 31% of the joint decreasing for watersheds in WWD, and the 23% of the increasing cropland LC but decreasing irrigation LC for watersheds in WWOD. Between cropland land cover and average NPP of cropland, the majority among nine possible directions is the 34% of the declining cropland LC with unchanging NPP for watersheds in WWD and the 37% of the increasing cropland LC with unchanging NPP for watersheds in WWOD. In contrast, the wetlands or even croplands might have been inundated or submerged under the reservoir water. On the contrary, the corresponding data for irrigated land showed a similar trend for both groups. Most of the watersheds have experienced decreasing trends in both groups of watersheds with and without hydropower dams.

Table 3.5 Significance test results in cropland landcover percentage, irrigation cropland landcover percentage and NPP in cropland within both WWD and WWOD watersheds.

Change in Agricultural Indicators	**WWD**			**WWOD**		
	No.	Percent	Tau	No.	Percent	Tau
Cropland LC increase	11	34%	0.73	84	50%	0.75
Cropland LC decrease	16	50%	-0.66	39	23%	-0.7
Irrigation LC increase	10	31%	0.75	44	26%	0.75
Irrigation LC decrease	16	50%	-0.76	78	47%	-0.78
Cropland NPP increase	7	22%	0.44	28	17%	0.48
Cropland NPP decrease	1	3%	-0.53	2	2%	-0.59

The spatial patterns of changing trends in cropland, irrigated land and cropland NPP changes, as indicated by Sen's slope (Fig. 3.4), showed some significant differences among those food indicators, suggesting a differential impact of dams on food security. The watersheds with decreasing cropland areas are primarily located in the northern of MRB. The declining irrigated lands tend to be in the north and the western part of the basin, which do not correspond to the locations of hydropower dams. In contrast, increases in NPP of cropland in the northern and southeastern areas of the MRB correspond closely to the location of dams.

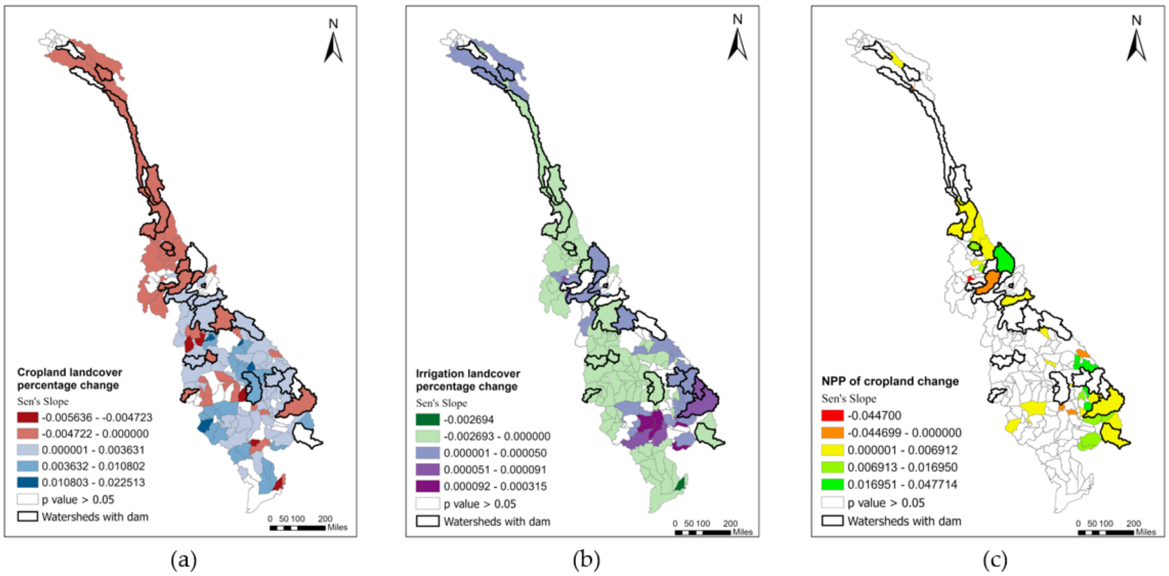

Figure 3.4 Spatial patterns of trends in (a) cropland landcover percentage, (b) irrigation landcover percentage, and (c) NPP of cropland (Sen's slope) for both WWD and WWOD groups.

There is no overall spatial pattern observed in the six watersheds with newly built hydropower dam (Table 3.6). Two of them have an increasing trend in cropland and irrigation land area before dam construction but decreased after the dams were built. One of them has a reversed pattern before and after dam construction. This indicates that the hydropower dam construction significantly impacts the local agriculture system within a short period.

Table 3.6 Changes in cropland, irrigated land, and NPP in cropland before and after dam construction within the selected six (6) watersheds where dams were constructed during the 2001-2017 period.

Watersheds ID	**Dam Year**	**Cropland Change**		**Irrigated lands Change**		**NPP in Cropland Change**	
		Before	**After**	**Before**	**After**	**Before**	**After**
#13	2004	No change	No change	No change	No change	No change	No change
#31	2014	p=0.01, tau=-0.55	No change	No change	p=0.04, tau=-0.95	p=0.04, tau=0.44	No change
#60	2014	p<0.01, tau=0.97	No change	p<0.01, tau= 0.81	No change	No change	No change
#61	2016	No change	No change	No change	No change	No change	No change
#110	2015	p<0.01, tau=0.82	No change	p<0.01, tau=0.94	No change	No change	No change
#111	2009	p<0.01, tau=0.93	p<0.01, tau=0.78	p<0.01, tau=0.90	No change	No change	No change

3.3.3 Socioeconomic implications

The urban area and population density were used as socioeconomic indicators to assess the impacts of hydroelectric dams in the MRB. The statistical significance test results (Table 3.7) suggest that the WWWD group has an overall lower urban cover (%). However, the trend of change in urban land is increasing, similar to that of the WWOD group. Population density and its rate of change are relatively similar in both groups, suggesting renewable energy development did not significantly impact the local economies.

Table 3.7 Significance test results in urban land percentage and population density between WWD and WWOD groups.

Significance test	Mean	Kolmogorov-Smirnov test p	t-test p	Mann-Whitney test p
Urban land (%) in WWD	0.33%	0.026*	0.633	0.554
Urban land (%) in WWOD	0.40%			
Tau of urban land (%) in WWD	0.313	0.932	0.352	0.399
Tau of urban land (%) in WWOD	0.242			
The population density in WWD	49.6	0.338	0.121	0.324
The population density in WWOD	77.2			
Tau of population density in WWD	0.433	0.123	0.404	0.181
Tau of population density in WWOD	0.354			

The percentage of watersheds that have experienced major changes in urban land area (%) and population density (Table 3.8) is quite similar in both WWD and WWOD, most of which witnessed an increasing trend. A significant urban expansion was observed in 34% of watersheds in WWD and 27% in WWOD. Approximately 60% of watersheds had a growing trend of population density in both groups, but 13% had a declining tendency. A combination matrix between two indicators was conducted. Between the urban land cover and population density, the majority among nine possible directions is the growing population with unchanging urban land for watersheds in both WWD and WWOD, with 41% and 46%, respectively.

Table 3.8 Significance test results in urban landcover percentage and population density within WWD and WWOD watersheds.

Change in Social-Economic indicators	WWD			WWOD		
	No.	Percent	Tau	No.	Percent	Tau
Urban LC increase	11	34%	0.88	45	27%	0.84
Urban LC decrease	0			0		
Population increase	19	59%	0.79	94	56%	0.51
Population decrease	4	13%	-0.56	22	13%	-0.43

The population grew rapidly at most places within the MRB in general (Fig. 3.5). There was a small cluster of low growth rates in the center of the basin, corresponding to the cluster of rapid urban expansion. However, these observed changes were no obvious differences between watersheds with and without dams, suggesting a minor role of hydro dams in the population density changes.

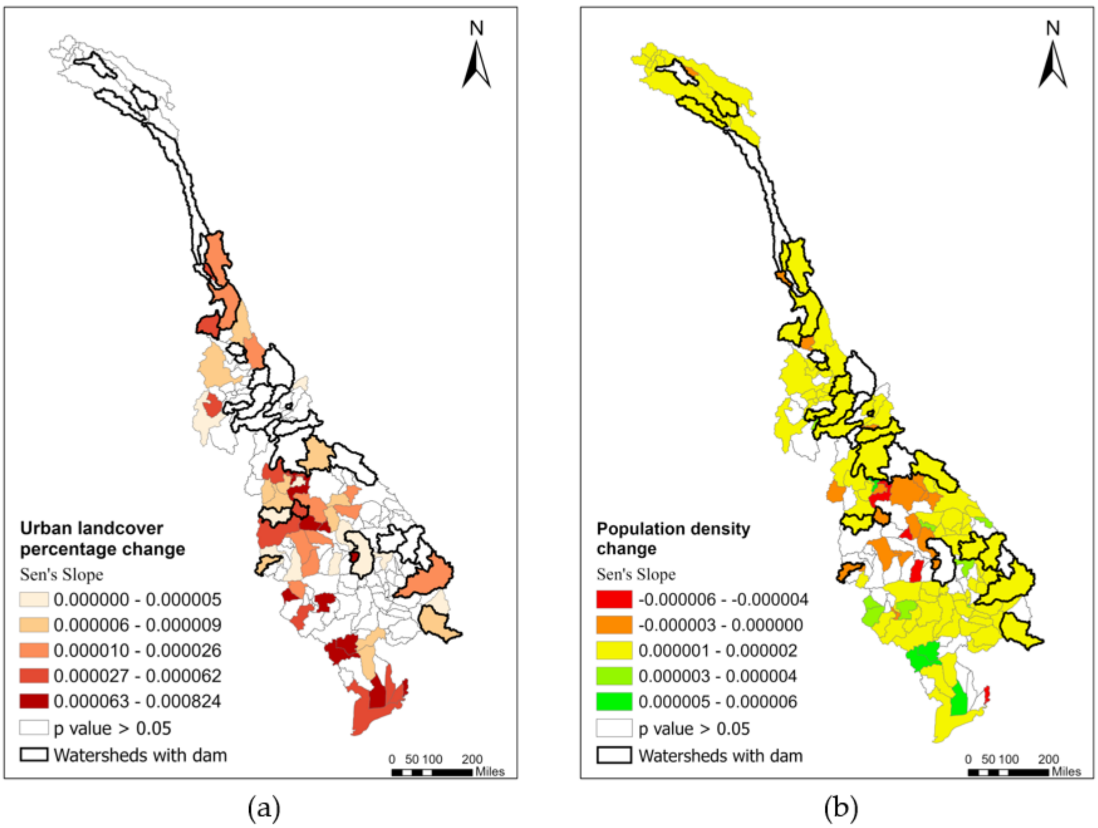

Figure 3.5 Spatial patterns of trends in (a) urban landcover percentage and (b) population density (Sen's slope) for both WWD and WWOD groups.

When comparing these indicators before and after dam construction, it is evident that urban land did not change significantly in the six watersheds (Table 3.9). However, four out of six watersheds had a rapidly increasing population density trend before dam construction compared to after dam construction. It suggests that hydropower dam construction in these watersheds did not attract more people to the region. Instead, migration might have moved people out of the inundated areas by newly built dams and associated reservoirs.

Table 3.9: Change of urban area and population density before and after dam construction within the selected six (6) watersheds where dams were constructed during the 2001-2017 period.

Watersheds ID	**Dam Year**	**Population density change**	
		Before	**After**
13	2004	No change	p<0.01, tau=0.74
31	2014	No change	No change
60	2014	p<0.01, tau=0.80	No change
61	2016	p<0.01, tau=0.54	No change
110	2015	p<0.01, tau-=0.85	No change
111	2009	p<0.01, tau=1	p<0.01, tau=0.83

3.3.4 Environmental and climate implications

To assess dam impacts on environmental sustainability and climate, we analyzed the EVI, precipitation, and land surface temperature indicators within and between WWD and WWOD. The statistical significance test results (Table 3.10) indicated that the watersheds with hydropower dams had higher EVI but lower land surface temperature than those without dams. Interestingly, however, the trend of increasing EVI and temperature was the same between the two groups. There was no difference in precipitation between the two groups. A combination matrix between two key indicators was conducted. Between average EVI and land surface temperatures, the majority among nine possible directions is the jointly unchanging EVI and temperature for watersheds in both WWD and WWOD, with 44% and 40%, respectively.

Table 3.10 Significance test results in EVI, land surface temperature and precipitation density between WWD and WWOD groups.

Significance test	Mean	Kolmogorov-Smirnov test p	t-test p	Mann-Whitney test p
EVI in WWD	0.38	0.021	0.133	0.031
EVI in WWOD	0.335			
Tau of EVI change in WWD	0.292	0.794	0.717	0.774
Tau of EVI change in WWOD	0.271			
Precipitation in WWD	1603.9	0.211	0.458	0.227
Precipitation in WWOD	1680.1			
Tau of precipitation changes in WWD	0.05	0.690	0.218	0.171
Tau of precipitation changes in WWOD	0.08			
Land surface temperature in WWD	24.16	<0.001	0.009	<0.001
Land surface temperature in WWOD	27.39			
Tau of land surface temperature WWD	0.166	0.877	0.763	0.617
Tau of land surface temperature in WWOD	0.154			

Approximately 40% of the watersheds in both WWD and WWOD groups had an increasing trend of EVI (Table 3.11), which indicates the MRB is getting greener. Indicates that the land surface temperature increased in 20% of the watersheds, regardless of dam existence or not within the watersheds, suggesting the MRB was getting warmer. In contrast, the average yearly total precipitation in most watersheds did not show any significant changes over the study period (2001-2018), but the increasing extreme weather and rainfall had been observed (Li et al., 2019).

