

The Impacts of Climate Policies on Tradeoff between Green Energy Transition and Economic Growth

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The Impacts of Climate Policies on Tradeoff between Green Energy Transition and Economic Growth

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**The impacts of climate policies on tradeoff between green energy
transition and economic growth**

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Bo Shi



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CERTIFICATE

The undersigned hereby certify that they have read and recommended to the Graduate School of Engineering for the acceptance of this thesis entitled, “**The Impacts of Climate Policies on Tradeoff between Green Energy Transition and Economic Growth**” by **Bo Shi** in partial fulfillment of the requirements for the degree of **Doctor of Philosophy in Engineering**.

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Abstract

With the climate change approaching to a severe level, the carbon emission abatement is enforced to mitigate negative impact of it on economic development and environmental protection worldwide. To reduce carbon emission, various environmental policies are studied to achieve carbon peak and carbon neutrality at lower risk on economic development, i.e., carbon tax. On the other hand, guaranteeing economic development and better life quality, the energy structural transition from traditional fossil fuel to new renewable energy without carbon emission is also urgent issue for developing countries, especially heavy polluters. However, similar to environmental policy, expensive renewable energy can be an obstacle to replacing thermal power, where electrification might be a good method to force substantial electricity consumption. Moreover, the intermittency of renewable energy also impedes its installation at large-scale at present. It also has been researched in depth about renewable energy improvement to replace fossil fuel at lower cost, i.e., subsidy and learning-by-doing.

This thesis figures out these conflicts of environmental policy implementation between economic development and environmental protection against carbon mitigation in developing countries with heavy reliance on fossil fuel, such as China. This study uses Computable General Equilibrium (CGE) model with learning-by-doing module to describe an economic system with endogenous technological enhancement on renewable energy, showing impacts of environmental policies on GDP growth, carbon emission abatement and renewable energy development. Furthermore, the uniform carbon tax is likely to induce heterogeneous impacts on differential industries, for example, energy-intensive industries is susceptible to price change of energy affected by carbon tax, while techno-intensive tertiary industries tend to be flexible. To ensure both environmental and economic benefits, this paper also discusses different impacts of industrial-differentiated and uniform carbon tax on sectoral carbon productivity, embodying renewable energy and its storage.

This thesis consists of four chapters. **Chapter 1** shows the overall background of the study. **Chapter 2** investigates the offset effect of renewable energy enhanced by subsidy financed by carbon tax and learning-by-doing on possible GDP loss caused by increasing carbon tax on industries. **Chapter 3** further explores different impacts of demand-side and supply-side regulation on energy-structural transition that whether electrification facilitates renewable energy improvement with learning-by-doing effect, including issues of solar and wind power storage for stable energy supply. **Chapter 4** examines economic and environmental impacts of industrial-differentiated and uniform carbon tax on all industries with renewable energy development and electrification on sectoral carbon productivity, taking industrial heterogeneity into consideration. **Chapter 5** draws the conclusion for studied issues and provides policy implication.

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Chapter 1 Introduction

1.1 Background

With the pressure of climate change approaches, national determined contributions (NDCs) are released to control the increasing carbon emission from fossil fuel consumption. Thus, environmental policies for carbon abatement are proposed to mitigate climate change. However, environmental protection attracts the attention, the negative impact of actions to abate carbon emission on economic growth also concerns policymakers worldwide. Environmental policies such as carbon tax for carbon abatement has been studied for a long time, inducing a common sense that this external intervention is likely to cause GDP loss because of markup on fossil fuel. The higher carbon tax leads to higher GDP loss that from 0.1% to 5% loss caused by carbon tax at different level (Fu et al., 2021; Nong et al., 2021; Lim and Kim, 2012; Cao et al., 2021). Furthermore, differentiated carbon tax considering industrial heterogeneity is also needed to evaluate for the Chinese national emission trading market in the near future.