Table 3.11 Significance test results in EVI, land surface temperature, and precipitation within WWD and WWOD watersheds.

Change in Environmental Indicators	WWD			WWOD		
	No.	Percent	Tau	No.	Percent	Tau
EVI increase	12	38%	0.57	68	41%	0.57
EVI decrease	0			2	1%	-0.35
Temeprature increase	6	19%	0.41	33	20%	0.45
Itemperature decrease	1	3%	-0.34	3	2%	-0.52
Precipitation increase	1	3%	0.35	4	2%	0.38
Precipitation decrease	0			0		

When comparing these indicators within the six (6) watersheds before and after dam construction, all three environmental indicators remained more or less; dam construction did not significantly impact regional climate, at least in the short term. The clusters of increasing greenness occurred in the west of MRB, from north to south (Fig 3.6). Watersheds with a significant increase in greenness corresponded to the locations where no temperature change was observed.

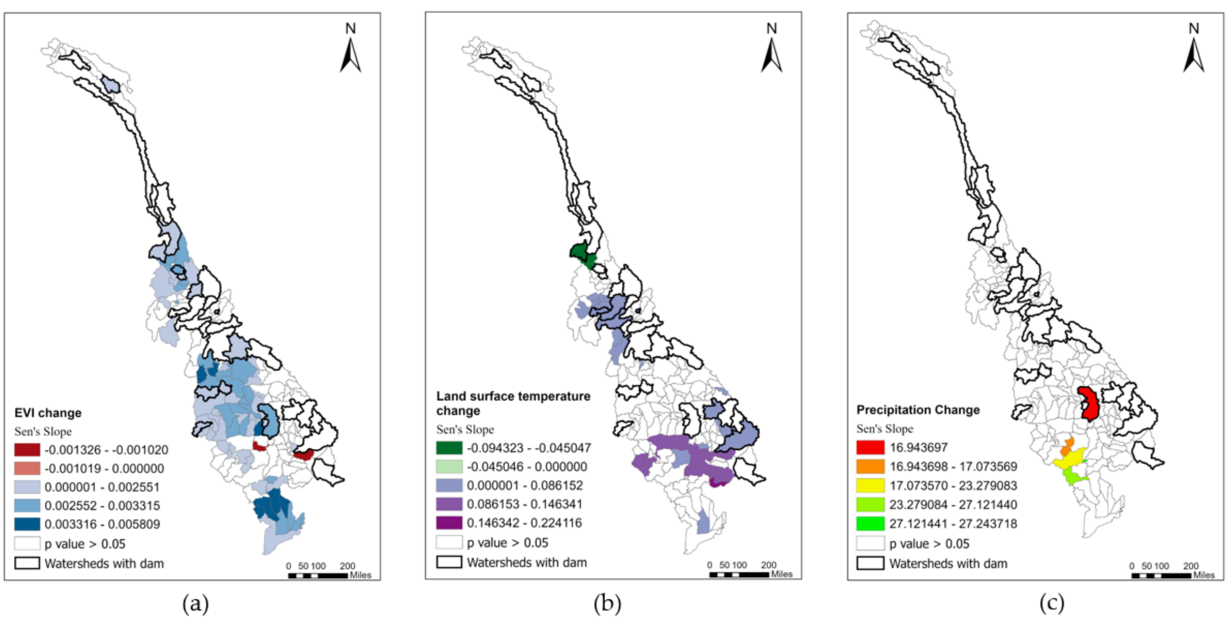

Figure 3.6 Spatial patterns of trends in (a) EVI, (b) land surface temperature and (c) precipitation (Sen's slope) for both WWD and WWOD groups.

3.4 Discussion

3.4.1 Diagnostic method for tradeoff and synergy analyses

Renewable energy development within the MRB through hydropower dams certainly has sustainability implications in the energy sector, but the tradeoffs are far more beyond energy itself (Pratiwi & Juerges 2020; Gao & Wang 2021). Through flow regulation, interception and diversion, hydropower dams triggered changes in surrounding land uses and imposed significant implications on the local communities' food systems, environments, and socioeconomic benefits or tradeoffs (McNally et al. 2009; Liu et al., 2013; Tahseen & Karney 2013; Moran et al., 2018; Wang et al., 2010; Briones-Hidrovo et al., 2019; Vogl et al., 2016; Zhao et al., 2010). As we know, the primary purpose of most hydropower dams is to enhance energy production (Zarfl et al., 2015), as in the case of Mekong River Basin dam construction, but the implications in other ecosystem services, particularly freshwater and food sectors, have not been fully documented to provide quantitative literature to discern hydropower dams impacts from other exogenous drivers such as climate change or a process of globalization (Galea et al., 2020; Liu et al., 2021).

The WEF nexus framework provided a theoretical basis to assess the water-energy-food system holistically (Zhang et al., 2018; Endo et al., 2020; Gallagher et al., 2020; Keskinen et al., 2015; Mabrey & Vittorio 2018; Gao et al., 2021). The developed approach provided a specific example to diagnose the tradeoffs by statistically comparing key WEF indicators in watersheds with and without dams in them. The key indicators (Table 3.12) included proxies of food (cropland, irrigation, NPP), water resources (permanent and seasonal water surface area percentages), environment (greenness measures with EVI, temperature and precipitation), and socioeconomic wellbeing (urban land area percentage and population density). These indicators are not exhaustive, but they are relatively easy to obtain from earth observation satellites observations, as shown in Table 3.12.

These indicators are the nexus of the water-energy-food systems as any one of them is tightly linked to all three components (Table 3.12). To quantitatively examine synergies and tradeoffs among these three, these indicators are treated as observations, and they were separated into treatment and control groups based on the hydropower dam's existence. Placing the watersheds with dams in the treatment group and those without dams in the control group is scientifically sound and well-justified traditional methods of field experiments to test hypotheses (Williams 1971). In the case of the MRB, the control group had 167 watersheds. In contrast, the treatment group had only 32, which may be further improved by dividing those watersheds into even smaller sub-watersheds, which may be further analyzed in future studies.

Table 3.12 Selected ten (10) nexus indicators used in this study and their interrelations among water, energy, and food components.

Indicators	**Water**	**Energy**	**Food**
Permanent water surface area	Freshwater storage, supplies, flood buffering, erosion protection	Hydropower, transportation, supplies, water diversion	Fisheries, livestock consumption, crop irrigation
Seasonal water surface area	flood and drought risk	Hydropower	shifting cultivation
Cropland land cover	Water pollution, infiltration, soil erosion, and freshwater withdrawal, evapotranspiration	Water pumping for irrigation, Biofuel crops, food processing, fertilizer, pesticides	Food crop production
Irrigation land cover	Irrigation water withdrawal	Water pumping for irrigation, Biofuel crops, food processing, fertilizer, pesticides	Food crop production and aquaculture associated
NPP in cropland	Water input in cropland	Water pumping for irrigation, Biofuel crops, food processing, fertilizer, pesticides	Food crop production
Urban land cover	Freshwater withdrawal, water pollution, water stress	Energy demand for industrial and household	Food consumption in public and household
Population density	Household water consumption	Household energy consumption	Household food consumption
EVI	Erosion protection, evapotranspiration, precipitation	Biofuels	Wild vegetables and fruits
Precipitation	Freshwater storage, supplies, flood risk	Cooling and warming energy consumption	Climate hazard on food production
Temperature	Water evapotranspiration, drought risk	Cooling and warming energy consumption	Climate hazard on food production

Once separated into treatment and control groups, we designed and performed three tests that enable us to isolate the estimated effects of dams on the performance of these indicators. First, we evaluated the overall performance of the indicators over a certain period of the two watershed groups. This allows a horizontal (across a spatial domain) assessment of the WEF statuses by comparing the treatment group (i.e., watersheds with dams) with the control group (i.e., watersheds without dams). Second, taking advantage of available time-series observations and dam construction information, we conducted a vertical (temporal domain) assessment along the dimension of time by examining the trajectories (trends) of the indicators of the two contrasting groups. Last, by isolating the interacting effects of multiple dams, we further selected a subgroup (6) of watersheds where only one dam had been constructed during the study period to examine their trajectory changes before and after dam construction.

These analyses allowed us to achieve our primary goal to quantitively discern the dam's impacts on the WEF systems from other exogenous drivers such as climate and globalization processes. The analysis methods offered a groundbreaking approach that statistically represents the nexus by assessing indicators that showed how the change of one sector impacts other elements in WEF and local sustainability. Dam impacts have been long attracting researchers' interest. Most researchers only focus on the hydropower dam's effects on the whole dammed basin or some specific sub-watersheds (Piman et al., 2015; Wild et al., 2019). Some researchers are trying to focus on the surroundings of hydropower dams by creating buffers toward hydropower dams. The buffer distance varies from 1km to 50km, and assessments based on buffers are applied (Zhao et al., 2010; Ouyang et al., 2013). The shape of buffers also varied from regular circles (Houssain et al., 2012) to asymmetric shapes (Cho & Qi 2021). However, the difference comparison between places with or without hydropower dams is crucial. To our best knowledge, this paper is the first time to use the comparative method based on a statistical trial design by separating control groups and the treatment group representing the hydropower dams. This approach provides a better way to assess the dissimilarity of hydropower dam constructions. Given the reliability and accessibility of the input data, the approach used in this paper has the potential to be widely applied and flexibly generalized to examine various issues regarding the impacts of human interventions on the WEF nexus and inform related environmental policymaking.

3.4.2 Tradeoffs and synergies associated with the construction of hydroelectric dams

The construction of hydropower dams is an effort to improve regional energy production. Since the three elements in water-energy-food systems are linked and intercorrelated, such unilateral attempts can be considered lopsided and likely lead to tradeoffs and sustainability impacts. Guided by the developed analytical framework, this study comprehensively evaluated the WEF nexus by assessing the ten (10) nexus indicators and their interactions. Synergies and tradeoffs in the WEF nexus are revealed (Fig 3.7).

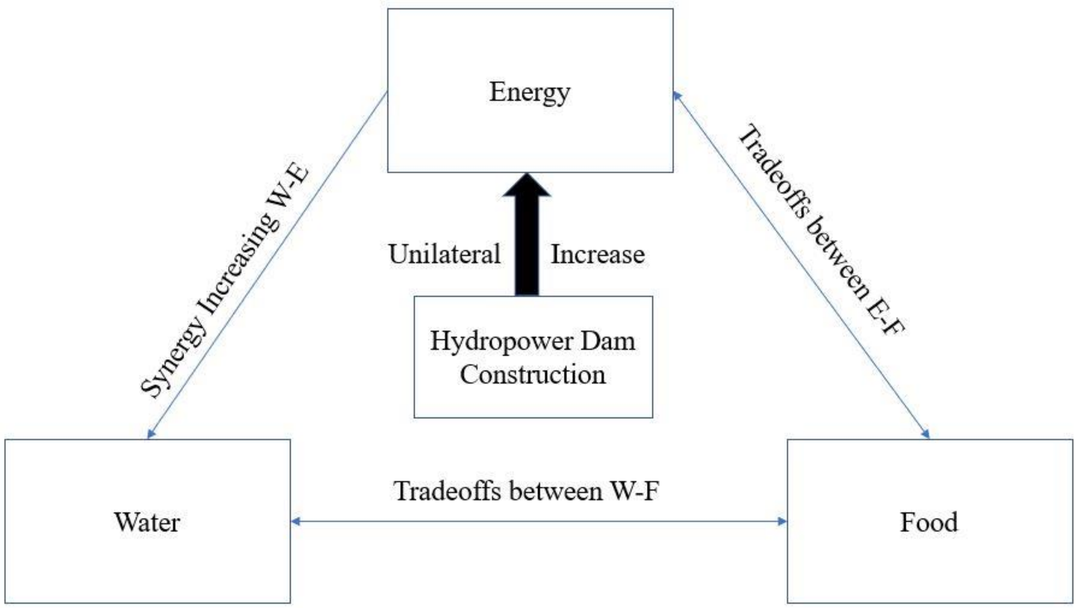

Figure 3.7 Diagram of the WEF synergies and tradeoffs of hydropower dam construction in MRB

The water resource is directly related to the hydropower dams as the reservoirs and dam construction significantly impact surface water availability for irrigation (Zeng et al., 2017; Branche et al., 2017), urban development (Siciliano et al., 2015) and ecosystem primary productivity (Wang et al., 2010; Briones-Hidrovo et al., 2019; Vogl et al., 2016). Significant differences exist between watersheds with and without hydropower dams in water surface areas and their annual changes. During the study period from 2001 to 2018, the average surface water areas were generally low in watersheds encompassing hydropower dams; however, they rapidly increased with a significantly higher increasing rate for both permanent and seasonal water surface areas. Therefore, hydropower dams have benefited local water resources by increasing the water surface area (Herndon et al., 2020; Xie et al., 2021) and volume, and thus water availability. Further, dams and reservoirs secure water availability and stability in case of droughts. Seasonal water levels were more stable in the watersheds consisting of dams (Fig. 3.8), suggesting that dams could benefit communities through flood controls (Tabari 2020). Water resource improvement triggered by energy enhancement is the observed synergy in MRB's WEF nexus system.

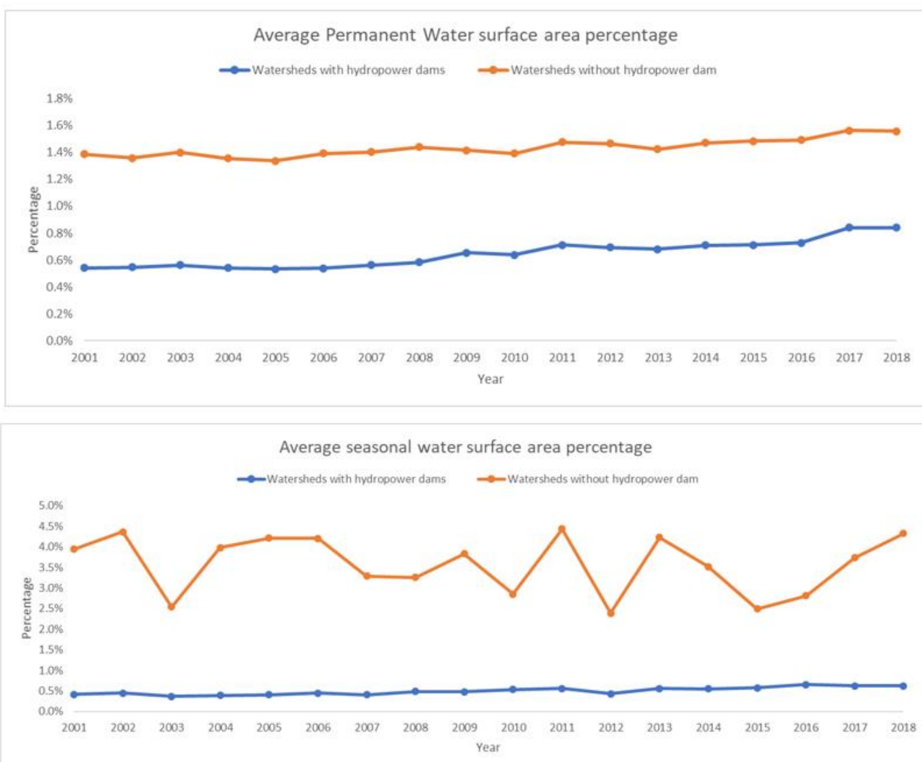

Figure 3.8 Average of permanent and seasonal water surface area percentage change in two groups of watersheds through the years.

However, the tradeoffs between energy and food are notable. Food is another crucial element in the WEF nexus and is impacted by the construction of the hydropower dams (Golden et al., 2019; Begossi et al., 2018). There is evidence that food production from aquatic ecosystems, both fish and invertebrates, declined after dams were built, including those on the Mekong River (Yoshida et al., 2020). Dam-induced hydrological changes, physical blocking of fish movement, reduced silting, and saltwater intrusion threaten these seafood organisms (Pokhrel 2018).

Land-based agricultural food production is known to be impacted by hydroelectric dams (Fredén 2011). Our analyses quantitatively conferred these arguments (Zeng et al., 2017; Pratiwi et al., 2020; Digna et al., 2018) and provided statistical evidence that the percentage of cropland in watersheds with hydropower dams is reduced, contrasting the fact that cropland areas in watersheds without dams were growing, resulting from reduced wetlands and water areas. We also quantitatively showed that the water resource increased at a significantly faster rate in watersheds with hydropower dams than those without dams.

In addition, there was an overall declining trend in the extent of irrigated cropland in both watersheds with and without dams, with a general increasing trend in water resources in MRB. Therefore, the hydropower dams have not benefited the cropland production as expected (Tilmant et al., 2009; Chatterjee et al., 1998), even though they improved water resource availability.

One critical line along the major findings related to the WEF nexus is the simultaneous changes in water and food dimensions impacted by dam construction. We found that dam constructions have slightly more impacts on the surface area of seasonal water than permanent water but generally cause an adverse change in cropland areas and associated land quality (e.g., as measured in NPP) despite the overall increasing trends of surface water. With expected outcomes for the water change, dams regulate surface water by creating water storage in reservoirs, which inevitably affect the appearance of surface water by viewing the boundary; however, the change in cropland is not as expected, which is probably due to the evacuation of villages in the vicinity of the dam location (Singer & Watanabe 2014) who are essential for providing labor on land cultivation. It should also be noted that such effects take time to make substantial changes, as evidenced in our analyses for watersheds with recently built dams. Thus, the outcomes are expected to be accumulative, evolving, or fading through time. For example, as surface water areas continue to increase with more water storage, dams can benefit irrigated cropland areas by facilitating better accessibility of water resources downstream in the long run, subsequently making more crops yield possible.

From socioeconomic and environmental perspectives, the watersheds consisting of hydro dams have a slightly smaller number but a higher increasing rate on urban land cover type, which mimics percentage and lower population density. But the difference between the two groups of watersheds is not significant.

The results indicated that hydropower dams tend to be built in relatively less developed locations, and the dam construction did bring substantial local social-economic development. Still, the magnitude is not as large as expected. The EVI in watersheds containing hydropower dams is significantly higher than in watersheds without hydropower dams. It also makes sense that the temperature is lower in watersheds without dams than in those with dams because of the linkages between vegetation cover and land surface temperature (Chow et al., 2016). Even if there were a significant difference between the mean EVI and land surface temperature, they would share the same changing trend of getting warmer, greener, and wetter across the MRB. Therefore, the tradeoff of hydropower dam construction with sustainability in the MRB is not as significant as expected (Sahin et al., 2017; Räsänen et al., 2015; Bussi et al., 2021; Wild et al., 2019).

3.4.3 Limitations and future study

In this study, we only considered the local impacts or the impacts of hydropower dams' surroundings. Further, the watersheds were not totally independent and uniformly distributed throughout the basin. Remote upstream dams may also have significant implications on the distant downstream watersheds (Kuenzer et al., 2013), possibly with a time lag (Van Binh et al., 2020). A more detailed spatial analysis is required to understand the interactions between within-watershed dams and distant dams related to WEF systems. A distance weight-based analysis (Qian & Philip 2019; Ligmann-Zielinska & Jankowski 2012; Zhang et al., 2018) is suggested in future studies. On the other hand, this paper only uses Land-based agricultural food as a proxy. However, we acknowledge that in the MRB context, which is the largest fishery in the world, millions of people rely on aquatic resources for their food (Pokhrel et al., 2018; Yoshida et al., 2020; Galea et al., 2020). Replacing lost aquatic food by expanding crop production requires further investigation.

Further, this study focused on how the unilateral change in energy proxy (hydropower dams) would impact local WEF nexus and sustainability. However, we did not use indicators representing energy itself because we understand that energy production would increase with hydropower dams (Yuksek et al., 2006). If the developed diagnostic approach is to be applied in other studies, such as how water regulation would impact the WEF nexus, we suggest adding some energy indicators in addition to hydropower dams. One of the energy indicators suitable for such research and available globally is the night light data. The nightlight data can provide energy consumption differences between the two groups. The commonly used nightlight data is the combination of the Defense Meteorological Program Operational Linescan System (DMSP-OLS) (Baugh et al., 2010) and the Visible Infrared Imaging Radiometer Suite (VIIRS) (Elvidge et al., 2017). The nighttime light data can also be treated as an indicator of social-economic development. In this study, I only evaluated population density and urban land area in social economic part. Integrating night light data combined with the gridded Gross domestic product (GDP) data can provide a more comprehensive understanding.

Additionally, the spatial resolution of the data used in this study was relatively coarse and should be improved by incorporating ground-based data and information.

The geographic locations of the dams and the groupings are not randomly distributed throughout the watershed. This study provided a comparative study on two groups of watersheds, one being within watersheds with dams while another without hydropower dams and considered dams as a treatment. The better way to perform a study is to have a double-blind clinical trial (Benignus et al., 1993). However, the geographic locations of the dams and the groupings are not random. Even we used the “blind” delimiting method, the assignment of the dams and the sample observation selections are still not actually random, which may be further improved when considering a much larger geographic area or domain of study. However, this study is still a proof of concept of the diagnostic approach to addressing tradeoff assessment in the complex watersheds with hydropower dam networks. When more data are available, it is feasible to conduct a thorough analysis using methods like propensity score (D’Agostino Jr et al., 1998) to resample watersheds and thus reduce any potential bias.

3.5 Conclusions

This study developed a diagnostic approach that employs the power of statistics and experimental design of treatments versus controls to assess the impacts of hydropower dams as a unilateral change in WEF systems within the MRB. The approach used a set of indicators and metrics to evaluate tradeoffs among WEF components and an ecosystem's sustainability. Hydropower dams had significant benefits on water resources but not so much on agricultural food production. The benefits to the local social-economic and the negative impacts on local sustainability brought by hydropower dams do not seem to be justified in large scale comparison between watersheds with and without hydropower dams.

The data used in this approach are based on globally available remote sensing observations, and thus this approach can be applied in other geographic areas. With additional data from field-based observations and other socioeconomic data, this approach could be used to address a much broader set of issues related to hydropower dam impacts and tradeoffs of WEF systems.

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4. CHAPTER 4: TOWARD A CARBON NEUTRAL STATE： A CARBON-ENERGY-WATER NEXUS PERSPECTIVE OF CHINA'S COAL POWER INDUSTRY

Abstract

Carbon neutrality is one of the most important goals for the Chinese government to mitigate climate change. Coal has long been China's dominant energy source and accounts for more than 70% of its carbon emissions. Reducing the share of coal power supply and increasing carbon capture, utilization, and storage (CCUS) in coal power plants are two primary efforts to reduce carbon emissions in China. However, the extra energy and water consumed in the CCUS efforts combined with the consequent energy consumption reduction may lead to tradeoffs from the carbon-energy-water (CEW) nexus perspective. This paper first developed an Assessment Tool for Portfolios of Coal power production under Carbon neutrality goal (ATPCC) to help better understand the tradeoffs in China's coal power industry. By applying different coal industry development scenarios, we illustrated potential strategies to achieve a zero-emission possibility in China's coal electricity industry. We further showed that the reduced water and energy consumption in the energy transition is not enough to balance the extra energy consumption in the CCUS efforts. The synergies of CCUS and efforts to reduce coal electricity share need to be well thought through. Additionally, the economic loss resulting from the coal reduction can be compensated by the carbon market. Carbon trading has the potential to be the dominant profit-making source for China's coal power industry. The radical scenario with the most rapid reduction in coal power production combined with the carbon captured from CCUS would be more sustainable from the CEW nexus perspective. However, when economic revenues are considered, then the scenarios with moderate energy transition and CCUS efforts would be more sustainable. Nevertheless, the ATPCC allows one to customize coal production scenarios to according to its targeted emission reductions, thus making it adoptable not only in China but also

in other regions where coal power industry, energy demand, and carbon neutrality are interwoven.

Key words: Carbon-energy-water nexus, CCUS, energy transition, life cycle coal power production

4.1 Introduction

Greenhouse gases absorb infrared radiation and retain heat, warming Earth's surface and driving global warming. If the planet rapidly reduces CO_2 emissions rather, research indicates that projected global warming is more likely to be constrained to 1.5 °C, relative to pre-industrial levels, rather than 2°C (IPCC, 2020). Anthropogenic emissions have contributed most of the atmospheric CO_2 over the past 150 years (IPCC, 2021). Therefore, reaching carbon neutrality is one of the world's most urgent missions. Carbon neutrality indicates that emitted CO_2 is equal to the eliminated/sequestered CO_2 in the atmosphere within the same period (European Parliament, 2019). To global warming impacts including risks of extreme weather and negative impacts on rising sea level, terrestrial and aquatic ecosystems, and food security, we must constrain global warming to 1.5°C and utilize carbon neutrality by 2050 (IPCC, 2021).

Globally, electricity and heat-related energy production accounts for around 31% of carbon emissions and is the most significant contributor by sector. As the most populous country and the largest fast-growing economic entity globally, China has the biggest energy consumption and is increasing demand (EIA 2020). Around 3,000 million tons of oil equivalent (Mtoe) energy consumption each year makes China the largest emitter in the world, as it accounts for about 28% (9.8 gigatons/year) of global greenhouse gas emissions (ETC 2019). Besides the large population and fast economic growth, another main reason for the significant emission from China is the type of energy source. For electricity generation only, traditional thermal sources take about 70%

compared with a 30% share of green energy sources, such as wind, hydro, and nuclear. Coal contributes to around 92% of all thermal sources, making it the dominant energy source in China for electricity generation (China Energy Portal, 2021). In 2019, coal accounted for greater than 60% of the total energy consumption in the country.

Coal has long been one of the biggest shares in the mix of energy sources due to its low cost and high accessibility in China (Yan et al., 2019; Dai et al., 2020). However, the economic benefit comes hand in hand with negative impacts on the environment (Chen et al., 2014; Cui et al., 2012; Vujic et al., 2012). Coal combustion has long been recognized to account for an enormous carbon emission (Hong et al., 1994; Chadwick et al., 2013). In China, approximately 80% of CO_2 emissions between 2000 and 2013 in China were from coal combustion alone (Liu et al., 2015). Far beyond that, carbon emission from the process of coal mining is also significant. Mining activities release a large amount of methane (CH_4), the second most important greenhouse gas after CO_2, as well as CO_2 and other gases from coal and surrounding rock strata (Cheng et al., 2011). Additionally, emissions during the process of mining and washing, as well as transportation, significantly contribute to the total carbon emissions of generating coal power (Wang et al., 2018; Spath et al., 1999; Han et al., 2019). Therefore, it is essential to consider the entire coal power generation process in calculating total carbon emission and the environmental cost of utilizing coal power.

In the 2020 United Nations General Assembly, President Xi Jinping declared that China would aim to reach an emission peak before 2030 and pledged to achieve carbon neutrality before 2060 (Dong et al., 2022). To accomplish this goal of carbon neutrality, the energy sector, especially the section of coal power generation, should be listed as the first emission source that needs urgent action. Generally, two pathways of action can reduce carbon emissions in power generation in countries where coal leads the list of power sources. The first is to reduce the share of coal power in the country's total power supply, and the second is to reduce carbon emissions from coal power generation by applying the technology of carbon capture, utilization, and storage (CCUS).

The best and only approach to supply sufficient power and mitigate harm to the environment is energy transition, defined here as shifting the energy sector from fossil-based production and consumption systems to renewable energy sources (Liu & Peng 2022; Zhang & Chen 2022). Currently, China is enthusiastically promoting zero-emission green energy, such as wind, solar, and hydropower, to replace coal power to reduce emissions. In the past 30 years, China has reduced the share of coal power by ~20% and vastly increased the percentage of green energy by distributing subsidies to the industry.

In addition to reducing the use of coal energy, investing and applying the technology of CCUS is another influential part of the national strategy to reduce carbon emissions (Jiang et al., 2020; Jiang et al., 2021; Yao et al., 2018). The CCUS is a processing chain that aims to capture and compress carbon emissions at the source plant and then transport the emissions for another utilization cycle or geological sequestration (Metz et al., 2005; Chu, 2009; Hasan et al., 2015). This technique is among the most cost-effective approaches to reducing carbon emissions and has the potential to reduce 20% of total emissions across the industry sector, which is projected to be above 28 Gt CO_2 by the year of 2060 (IEA, 2019). Currently, China has pushed the efforts for developing and utilizing CCUS in coal power plants. By the end of 2017, around 26 sites of CCUS had been put into service throughout the country (Liu et al., 2017; Xie et al., 2021).

When considering a sustainable coal power system, the water sector cannot be ignored. A massive amount of water is required in the life cycle of coal electricity production. Water is not only consumed in the mining, washing, and refining process, but also in the combustion at power plants (Shirkey et al., 2021). Most coal mines are in arid western China. The energy transition process would significantly reduce water stress, since most of the alternative power sources consumes less water, except for nuclear power. However, extra water consumption is needed for CCUS application in coal electricity power plants. Studies show that the consumption of water in power plants increased by 50-90% after equipping CCUS (Li et al., 2016; Zhai et al., 2011; Newmark et al., 2010). Therefore, water is another stressed resource in coal-based power generation that could be alleviated when the share of coal-based energy is reduced, but again exacerbated by integrating CCUS.

Similarly, the CCUS application would significantly increase energy consumption. Therefore, it is crucial to understand the tradeoffs on water, energy, and carbon affected by the two coupling efforts on carbon reduction. The Carbon-Energy-Water (CEW) nexus approach could be a solution as the sustainability assessment perspective. CEW nexus has drawn attention to recent studies because of the interaction effects between factors and the functionality as an entire system on the environmental and related research areas. Dynamics within the nexus have been widely discussed, focusing on different driving forces. Some studies explored how external factors lead to the dynamics in the nexus. For example, Yu (Yu et al., 2022) assessed the effects of agricultural activities on the CEW nexus, and Li (Li et al., 2020) and Liang (Liang et al., 2022) both considered socioeconomic cost a significant external driving factor when investigating the CEW nexus. Internal driving forces are also widely discussed. Lim (Lim et al., 2018) performed an energy-centric study that assessed how each factor in the nexus affects energy generation and the ultimate achievement of long-term energy plans in the United Arab Emirates. Other energy-centric CEW studies took varied perspectives on energy sector changes, including a new energy technique proposal and analysis on how it will affect the dynamics in CEW (Vakalis et al., 2020).

Water-centric (DeNooyer et al., 2016; Chhipi-Shrestha et al., 2017; Lee et al., 2017; Trubetskaya et al., 2021), and carbon-centric (Liu et al., 2021; Zhu et al., 2017) studies on the internal dynamics within CEW nexus were also conducted. However, most of these studies primarily investigated only one individual sector's fluctuation in the nexus as an intrinsic driving factor for the dynamics.

The research focusing on only one centric driver of CEW nexus can help to understand the change of one sector and identify the relationship between the centric aspect and the change of all other aspects in the system but may lose the information of interactions between two or more elements and their coupled effects on the dynamics of the nexus. There is a need to consider the coupling effect, or to our interest, to consider both carbon and energy sectors as intrinsic driving factors to the dynamics of the nexus. Under this research structure, we can explore the relationship between the two sectors and investigate how the two individual sectors plus their coupling effects impact the change of the CEW nexus.

CEW studies also set implementation goals in varied industries or sectors, which implies the versatility and significance of CEW research. Wang (Wang et al., 2020) organized their study to assist China's iron and steel industry achieve water and energy cost-effectiveness while reducing carbon emissions. Similar applications of CEW in industry were also explored for food and beverage products (Leivas et al., 2020) and ceramic tile production (Ma et al., 2022). Scott (Scott et al., 2011), Gu (Gu et al., 2016), and Trubetskaya (Trubetskaya et al., 2021) aimed to put forward policy recommendations on water management or wastewater treatment. Emissions by share of sectors, (*e.g.*, agriculture, urban household, energy generation, and industry), were widely calculated and broadly discussed in the CEW framework (Yang et al., 2018; Li et al., 2019; Yang et al., 2019; Wang et al., 2020; Li et al., 2021). As coal-power generation must be critically investigated, as it is the most crucial energy sector supplier and emitter in present-day China.

However, CEW studies on the coal sector are still lacking. To narrow this research gap, the CEW nexus in China's coal power sector is first explored herein.

In this paper, we ask the following research questions: (1) How is it possible to make a sustainable coal strategy in the context of carbon neutrality goals? (2) What are the tradeoffs in CEW nexus within life-cycle coal-fired electricity production under carbon neutral policy? To address these questions, we proposed a scenario-based life-cycle coal power strategy assessment model (ATPCC) that consists of all parameters and the respective changing trends over time, including energy consumption, water consumption, carbon emission and economic profits with carbon-reduction efforts and the impacts on embedded parameters. We applied three different coal power development portfolios representing different carbon-mitigation efforts levels. By utilizing the tool to model potential scenarios, we evaluated the tradeoffs of the CEW nexus between portfolios and stated the pathway of sustainable coal development in China.

4.2 Methodology

4.2.1 The conceptual framework

The coal electricity production portfolio under carbon neutrality goal is crucial for policymakers in China toward a sustainable, profitable future or the other way around. The feasibility of the given scenario should consider and respect the tradeoff and synergies between the policy of energy transition and the policy of CCUS in the way of CEW nexus and economics. This is not only an issue for the central government but also crucial to every policymaker in China, from provinces and municipalities to counties. Especially for places at risk of natural resources like water, or places that care most about environmental costs. There is a need to find a way toward a sustainable and profitable coal system under a carbon-neutral perspective.

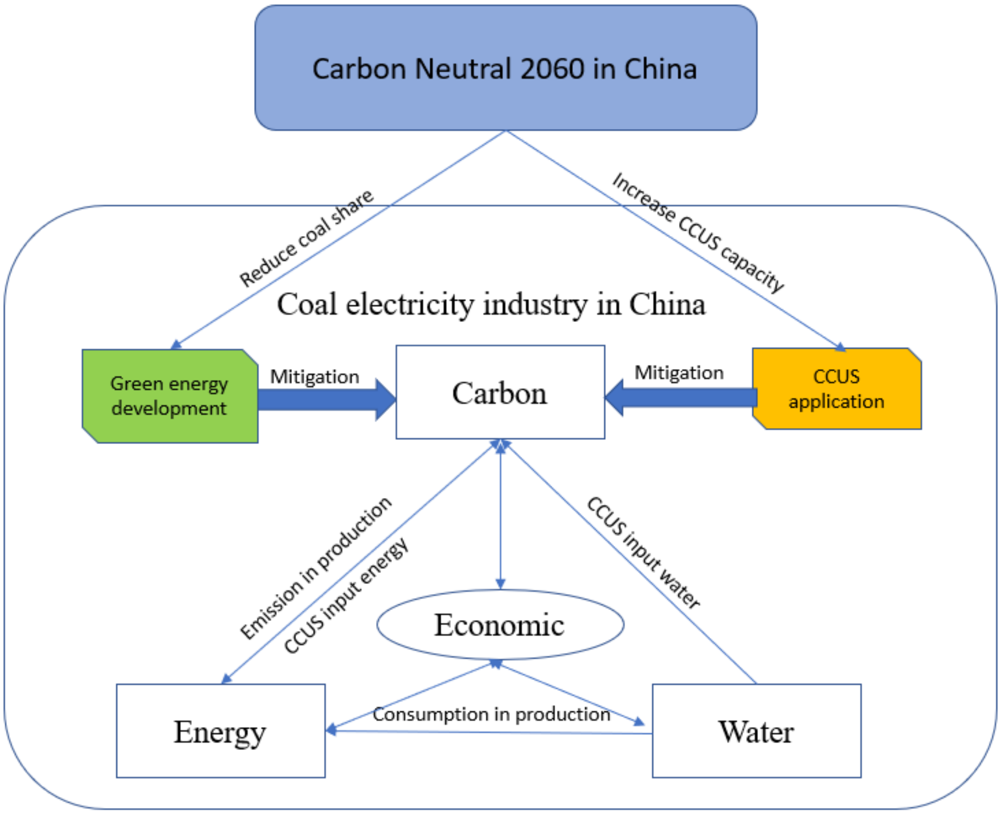

Figure 4.1 The conceptual framework of Chapter 4

The life cycle of coal electricity production is directly linked to energy, water, carbon emission, and financial profits. The life cycle of coal electricity production includes coal mining and washing, coal transportation, and coal electricity production in power plants. Each process has a carbon, energy, water footprint and is associated with economic measurement. This also works for the implementation of CCUS in coal industries with the extra energy, water footprint, and the financial profit regarding Carbon trade. Therefore, considerations for energy portfolio development and policies should endeavor the tradeoffs and synergies study on elements including energy, carbon, water, and economic profits (Fig. 4.1).

By applying scenarios that consist different degrees of coal power share reduction and CCUS implementation, the quantitative output of the total amount of water/energy consumption including reduced consumption in life cycle coal power production and the increased amount water/energy used through CCUS application is needed from natural resource intensive consideration. The total carbon emission from the coal power system is critical for carbon-neutrality goal accomplishment. The general financial profits from the Chinese coal power system are also crucial for the economy.

4.2.2 The Assessment Tool for Portfolios of Coal power production under Carbon neutrality goals (ATPCC)

To study the tradeoffs and synergies of two main carbon neutral policy impacts on the CEW nexus in the Chinese coal power system with complex interconnections, we proposed and developed a framework named "The Assessment Tool for Portfolios of Coal power production under Carbon neutrality goals" (ATPCC). This tool was the first to integrate all of China's coal production processes, including carbon, energy, water, and profit, with a CEW nexus system approach under coal power portfolios in China. The scenario-based ATPCC enables policymakers to create coal electricity portfolios based on carbon-neutral policies. Policymakers could assess portfolio scenarios' ATPCC outputs by evaluating the CEW and economic sustainability in China's coal industry.

The ATPCC (Fig. 2) provides quantitative factors for the life cycle of coal power production in four sub-processes: coal mining and washing/refining, coal transportation to power plants, coal-fired electricity production in power plant, and the CCUS application in coal power plant. The quantitative parameters, factors, and their predicted changing trend in the future from 2020 to 2060 are coming from literature and consultation with experts. The energy consumption studied in the tool includes nine types of energy sources: raw coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas, and electricity. They are all measured as standard coal with transformation coefficients (Liu et al., 2019).

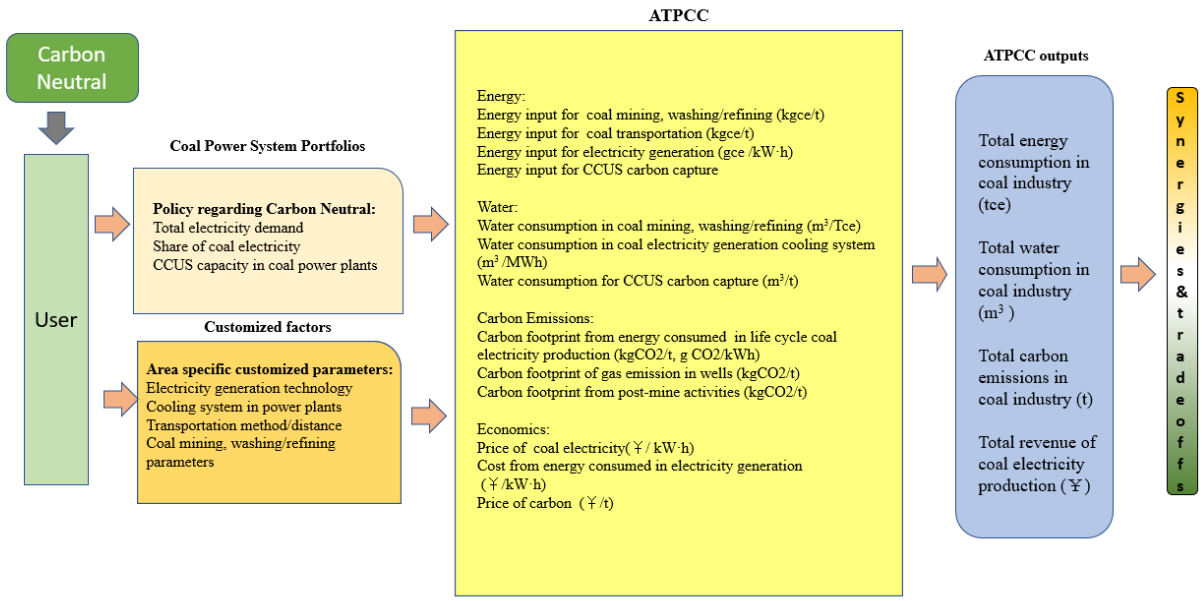

Figure 4.2: The ATPCC structure

In the coal mining and washing/refining process, there are around 4,700 coal mine pits in China, and approximately 7% of the coal comes from imports. Based on the national statistics on coal processing, the tool provides average parameters for all the domestic and imported coal, where most of the imported coal is raw coal and still participates in the washing/refining process (Wu & Yue 2013). Parameters include energy consumption, carbon emission, water consumption, and financial cost. The energy consumption aggregates the whole energy inputs of all mechanical equipment used across the entire process, including shearers, road headers, washing equipment, transportation equipment in the well, and power boilers for workers. The carbon emission is the sum of three subparts: energy-related emission, carbon emission equivalent from underground mine gas emission, and post mining emissions. Water consumption is the sum of water usage in mining and cooling without considering the grey water footprint. The financial cost is the price of the sum of the energies used.

The tool provides the average distance of coal transportation to power plants in highways and railways in the transportation process. The energy consumption factors come from the sum of the usage of diesel and electricity. Carbon emission parameters are calculated based on energy consumption. The energy consumption also calculates financial costs. In coal-fired electricity generation, the tool provides two different options for inputs scenarios. Besides the usage of average factors, by offering the parameters of selected types of electricity generation sets, the portfolio can provide the usage percentage of sets usage to get a unique factor for each scenario. The ATPCC provides factors and sets parameters for average energy consumption, carbon emission related to energy, water consumption, and the cost of energy used. The tool also offers the extra energy and water consumption factors for CCUS application in coal power plants.

The ATPCC is a policy-driven, carbon-energy coupling effective tool, allowing users to apply it to any governance level or geographic area with the coal industry and under China's carbon-neutral requirements. The user input portfolios comprise two major sub scenarios: the total electricity generation from the coal industry and the total carbon captured by CCUS in the coal industry. Additionally, there is also a customized option for users to input electricity generation and cooling sets status in the power plant or directly replace parameters and their changing trend in ATPCC based on their status quo.

Given the scenarios inputs and the potential customized parameters, the tool can quantifying deliver the following outputs of the life cycle coal industry in China: total water consumption, total energy consumption, total carbon emissions, and total financial profits. Thus, a tradeoff analysis can be drawn based on ATPCC outputs and help policymakers find a sustainable pathway for coal power development. The customization feature of ATPCC can help local users to generate area-specific scenarios and the related tradeoff analysis.

4.3 ATPCC model parameters

4.3.1 Energy consumption in life-cycle coal electricity production

The energy consumption in life-cycle coal electricity can be present as a function that aggregates the energy input in mining and washing/refining, transportation, and coal combustion in power plants. Nine types of energy had been counted, including raw coal and electricity.

$$E_{Life\ Cycle} = E_{mine\ and\ wash/refine} + E_{transportation} + E_{electricity\ production}$$

4.3.1.1 Energy consumption in coal mining and washing/refine

$$E_{mine\ and\ wash/refine} = M * e_{mine\ and\ wash/refine}$$

$$e_{mine\ and\ wash/refine} = \sum_{i}^{9} \alpha_i \times T_i$$

Where M is the total raw coal consumed in powerplant. $e_{mine\ and\ wash/refine}$ is the energy consumption factor that represents the average energy consumption of coal supply. Ce is a unit for standard coal. α_i represent the conversion coefficient for each energy source to standard coal (ce). i=1， 2， ...， 9 indicates for raw coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas, and electricity, respectively. T_i is the mean energy input for unit coal production. Parameters of α_i, T_i and average $e_{mine\ and\ wash/refine}$ are shown in Table 4.1.

Table 4.1 Conversion coefficient of standard coal with different energy sources and unit energy consumption in coal mining and washing/refining process and transportation

Energy category	Comprehensive	Coal	Coke	Oil	Gasoline	Kerosene	Diesel	Fuel oil	Natural gas	Power
Convert coefficient (kgce/kg) or（kgce/m^3）or（kgce/kW·h）		0.7143	0.9714	1.4286	1.4714	1.4714	1.4571	1.4286	1.33	0.172
Energy consumption in coal mining and washing/refine by sources		27.3	0	0	0	0	0.21	0	2.4	9.3
Energy consumption of coal mining and washing converted for standard coal（kgce/t）	24.6	19.5	0.0	0.0	0.0	0.0	0.3	0.0	3.2	1.6
Energy consumption in coal transportation（kgce/t）	4.15				0.48		2.48			1.19

The current value of $e_{mine\ and\ wash/refine}$ is 24.6 kgce/t, but there is a continuous historical improvement of mechanization level of coal mining and washing in China and thus there is a good possibility to reduce the energy consumptions in the future (Zhang et al., 2019). The average energy consumption in coal mining and washing decreased rapidly from 30.6 kgce/t in 2010 to 24.6 kgce/t in 2020, with an average annual declining rate of 2.1% (Yan 2022). We assume such a declining trend would last till 2060, the predicted factor shown in table 4.2.

Table 4.2 Prediction of future trend of comprehensive energy consumption

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Comprehensive coal consumption of coal mining and washing (gce/t)	24.6	20.1	16.4	14.0	12.1	10.9	9.9	9.4	8.9
Comprehensive coal consumption in power generation and power supply (gce/kWh）	351.2	342.5	334.1	325.8	317.8	309.8	302.1	294.7	287.4
Coal consumption of coal power generation and power supply (gce/kWh)	305.5	297.9	290.6	283.4	276.4	269.5	262.8	256.3	250.0

4.3.1.2 Energy consumption in coal power transportation

When we consider only domestic transportation, the average coal transport distance is 651km in railway and 162.7km in the highway. The railway coal transport is around 80% and 20% for highways (Statistical yearbook 2020). The average energy consumed in the railway has 55% of diesel and 45% of electricity. The mean fuel mix of highway transport is 68% diesel and

32% gasoline. The energy intensity for coal transportation in railways and highways are 5.06/t·km and 46.53 gce/t·km, respectively (Ou et al., 2010).

Therefore, the energy consumption of coal transportation function is:

$$E_{transportation} = M \times e_{transportation}$$

$$e_{transportation} = \sum_{i}^{2} \theta_i \times D_i \times \ni_i$$

Where θ_i represent the percentage of coal transported by transportation types, $\ni_i$ represent the average energy consumption by distance, D_i represent the average distance for transportation types, i=1,2 is railway and highway.

The calculated average $e_{transportation}$ value is 4.15 Kgce/t and would apply in this study (Table 4.1). Waterway coal transportation also exists in China, but most of the studies and the statistic yearbook suggest only considering railway and highway transportation of coal. This may lead to an underestimate of the energy consumption and the related carbon emission by 32-38 times (Peng et al., 2021). However, we still use this number due to the lack of historical data and references. We also assume the energy consumption factor in coal transportation will remain the same in the future.

4.3.1.3 Energy consumption in coal power generation

There are many kinds of coal electricity generator sets in the Chinese coal-fired power industry, separated by the type (domestic, subcritical, supercritical, ultra-supercritical); capacity and the cooling method (air/water cooling). We specified nine typical sets and provided the unit consumption parameters for each energy source in table 4.3. Thus, the total energy consumption in coal electricity can be calculated by

$$E_{\text{electricity production}} = \sum_{i,j} (Q \times \phi_{ij})\, e_{\text{ij}}$$

Where Q is the total production of coal electricity, ϕ_{ij} is the share of different typical sets used, e_{ij} is the unit energy consumption for each typical set, and the conversion standard coal is based on coefficients listed in Table 4.1. The results are shown in Table 4.3 (Want et al., 2019).

Table 4.3 Energy consumption of power generation under different capacities of typical units

Type	Capacity (MW)	Comprehensive (gce /kW·h)	Coal (gce /kW·h)	Coke (mgce /kW·h)	Oil (mgce /kW·h)	Gasoline (mgce /kW·h)	Kerosene (mgce /kW·h)	Diesel (mgce /kW·h)	Fuel oil (mgce /kW·h)	Natural gas (gce /kW·h)	Power (gce /kW·h)
Domestic	100	417.9	363.5	114.6	0.45	85.1	8.1	195.1	13.3	15.96	38.01
Domestic	125	342.7	298.1	94.0	0.37	69.8	6.7	160.0	94.0	13.1	31.2
subcritical	300 Water-cooling	326.9	284.3	89.6	0.35	66.6	6.3	152.6	89.6	12.5	29.7
Supercritical	660 Water-cooling	314.2	273.3	86.2	0.34	64.0	6.1	146.7	86.2	12.0	28.6
subcritical	600 Water-cooling	321.9	280.0	88.3	0.34	65.6	6.2	150.3	88.3	12.3	29.3
ultra-supercritical	660 Water-cooling	294.2	255.9	80.7	0.31	59.9	5.7	137.4	80.7	11.2	26.8
ultra-supercritical	600 Air-cooling	341.1	296.7	93.5	0.36	69.5	6.6	159.3	93.5	13.0	31.0
subcritical	600 Air-cooling	337.7	293.7	92.6	0.36	68.8	6.6	157.7	92.6	12.9	30.7
ultra-supercritical	1000 Water-cooling	303.4	263.9	83.2	0.32	61.8	5.9	141.7	83.2	11.6	27.6

The current energy consumption factor in electricity generation $e_{electricity\ production}$ is 351.2 gce/kW·h (Table 4.4). According to the China Energy Big Data Report (2021), the average coal consumption of Chinese coal-fired power generation also has had a declining trend in the last decade. Reduced from 385.4 gce/kW·h in 2010 to 362.1.0gce/kW·h in 2015, with an average annual reduction of 1.2%, slowly decreased to 351.2 gce/kW·h in 2020, with a slighter yearly average decrease of 0.6%. Therefore, we assume the annual reduction rates coal-power energy consumption will remain 0.5% till 2060. The specific predicted energy and coal consumption are shown in Table 4.2, with the assumption that the proportion of energy consumption in coal power production will not change.

Table 4.4 Unit energy consumption in coal power plant and the proportion of energy consumption

Energy category	Integrated	Coal	Coke	Oil	Gasoline	Kerosene	Diesel	Fuel oil	Natural gas	Power
Energy consumption in coal power generation （gce /kW·h）	351.2	305.5	0.1	0.0	0.1	0.0	0.2	0.0	13.4	32
Proportion of energy consumption （%）	100.00	86.98	0.03	0.00	0.02	0.00	0.05	0.00	3.82	9.10

4.3.2 Carbon emission in life-cycle coal electricity production

The carbon emissions in life-cycle coal electricity production process can be divided into three categories: carbon emissions from energy consumption, gas emissions in mining (carbon emissions equivalent) and post-mine coal emissions (DROC 2014). Energy-related emissions are the emissions through the consumption of input energy. Gas emissions in mining mainly represent the CH4 escaping from wells and open-pit mining before and during mining (converted to Carbon emission). Post-mine activities carbon emissions are the emissions from open-pit mining, abandoned mines, and fugitive emissions during transportation, washing, refining, and storing raw coal. The function of total carbon emission is:

$$C_{Life\ cycle} = C_{energy\ consumption} + C_{gas} + C_{postmine}$$

The carbon emission related to energy consumption can be calculated by the total energy consumption times the carbon intensity coefficient widely used in then Chinese industry, δ = 2.66 kg CO2/kgce (Tu & Liu 2014). Therefore, we can have the function of carbon emission from energy input in function:

$$C_{energy\ consumption} = \delta \times E_{life\ cycle}$$

The prediction on future trend on carbon emission intensity following the same trend of energy intensity and shown in Table 4.5.

Table 4.5 Prediction of future trend of carbon emission intensity life cycle coal electricity production

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Carbon emission intensity of coal mining and washing/refine (kg CO2/t)	65.4	58.8	52.9	49.0	45.5	43.2	41.1	40.1	39.1
Carbon emission intensity of coal transportation (kg CO2/t)	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46
Carbon emission intensity of coal-fired power supply (g CO2/kWh)	934.3	911.0	888.7	866.7	845.3	824.2	803.7	783.8	764.5
Gas carbon emission intensity per ton of coal (kgCO2/t)	67.6	50.1	37.2	27.6	20.5	15.2	11.3	8.4	6.2
Carbon emission intensity of post-mine activities (kgCO2/t)	18.0	16.5	15.2	13.9	12.8	11.7	10.8	9.9	9.1

Coal mine gas is one of the most important sources of carbon emissions in coal production (Miller et al., 2019). The carbon emission of gas emissions in coal mining and washing mainly lies in the direct emptying after gas extraction (Zhou et al., 2020). In recent years, with the improvement of the utilization rate of gas extraction, the carbon emission intensity of gas per ton of coal has shown a trend of gradually declining, from 123.7 kgCO2/t in 2010 to 67.6 kgCO2/t in 2020, with an average annual reduction rate of 5.8% (Li 2021). Therefore, we assume the carbon emission intensity of coal gas emissions per ton of gas will continue to decrease at an average annual rate of 5.8%, as shown in Table 4.5.

Carbon emissions from post-mine activities refer to the amount of gas discharged during storage, transportation, and stacking after the coal is lifted and transported out of the mine, the gas content remaining in the coal. In recent years, with the widespread application of mine gas drainage prevention and control technologies before and during mining, the carbon emission intensity of activities after ton of coal mines has also shown a trend of gradually decreasing, from 21.5 kgCO2/t in 2010 to 18.0 kgCO2 in 2020 /t, with an average annual reduction rate of 1.7% (Li et al., 2021). Therefore, we assume that it will continue to decrease at an average annual rate of 1.7%, shown in table 4.5.

4.3.3 Water consumption in life cycle coal electricity production

The summation function can express the water consumption in the life cycle of coal electricity production for water consumption in coal mining and washing/refining and water consumption in the cooling system of coal electricity production. We ignored the water consumption in coal transport since it only accounts for less than 1% of the total water consumption (Zhu et al., 2020).

$$W_{life\ cycle} = W_{mine\ and\ wash/refine} + W_{electricity\ production}$$

4.3.3.1 water consumption in coal mining and washing/refine

The water consumption in coal mining and washing/refining is the summation of mining, washing, processing, and dressing. Water consumption varies greatly in different regions of China, which is mainly determined by the water resources, economic conditions, and mineral conditions in different regions. from 0.34 to 3.5 m^3/t (Shang et al., 2018). The average coal mining and washing/refining consumption is estimated 3.1 m^3/t in 2020. A continuous declining trend of water consumption in coal mining and washing is predicted and assumed that after 2030, the water consumption will reach the level of water areas in western China. The predicted water consumption is shown in Table 4.6.

Table 4.6 Prediction of future trend of water consumption factors

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Water consumption in coal mining and washing	3.1	2.55	2	1.35	0.85	0.68	0.47	0.33	0.14
Water consumption in coal power generation (m^3/MWh)	1.34	1.22	1.10	1.00	0.90	0.80	0.75	0.71	0.68

4.3.3.2 water consumption in coal electricity production

Generally, the cooling method in Chinese coal electricity generator sets can be divided into three categories: closed-loop cooling; open-loop cooling and air cooling. We picked 12 typical cooling sets for a customized cooling portfolio. Thus, the total water consumption in coal electricity can be calculated by:

$$W_{electricity\ production} = Q \times \sum_{i,j}^{12} w_{ij} \times \gamma_{ij}$$

Where the Q is the total electricity generated, γ_{ij} represents the percentage of the total electricity generated by each set, w_{ij} represent the water consumption intensity for each set (Table 4.7).

Table 4.7 water consumption coefficient in coal power generation

Cooling Method	Capacity (MW)	Leading (m^3/MWh)	Advanced (m^3/MWh)	Base (m^3/MWh)
Closed-loop cooling	<300	1.73	1.85	3.20
	300	1.60	1.70	2.70
	600	1.54	1.65	2.35
	1000	1.52	1.60	2.00
Open-loop cooling	<300	0.25	0.30	0.72
	300	0.22	0.28	0.49
	600	0.20	0.24	0.42
	1000	0.19	0.22	0.35
air cooling	<300	0.30	0.32	0.80
	300	0.23	0.30	0.57
	600	0.22	0.27	0.49
	1000	0.21	0.24	0.42

Due to technological development and changes in national water-saving requirements, the water consumption of coal-fired power generation has a downward trend. Based on the literature (Li et al., 2021; Zhang et al., 2018; Zhang & Li 2020), the average water consumption factor is 1.34 m^3/MWh. We also provided a prediction on its changing trend in table 4.6.

4.3.4 Profits in life-cycle coal production

The economic profits of coal electricity production can be calculated through the difference of income and the cost of energy consumed in life-cycle coal power production, including coal and other energy inputs.

$$Profit_{\text{life cycle}} = price_{electricity} \times Q - Q \times Cost_{\text{life cycle}}$$

$$Cost_{\text{life cycle}} = Cost_{electricity\ production}$$

Table 4.8 Different energy consumption costs per unit of power generation in coal power plant

Energy category	Comprehensive	Coal	Coke	Oil	Gasoline	Kerosene	Diesel	Fuel oil	Natural gas	Power
Energy prices (￥/tons) or (￥/m³) or (￥/kW·h)		600	2600	4800	5700	3600	4800	3600	3.40	0.45
Energy consumption of coal power generation (gce/ kW·h)	351.2	305.5	0.1	0.0	0.1	0.0	0.2	0.0	13.4	32.0
Cost of coal power generation (￥/kW·h)	0.397	0.26	0.03	0.00	0.00	0.00	0.00	0.00	0.03	0.08

Since the cost of coal mining, washing, and refining are included in the energy price, we only calculate the profits in coal power plants. The energy price for energy inputs and the calculated $Cost_{electricity\ production}$ is shown in table 4.8.

It is hard to predict the changing trend of raw material and currency inflation. Therefore, we assume the price of all energy inputs raw materials remain unchanged through years. However, the cost is declining due to the reduction of unit energy consumption, The predicted cost and profits are shown in Table 4.9.

Table 4.9 Prediction of energy consumption cost in the future

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Cost of coal power generation(￥/kW·h)	0.40	0.39	0.38	0.37	0.36	0.35	0.34	0.33	0.32

4.3.5 The CCUS impacts

4.3.5.1 CCUS impact on energy and water consumption

Implementation of CCUS projects consumes water and energy during the progress of capturing and storing carbon. The additional energy consumption is around 68.2-85.4 (kgce/t) (Zhang et al., 2021) and the water consumption is around 20 to 40 (m^3/t). There is no clear evidence for the development level of CCUS technologies. We here provide our prediction that the intensity of water and energy consumption by the CCUS processes will decrease with an average annual rate of 5% and the results are shown in Table 4.10.

Table 4.10 Prediction of the increased water and energy consumption with CCUS

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Increase in energy consumption by adding CCUS (kgce/ton)	76.8	59.4	46	35.6	27.5	21.3	16.5	12.8	9.9
Water consumption increase intensity (m3/ton)	30	23.2	18	13.9	10.8	8.3	6.4	5	3.9

4.3.5.2 CCUS impacts on economic profits

The national carbon trading market was officially established in December 2017. The first batch of about 1,700 power generation enterprises was selected be involved in the carbon emissions trading market. (Yi et al., 2019; Wang & Zhao 2019). In 2020, China's average carbon trading price is 28.6 yuan/ton. There are various types of predictions on the carbon price, the price is expected to grow in the future, and the driver includes inflation and, most likely, carbon policy (Staler et al., 2021). We excluded the inflation impact under the assumption of no change of energy and electricity prices. An official survey has shown that the carbon price in 2021-2022 is around 50 yuan/ton and is expected to reach 87 and 139 yuan/ton in 2025 and 2030, respectively (Staler et al., 2021). Based on the 25% yearly increase rate between 2020-2025 combined with the 10% annual increase rate between 2025-2030 calculated from this prediction, this study provides assumptions for the future that the increasing annual rate is 9% in 2030-2040, 8% in 2040-2050, and 7% in 2050-2060. The predictions are shown in table 11. Carbon price would reach 710 yuan/ton and 1397 yuan/ton in 2050 and 2060. This is lower than the prediction of the World energy outlook (Cozzi et al., 2019) that the carbon price would reach 250 $/ton in advanced economies and 200 $/ton in China in 2050 under a zero-carbon emission world scenario. However, our estimation excludes the impact of inflation, and China's carbon neutrality goal is 2060 rather than 2050. Therefore, based on our prediction, the 2060 carbon price of 1397 yuan/ton or 216 $/ton fits into the 200-250 $/ton range and is more reasonable for this study.

Table 4.11 Prediction on carbon price in 2020-2060

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Carbon Price (yuan/ton)	28.6	87	139	214	329	483	710	996	1397

4.4 Case study for China's coal power industry before 2060

4.4.1 Scenarios of ATPCC inputs for China's coal power industry before 2060

4.4.1.1 Baseline Scenarios

4.1.1.1.1 Predicted electricity demand in China

Literature has forecasted future electricity demand in China using various methods and models based on key indicators. We selected an integrated prediction based on literature (Xie et al., 2021), which calculated the average of seven existing models and applied it to the baseline scenario input as shown in table 4.12.

Table 4.12 Prediction of future electricity demand in my country

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Electricity demand (trillion kWh)	7.4	8.8	10.2	11.3	12.2	13.1	13.6	14.1	14.4

4.1.1.1.2 Predicted change of the coal-electricity share

The proportion of coal-fired power generation in China has dropped from 67.9% to 60.8% in 2015-2020. We further applied the companion prediction with electricity demand in the previous study by Xie et al. (2021) as baseline scenario input for coal electricity share (Table 4.13).

Table 4.13 Baseline scenario for coal electricity share in future

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Coal electricity share	60.8	49.9	40.9	33.5	27.5	22.5	18.5	15.2	12.4

4.1.1.1.3 Predicted change of the CCUS application in coal electricity production

According to the statistics collected by the Ministry of Science and Technology for CCUS demonstration projects nationwide, since the first CCUS demonstration project in China was put into operation in Shanxi in 2004, there are 38 CCUS projects operated before 2020, with a total capacity of 5 mtons/year (Zhang et al., 2021). Under the carbon neutrality target, the overall emission reduction demand of CCUS in China is 20~408 mt CO2 in 2030, 600~1450 mt CO2 in 2050, and 1~1.82 bt CO2 in 2060 (Cai et al., 2021). According to the CCUS special report of the International Energy Agency's power operation and maintenance platform, CCUS emission reduction capacity is expected to grow rapidly (IEA 2020). The capture scale of CCUS in China’s thermal power plants is about 190 mt CO2/a by 2030; about 770 mt CO2/a by 2050; and exceed 1.2 bt CO2/a by 2070. Based on the prediction, we deliver a new forecast of carbon mitigation from CCUS in Table 4.14 and take it as the input for the baseline portfolio.

Table 4.14 2020~2060 Coal power and national CCUS carbon dioxide emission reduction demand for baseline scenario

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
From Coal Power (mtons/Year)	3	20	190	370	520	655	775	880	985
Total carbon mitigation (mtons/Year)	5	9-30	20-408	119-850	370-1300	500-1350	600-1450	800-1650	1000-1820

4.4.1.2 Alternative portfolios and the difference with the baseline scenario

4.4.1.2.1 share of coal-electricity

The baseline scenario on coal electricity production share change is based on the study by Xie et al. (2021). The prediction is based on an assumed scheme of 18% of change for every five years. Combine with the fact that the proportion of coal-fired power generation in China has dropped from 67.9% to 60.8% in 2015-2020 and the enhanced efforts of energy transition after 2020. Another radical prediction had been made in that study as well for 23% decreasing of coal power share in every five years. However, there is a chance that the green energy transition would not goes well. But in the context of globally removal of coal power, even in the slow case, the reduction rate should faster than that in 2015-2020. Therefore, we assume the "slow" declining rate of coal electricity share in China would be 13% in every five years. Three portfolios representing three levels of carbon mitigation would be generated and further applied on ATPCC, named "Baseline", "Slow", and "Radical", respectively. The portfolios input of coal electricity share is shown in table 4.15.

Table 4.15 Scenarios for coal electricity share

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Coal electricity share (Baseline)	60.8	49.9	40.9	33.5	27.5	22.5	18.5	15.2	12.4
Coal electricity share (Slow)	60.8	52.9	46.0	40.0	34.8	30.3	26.4	22.9	20.0
Coal electricity share (Radical)	60.8	46.8	36.0	27.8	21.4	16.5	12.7	9.8	7.5

4.4.1.2.2 Carbon emission mitigation from CCUS

Based on the baseline scenario input of CCUS capture capacity, we further developed the inputs for carbon capture through CCUS for “Slow” and “Radical as the 80% and the 120% of the baseline CCUS carbon emission capacity. Where the two “slow”s are connected and reflect a less carbon emphasized future. “Radical represents the other way around. Thus, the prediction reflects the different levels of carbon neutral policy constraints and the CCUS capture capacity are shown in table 4.16.

Table 4.16 Scenarios inputs for CCUS carbon capture in 2020-2060

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
CCUS capture in Coal power plants (mtons/Year) (Baseline)	3	20	190	370	520	655	775	880	985
CCUS capture in Coal power plants (mtons/Year) (Slow)	3	16	152	296	416	524	620	704	788
CCUS capture in Coal power plants (mtons/Year) (Radical)	3	24	228	444	624	786	930	1056	1182

4.4.2 ATPCC assessment results for China’s coal power industry before 2060

4.4.2.1 Scenarios outputs

4.4.2.1.1 Baseline scenario outputs

The baseline portfolios are the expected or the most likely future in 2060 with the coal power share decrease to 12.4%, falls in the median of interval between the 20% claimed by the conservative studies and the less than 10% invoked by radical studies. In addition, around one billion tons of carbon could have been captured by CCUS applications. Outputs in Table 17 indicate that, in 2060, through the two-handed carbon mitigation efforts, total carbon emissions would reduce to 0.4 billion tons and thus very close to the carbon neutrality goal. Total energy consumption has a trend of first increasing and then decreasing with a peak year in 2040-2045. Extra energy consumption from the CCUS application would overtake the energy consumption from life-cycle coal production between 2025 and 2030. The total water consumption has an overall decreasing trend due to the technology development and the reducing amount of coal production. Extra water consumption from CCUS overtakes the water consumption from life-cycle coal production in 2035-2040. Total revenue in 2060 is highest among all three scenarios and is 6.4 times of the revenue in 2020 for China's coal industry, where 86% of the total revenue comes from the carbon trade through the CCUS application. The carbon trade becomes the dominant economic profits source would occur between 2040-2045 and closely to 2045.

Table 4.17 ATPCC Output of baseline portfolio

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Total energy (only coal?) consumption (Billion tce)	2.4	3.1	10.4	14.6	15.5	15.0	13.6	12.0	10.3
Energy consumption from CCUS (Billion tce)	0.2	1.2	8.7	13.2	14.3	14.0	12.8	11.3	9.8
Total water consumption (Billion m^3)	12.7	10.5	11.4	11.0	9.7	8.6	7.3	6.2	5.1
Water consumption from CCUS (Billion m^3)	0.1	0.5	3.4	5.1	5.6	5.4	5.0	4.4	3.8
Total carbon emission Billion tons (Billion tons)	4.8	4.2	3.7	3.0	2.4	1.8	1.3	0.8	0.4
Revenue from CCUS carbon trade (Billion Yuan)	0.1	1.7	26.4	79.2	171.1	316.4	550.3	876.5	1376.0
Total revenue (Billion Yuan)	251.2	277.7	328.1	388.4	475.6	610.4	823.1	1127.0	1599.4

4.4.2.1.2 Slow scenario outputs

In the "Slow" portfolio for coal power industry development, 20% of the coal electricity contributions to the electricity mix will remain in 2060, and around 0.8 billion tons of carbon will be captured annually through CCUS facilities in coal power plants. The total energy consumption will increase and then reduce, with the peak in 2040-2045 as in the baseline scenario (Table 18). Overall carbon emission is around 1.5 billion tons in 2060, three times the emissions in the baseline portfolio. The total consumed energy would be 8.7 billion tce, much less than the baseline portfolio. The extra water consumption of CCUS would overtake the water consumption in life-cycle coal power production in 2040-2045. Different from the occurrence time in the baseline scenario between 2035 and 2040. The total revenue in China's 2060 coal industry would increase 481% from the income in 2020. Economic benefits from carbon capture would overtake the electricity in 2045-2050, close to 2050. Fall behind from the baseline scenario. The CCUS profits would reach 75% of the total revenue in 2060.

Table 4.18 ATPCC outputs of “slow” portfolio

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Total energy consumption (Billion tce)	2.4	2.9	8.9	12.3	13.0	12.6	11.5	10.1	8.7
Energy consumption from CCUS (Billion tce)	0.2	1.0	7.0	10.5	11.4	11.2	10.2	9.0	7.8
Total water consumption (Billion m^3)	12.7	11.0	11.7	11.1	9.7	8.5	7.3	6.2	5.2
Water consumption from CCUS (Billion m^3)	0.1	0.4	2.7	4.1	4.5	4.4	4.0	3.5	3.1
Total carbon emission Billion tons (Billion tons)	4.8	4.5	4.2	3.8	3.3	2.8	2.3	1.9	1.5
Revenue from CCUS carbon trade (Billion Yuan)	0.1	1.4	21.1	63.3	136.9	253.1	440.2	701.2	1100.8
Total revenue (Billion Yuan)	251.2	293.9	360.5	432.5	522.3	649.0	829.6	1078.6	1461.1

4.4.2.1.3 Radical scenario outputs

The radical scenario has the least coal electricity share, only 7.5% in 2060, and with the greatest CCUS capacity, 1.2 billion of carbon could be captured through the CCUS application. However, we could notice from Table 19 that the CCUS capacity cannot be fully utilized at that time because the zero-carbon emission in coal power plant could have been achieved between 2055-2060. We proved that, through the energy transition and the CCUS technology utilization, carbon neutrality goals could be achieved even in coal power plants. The total carbon emission for the system would be very close to zero and thus would lead to the accomplishment of the national carbon neutrality goal. The output of this portfolio has the most minor energy consumption but the same changing pattern through the years as other portfolios. It also accounts for the least overall water consumption. The percentage of water consumption from CCUS would achieve to take more than half of the total water consumption between 2030-2035. This portfolio will create the least revenue of the three portfolios, but this is the fastest for carbon trade to dominate the incomes of the coal industry, between 2040-2045 and close to 2040. The total revenue in 2060 is 5.2 of the revenue in 2020, and the carbon trade would account for 90% of the total financial profits of China's coal industry.

Table 4.19 ATPCC outputs of "radical" portfolio

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Total energy consumption (Billion tce)	2.4	3.2	12.0	17.0	18.1	17.5	15.9	14.0	8.6
Energy consumption from CCUS (Billion tce)	0.2	1.4	10.5	15.8	17.2	16.7	15.4	13.5	8.2
Total water consumption (Billion m^3)	12.7	10.0	11.1	11.0	10.0	8.8	7.6	6.4	4.0
Water consumption from CCUS (Billion m^3)	0.1	0.6	4.1	6.2	6.7	6.5	6.0	5.3	3.2
Total carbon emission Billion tons (Billion tons)	4.8	3.9	3.2	2.4	1.7	1.0	0.5	0.1	0.0
Revenue from CCUS carbon trade (Billion Yuan)	0.1	2.1	31.7	95.0	205.3	379.6	660.3	1051.8	1159.5
Total revenue (Billion Yuan)	251.2	260.9	297.3	351.6	442.3	595.2	847.6	1213.3	1294.6

4.4.2.2 Trade-offs between scenarios of China's coal power industry before 2060

Carbon emissions mitigation is the most critical goal in the carbon-neutral context. The coupled policy implementation of energy transition and CCUS applications have synergy to improve carbon mitigation. Unintended, complex consequences of these policy implementations also lead to tradeoffs between carbon emission reduction and water/energy consumption. The radical portfolio has the potential to achieve zero-carbon emissions, but with significantly higher energy and water consumption companioned.

It is inspiring to show that zero-carbon emission could be achieved in China's coal industry. Nevertheless, compared to the 2055 and 2060 states in a radical portfolio and the outputs from the baseline scenario, we found the benefit of optimized equilibrium between the CCUS combined and the reduced share of coal-generated electricity.

The baseline and the slow scenario almost account for the same amount of water consumption in 2060. However, the slow scenario has a higher coal share and lower CCUS applications. With the same water constraints, energy consumption in the baseline scenario is much larger than in the slow scenario, but more economic profits would be gained. Therefore, choosing between revenue and energy inputs is crucial for energy-stress areas. Tough choices also occur in water-stress areas between radical and slow portfolios. With relatively same energy consumption, the radical portfolio accounts for less water consumption and carbon emissions. But lower economic gains.

The radical portfolio has the most negligible economic revenue, but it also accounts for the least carbon emissions. Besides that, it illustrates a new way for China's coal power industry to increase revenues. The carbon trading profits only accounted for less than 0.1% of the total revenue in China's coal power industry in 2020. But it would reach to more than 50% before 2050 in each scenario. The carbon trading profits would account for around 90% of the total revenue in the radical portfolio. This is an inspiring result for China's coal power industry development. One of the critical reasons is that although it is economically beneficial for coal electricity production in our study, many companies in China's coal industry are in a deficit situation in real life. It is mainly because we didn't include coal power companies' salaries and administration costs. However, the carbon market and the CCUS application could provide a new pathway toward financial profits and had been proven in this study. With the rapid growth amount of captured carbon and the increasing carbon price, the coal industry has the potential to transform the primary revenue source from selling electricity to selling the captured carbon.

4.5 Discussion

4.5.1 ATPCC and CEW models in the literature

Due to the complex interconnections between sectors in the CEW nexus, a comprehensive calculation of the perturbation of each aspect and the impact on the nexus is highly dependent on counting multiple sectors and steps. Therefore, process-based models are widely adopted in CEW nexus studies. The most applied modeling techniques are the environmental input-output (EIO) model and life cycle assessment. The environmental input-output model evolves from the economic input-output model that was designed to represent the interdependencies between different sectors of the economy (Wang et al., 2020a). EIO is very suitable for CEW nexus analysis because it can adequately address both direct and indirect contributions from each sector to the system's dynamics. It was widely applied in the studies on calculating the direct and indirect effects of separate sectors to the CEW nexus (Meng et al., 2019; Wang et al., 2020a; Li et al., 2020) as well as the individual and combined contribution from different regions to the entire study area (Chen et al., 2019; Wang et al., 2020b; Tian et al., 2022).

On the other hand, life cycle assessment is highly associated with all the stages of the life cycle of a product and is commonly used to assess environmental impacts from the entire process (Wang et al., 2018). Life cycle assessment is one of the most suitable approaches for those CEW nexus studies that need to comprehensively count procedural impacts on the CEW nexus from a sector (Lee et al., 2017; Wang et al., 2018; Moure et al., 2019) or industry (Leivas et al., 2020; Ma et al., 2022). However, previous studies mostly worked on a specific case study using EIO or life cycle assessment. In our opinion, it would be instrumental in generalizing these methods into a flexible tool to allow users in different research and spatial areas to fit in their cases and get their desired output. Therefore, we applied life cycle assessment in the process of coal power generation and proposed this method as a tool for customized users' data. In addition to this generalization, we also improve the tool by adding an external factor, CCUS implementation, which imposes a more complex feedback loop to the dynamics of the CEW nexus. Adding

CCUS as a factor in research for the CEW nexus is a significant improvement on this tool to provide more practical and valuable information for the coal electricity industry in China.

Since CEW nexus studies often aim at providing policy recommendations or provide environmental management solutions, scenario analysis is also a widely utilized approach to evaluate and compare the effectiveness of potential environmental acts (Zhu et al., 2017; Lim et al., 2018; Ifaei et al., 2019; Zhou et al., 2019; Zhao et al., 2022). ATPCC is scenario-based to inform future energy policy, especially for the policymakers that care for the coal electricity system in China. The ATPCC as a tool can offer a way to sustainably develop portfolios for China's coal electricity industry under carbon neutrality goals.

4.5.2 Carbon mitigation policies and CEW nexus in China

Findings in the tradeoff analysis between portfolios outputs are crucial. Our results proved the feasibility of carbon neutral 2060 goal in China if it confirms the zero-carbon emission possibility in China's coal industry, which has long been considered the most significant contributor to China's carbon emissions (Li et al., 2020). Most of the mitigated carbon emissions come from the decrease in coal electricity production share in China's electricity system. This is followed by China's green energy transition policy that converts thermal electricity dominated energy systems to renewable energy dominated (Zhao et al., 2022). However, the transformation process may lead to new issues and thus weaken the carbon mitigation efforts. Hydropower accounts for the largest share of renewable energy in China and has long been treated as green energy. However, recent studies raised the contest on its GHG emissions status and proved it can no longer be considered as a comparatively low emissions energy source in the Mekong River basin (Räsänen et al., 2018). The same pattern also happened to bioenergy. Compared with thermal energy sources, biofuels may account for more carbon emissions (Fan et al., 2021). The energy transition could be a solution toward a sustainable carbon mitigated power system in China, but the featured development energy source needs to be considered cautiously.

The regulation on reducing coal shares in China's electricity mix is also of concern. The rapid growth of green energy could put the country's power system into a vulnerable situation. The current dominant renewable energy sources, including hydropower, wind parks, photovoltaic and concentrated solar power plants (PV and CSP) are mostly naturally based. Especially the PV, CSP, and wind power are highly reliant on local weather conditions and possess intense space and time fluctuations. Hybrid power generation, including coupled renewable energy sources, is a proper solution (Wang et al., 2019) but there still is a need for coal energy to sustain the security of energy system (Xie et al., 2021).

Coal transportation is a major carbon emission source in coal power industry. It is due to the long distance between places of coal production and electricity production. Most coal mines are in the western China and the power plants are mostly located in eastern China. The reduced coal electricity shares triggered by the green energy transition could relieve the emission stress from coal transportation. It helped on the water stress related to coal mining and washing where western China has less water resource than the East. Life cycle coal electricity accounts for large amount of water consumption, its water intensity was higher than most of other energy resources, except for nuclear power. In this study, even our result is that the water consumption in coal power industry could not compete with the CCUS water consumption. This is mainly because we only considered the water consumed by evapotranspiration. There is large amount of water withdrawal and use in coal industry that is dissipated back to the environment as polluted water (Zhu et al., 2020). A "greywater footprint" study is needed for further assessment.

CCUS application in coal-fired power plant has been proven crucial and the tradeoffs on extra energy, water consumption should be considered as significant even when it is coupling with the implementation of the energy transition. However, the CCUS had great potential to reduce the extra water consumption by replacing the fracturing water with the captured CO_2 in the CCUS application (Wilkins et al., 2016). The energy transition with reduced shares of coal-powered electricity leads to decreased financial revenue from the coal industry and thus reduces the profits from the energy sector nationally. Despite the high cost of electricity in renewable energy sources compared to coal, re-arranging and treatment on abandoned coal power facilities leads to more investments. However, the revenues from the captured carbon through CCUS application can fill this gap and have potential to make more profits. A win-win future can be delivered through the well-organized coupling of CCUS applications and coal power reduction through energy transition, both economically and environmentally.

4.5.3 Limitations of the study

The APTCC tool was developed with a certain number of assumptions, similar to some other predictive models. Some assumptions are approximate due to limited data availability. Further, some parts within the life cycle coal electricity production were excluded in the dissertation. For instance, I only calculated the domestic transportation of imported coal, not including the transportation costs before coal arrives in China. Another thing is that, as mentioned earlier, I only accounted for the water consumption but not the water withdrawal. To simplify the calculations, I didn't track the energy associated with treatments of the waste and polluted water. Therefore, the indirect energy, water consumption, carbon emission, and economic costs were not included in the model, including the building of power plant, wells and the CCUS facilities. An enhanced and more comprehensive consideration in the ATPCC could be conducted when required data become available.

Furthermore, the parameters in ATPCC are all in the form of a single number, rather than a range to consider variations from different locations, different years, and different sectors. A fuzzy random number method to replace old parameters could be applied in ATPCC if users want to import uncertainty into the tool. The fuzzy set is commonly used to generalize a regular fuzzy number, and it does not refer to one single value but a connected set of possible values. Each possible value has its weight between 0 and 1 (Dijkman et al., 1983).

As a case study, I applied the ATPCC and three scenarios generated from the literature and our predictions to assess the potential development pathways of China’s coal power industry. However, the credibility of our results, as the predictive power of ATPCC needs to be further verified or validated. However, since the development of CCUS and carbon trade just started within scale and short period of time in China, sporadic data exist but not systematic enough for model verification or validation yet. Therefore, not only the randomness input mentioned above is needed for ATPCC, but a validation section is also needed to fully assess the accuracy of the ATPCC framework now. As such, there is a lack of supplemental data for a trace-back validation for ATPCC. Based on the literature review, however, more data regarding carbon price and CCUS should become available with the official carbon market starting in 2021, but unfortunately not soon enough to validate the current ATPCC model in my dissertation.

4.6. Conclusions

To better understand the synergies and tradeoffs resulting from the energy transition and CCUS application on China's coal power industry, this dissertation first developed a scenario-based life cycle assessment tool on China's coal power industry with carbon neutral efforts, from

CEW and financial perspectives. To comprehensively assess the sustainability of future China's coal electricity system, three portfolios representing different degrees of coal power share reduction in energy transition and carbon captured by CCUS applications are generated.

By applying potential China's coal power industry development portfolios, we demonstrated the possibility of zero-emission possibility in China's coal electricity industry. We also indicated that the extra consumption of water and energy driven by the CCUS application has the potential to lead to resource stress and might be the dominant consumption source in the future. On the other hand, the economic revenue lost in the coal industry because of production reduction can be compensated from the carbon market through the CCUS application. Revenues from the carbon market would be the dominant profit-making source for China's coal power industry in the future.

A comparison among the three ATPCC simulation portfolios showed that the baseline scenario has the highest energy consumption and economic profits but moderate water consumption and carbon emission. The slow scenario has the highest water consumption and carbon emissions, but moderate revenues and energy consumption. The radical scenario has the least carbon emissions, water and energy consumption, and financial profits. Therefore, the most sustainable strategy in the CEW nexus perspective for China's coal power industry is more like the radical portfolio: reduce more coal share and apply as many CCUS facilities as possible. The most profitable scenario is more like the baseline scenario that is trying to balance the energy transition and CCUS application.

The ATPCC is straightforward and flexible for policymakers to assess tradeoffs. The tool provides a simple approach for a complex issue with almost all parameters offered. Policymakers can evaluate the tradeoff by using the tool with only two numerical inputs by portfolios. The customized options for parameters commission are offered and thus can be applied to any level of government and agencies under carbon emission mitigation constraints.

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5. CHAPTER 5: DISSERTATION SUMMARY AND CONCLUSIONS

Main research conclusions

This dissertation evaluates and assesses the sustainability of ongoing carbon-neutral efforts from the water-energy-food nexus perspective. I investigated three specific major carbon mitigation efforts: 1) the large national scale of Conversion of Cropland to Forestland Program (CCFP) in China that represents an effort to enhance land-based carbon sequestration, 2) a large scale, basin wide effort to construct hydropower dams in the Mekong River Basin (MRB) that represents renewable energy development as an alternative to fossil fuels, and 3) a new policy effort in China to gradually reduce coal power production and at the same time promote and implement Carbon Capture, Utilization and Storage (CCUS) activities that represents synergistic carbon emission reduction and carbon sink enhancement efforts.

The results and findings in the preceding chapters address the three different research questions of this dissertation:

1. *"How do the carbon sequestration efforts in China impact its WEF system security and WEF nexus?"*
2. *"How do the carbon emission reduction efforts impact WEF nexus in a way of energy transition, using an example from the hydropower development effects on MRB's local WEF nexus?"*
3. *"How to find an equilibrium solution regarding WE nexus and carbon mitigation in China's coal power industry, under the context of CCUS application and renewable energy transition?"*

Research question #1 was addressed in Chapter 2, where I provided an integrated evaluation of the spatial and temporal changes in the land use and land cover as well as their associated attributes using remote sensing data products. It provides evidence for assessing CCFP implications and the synergy/tradeoff analysis from a WEF nexus perspective. This published article concludes with four points. First, it proves the success of the CCFP policy through the land use and land cover change perspective. A significant amount of cropland is converted to grassland or forest. Second, it provides evidence that CCFP's negative impacts are not substantial. Irrigated cropland was comparatively more productive than rainfed cropland, primarily transformed by the force of urban expansion rather than CCFP. The land parcels converted from cropland to grassland or forest are proved to have high slopes and low productivity. Third, the increasing water yield on vanished cropland pixels indicates a growing water resource triggered by CCFP. Finally, the synergy between energy and proliferating water resources can be observed. As a study that systematically evaluates the impacts of CCFP using WEF nexus observations gained from remote sensing data. It provides a relatively new angle of interdisciplinary assessment toward national policy and how it changes the LULC from a temporal and spatial perspective view.

The research question #2 was addressed in Chapter 3, by examining how renewable energy transition had affected local sustainability from the WEF nexus perspective. In this Chapter, I adopted a traditional experimental design theory to quantitatively examine the "control plots" which represent sub-watersheds without hydro dams, with those "treatment plots" of watersheds with hydro dams. Specifically, I proposed a diagnostic tool based on statistical analysis and indicators to study how unilateral enhancement of energy production (hydropower dams) would affect local sustainability and WEF security. For the first time, the diagnostic tool separated the MRB into two groups and regarded hydropower dams as treatment. Like the way in a clinical trial, WEF, social-economic, and environmental indicators are treated as the "symptom level reflecting the treatment received." By comparing the difference between two groups of sub-watersheds, the diagnostic tools can assess the sustainability of hydropower dam constructions.

There are three main findings in this Chapter. First, it proves that hydropower dams can benefit water resources from availability and stability perspectives. Second, increased water resources in watersheds with hydropower did not increase land-based food production, a perception in the literature. The cropland land cover in the watersheds with dams declined faster than in those without dams. Third, watersheds with hydropower dams did not show a significant degradation trend of greenness compared to other watersheds, suggesting hydropower dams did not result in environmental degradation from greenness perspective. The MRB has a general trend of becoming greener. This assessment tool was applied to MRB but in theory can also be applied to other watersheds, because all indicators are globally available and free to access.

The research question #3 was addressed in Chapter 4, which is to assess the sustainability issue of ongoing China's carbon neutrality efforts: reducing the share of coal power supply and CCUS implementation in coal power plants. This chapter proposed a life cycle scenario-based carbon, energy, and water (CEW) nexus assessment tool to help better understand the tradeoffs in China's coal power industry from CEW and financial perspectives. Three scenarios representing different energy transition levels and CCUS implementation plans were generated to demonstrate how the framework works, using China's coal power industry before 2060 as a case study. Three major findings were drawn from this Chapter: 1) It is feasible to achieve net-zero carbon emission in China's coal electricity industry, if proper actions are taken, 2) The reduced water and energy consumption in the green energy transition and reduction in coal power production could not balance the extra consumption resulting from the CCUS implementations, and 3) the economic revenue lost in the coal industry as a result of reduced coal production can be compensated by the carbon trade mechanism using the credits gained through the CCUS implementation. The major economic profits in China's coal power industry can shift from the electricity centric market to the carbon trade market.

The developed assessment tools in this chapter can help policymakers better regulate and understand the synergies and tradeoffs between two major carbon mitigation efforts in China. With the flexibility in production methods and adaptive parameters, the model developed in this study can be applied for national assessment in China and be utilized in other places that are facing similar issues in their home universities,

Intellectual merit

This dissertation has contributed to a better understanding of the synergies and tradeoffs in carbon-neutral efforts from the WEF nexus and sustainability perspectives. The dissertation fills knowledge gaps regarding the role of carbon-neutral efforts in sustainability from water, food, energy, environment, social-economic, and geographic perspectives.

A theoretical advance was made in the dissertation that synergies and trade-offs among water, energy, food, environment, and socioeconomics in the process of implementing conservation policies can all be systematically examined and assessed, as demonstrated in this dissertation using the China's CCFP program. Methodologically, two state-of-the-art assessment methods were introduced in this dissertation in a new WEF assessment framework with remote-sensing data. One is the statistical grouping method to discern the water-energy-food impacts of the hydropower dams from other factors, using the Mekong River Basin as a case study. The other is a scenario-based method to evaluate the coupled effects of energy transition policies and CCUS implementation in China's national carbon neutrality plan. These methodological contributions to developing and utilizing WEF assessments can help decision makers and scholars to better understand the nexus of carbon-neutral efforts, hydropower developments, and the water-energy-food securities.

In addition to the theoretical and methodological contributions, this dissertation also developed a practical assessment tool kit, where three main carbon-neutral policies were integrated to examine what-if scenarios. Such a tool kid should be useful for policymakers and scholars who are facing complex challenges in carbon emission mitigation, particularly in places where data are limited. The use of remote-sensing observation data in Chapter 2 presents an example of dealing with data scarcity issues, while the diagnostic grouping in Chapter 3 can help science community to discern human impacts from other external driving forces. The scenario-based assessment tool in Chapter 4 should help decision makers to play what-if scenarios for future planning.

Limitations

There are several limitations in this dissertation. In Chapter 2, some results and the related conclusions have potential causal relationship issues, like the relationship between CCFP and the measurement of the significant growth of carbon sink, water, etc. However, these points are not a major issue in this Chapter. For instance, the growing carbon sink is a cooperation of many efforts. CCFP is one of them, the transformation between vanished cropland to grassland and forest can partly prove it. This also happens to the water resource improvement. The CCFP has been proved it could reduce soil erosion and thus increase water conservation. Evidence provided in the chapter that the conversion from cropland to forest could significantly increase the water yield. In short, the CCFP's impact had been proved, but the magnitude on its own is hard to measure.

In Chapter 3, the study only considered the local impacts of hydropower dams. Further, the watersheds were not totally independent and uniformly distributed throughout the basin. Remote upstream dams may also have significant implications on the distant downstream watersheds. Also, only land-based food sectors have been considered, but the MRB depends heavily on fisheries. Since the purpose is to study the unilateral change of energy to the whole WEF nexus, I did not use energy indicators in this chapter. Another limitation in Chapter 3 is regarding the grouping method. The geographical locations of the hydropower dams and the groupings of watersheds are not random, thus cannot make this method a double-blind clinical trial, but the single-blind approach can also provide less-biased results.

In Chapter 4, like many other scenario-based tools, ATPCC had many assumptions and may affect the predictive power. Further each parameter offered in the ATPCC is in the form of a single number instead of a range with variations. This may also lead to less randomness and credibility of the tool as discussed in the chapter.

Future works

Moving forward with this dissertation, the limitations mentioned above need to be solved. Specifically, in Chapter 2, the climate issue, especially the precipitation and temperature trend, is not well studied and needs more attention. The lack of in-situ data may lead to an inaccurate evaluation and the mentioned causal relationship issues. Fieldwork, including a survey for CCFP and other policy implementations, is necessary to understand how the CCFP worked and how the farmers reacted toward the policy. This can help identify which policy or the market reform in China played the most crucial role in cropland conversion.

In Chapter 3, as mentioned above, the food sector is not only the inland cropland production. Aquatic food loss by expanding crop production requires further investigation. In this regard, a fieldwork study on MRB is needed for two primary purposes: 1) to provide ground truth for remote sensing data and 2) to collect aquaculture production data. More indicators like night light and GDP data can be integrated into future studies to provide a more comprehensive assessments on socioeconomic implications.

For Chapter 4, many assumptions had been made and may not accurately reflect the real world. More data from the experts in the coal power industry and the literature is needed. The lack of randomness of parameters used in the model can be solved by using fuzzy random parameters. When the set (Max, Min, Median, Mean) values were collected for parameters, a fuzzy random number could be generated and applied to the ATPCC. I would further conduct a validation on ATPCC when more data become available. The predictive power of ATPCC needs to be further assessed. For example, the three fixed scenarios input can be replaced by utilizing a simulation method to find the optimized scenarios. I plan to further develop a web-based toolbox based on the ATPCC to make it publicly available.

Even though I believe that the dissertation provides comprehensive assessment tool kits that can help policymakers and the public better understand the synergies and tradeoffs of carbon-neutral efforts in the WEF nexus perspective, the assessment tool needs to be further expanded to include more dimensions of the water-energy-food systems. My research goal is to build a larger squad of studies that can provide a wider and deeper assessment of carbon-neutral efforts for global policymakers. Future studies including but not limited to the wind power system, petroleum industries, solar power system, and many other systems that carbon, energy, water, and food are interwoven.

Most importantly, through the progress of this dissertation work, I learned how to think comprehensively in a scientific way. It was a massive challenge for me to change my major to Geography, but I did benefit a lot from the spatial thinking that I learned from the geography discipline. I also shifted from a scientific technician after the graduation of my master's degree, who was constantly following other instructions, to an independent thinker through these years. Now I am prepared to continue to search for new advances and inspiring results from literature to further enhance my geography knowledge. The interest-driven research leads to a more comfortable working atmosphere.

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