On the other hand, to reduce fossil fuel consumption, alternative energy is also urgent to be applied for that green energy transition is important. Since the fossil fuel is indispensable to human activity as energy source and production, new and clean energy has been explored to replace the traditional dirty energy, namely renewable energy (RE). RE as a clean energy for power supply, it has substantial potential to replace thermal power that developed countries experienced energy structural transition focus on RE development, such as UK (Olabi and Abdelkareem, 2022). To catch up with energy revolution, China as the biggest developing country and emitter also released ambitious goal that carbon and peak carbon neutrality will be achieved by 2030 and 2060, respectively. Furthermore, the Chinese government also pledged to achieve the ratio of non-fossil fuel consumption ratio to total primary energy consumption to 25% by 2030, where the ratio is less than 15% in 2017 (National Bureau of Statistics of China, 2018a). Electrification is a demand-

side regulation different from supply-side policies that it requires mandatory electricity consumption at industry-level to reduce fossil fuel consumption, for example, upgradation of traditional equipment to that of in new and electrified (Misconel et al., 2022). However, both developed and developing countries are facing with difficult challenges of energy structural transition, where electrification might lead to more carbon emission because of more thermal power consumption.

The first challenge is the high cost of RE that solar and wind power is more expensive than traditional thermal power at present (International Renewable Energy Agency, 2022a). The cost of RE could be 2 times bigger than that of thermal power in China, which means that increased share of RE in electricity market will lead to markup on electricity otherwise power grids afford the price to ensure electricity price for consumers at lower price (Song et al., 2021). However, RE becomes feasible to replace thermal power gradually recently due to learning-by-doing (LBD) effect that cost of RE, especially solar and wind power, has been decreasing rapidly. For example, onshore wind power has been reducing nearly 50% from 2010 to 2020 (International Renewable Energy Agency, 2022a). Such technological improvement on RE can be explained by Acemoglu et al. (2012) that high elasticity of substitution between thermal power and RE for consumers shows great potential of induced technical change (ITC) effect on clean (RE) goods replacing dirty (thermal power) goods. The technological innovation of RE shows the potential to replace fossil fuel in the long term as long as the cost is lower than thermal power, covering the economic loss.

The second barrier to replacement is the intermittency of RE, especially solar and wind power. Due to more RE installed capacity leads to fluctuation of power supply, storage becomes important to guarantee stable power supply with gradually increasing RE share in electricity market (Dai et al., 2017). Similar to RE itself that storage of RE is also expensive except hydro pumped storage (PHS), however, hydro power always shows more stable power supply than wind and solar power. The cost of storage could be 1.5 to 3 times larger than power generation in China (China Electricity Council, n.d.; National Energy Administration (NEA), 2018). In addition, over 80% of electricity

in China is stored by battery and RE also highly relies on battery storage (Xiao et al., 2022). Therefore, the improvement on battery storage is likely to tackle the problem of intermittency. Different from generation, battery storage is susceptible to electricity price change that expensive electricity leads to less innovation (Feng and Lazkano, 2022). Therefore, it induces a new issue that whether development of RE will be affected by storage improvement positively or negatively with rapid and ambitious RE development goal.

In summary, to fulfill carbon peak and neutrality, any effort should be put into replacing fossil fuel with RE in the future. In addition, the sluggish storage development can affect RE development, thereby enlarge the economic loss caused by environmental policies and expensive RE, leading to an energy transition with economic loss. Environmental protection seems to be inevitable to be achieved with the price of decline in economic development. The tradeoff between energy structural transition and economic growth is manifested against the goal of carbon neutral, especially China. The energy dilemma of replacing fossil fuel (thermal power) with RE proves the energy impossible trinity (EIT) that the energy cost, security and less pollution are unlikely to be allowed simultaneously (Thaler and Hofmann, 2022). Thus, the solution to EIT might gain both environmental and economic benefits, where the RE development plays a key role in eliminating disadvantages of RE.

CGE model with LBD module in this study is applied to simulate the impact of carbon tax, subsidy and electrification on GDP growth and environmental benefits with improved renewable energy and storage from 2017 to 2060. This paper discusses the tradeoff between RE development and economic growth that offset effect induced by improvement on RE whether can overwhelm GDP loss caused by environmental policies, following the energy impossible trinity.

1.2 Thesis Framework

As forementioned, by using CGE model with endogenous LBD module, this paper discusses impacts of environmental policies on economic and environmental benefits at national and sectoral level in China's case because it is the biggest thermal power and RE consumers. Traditional fossil fuel is affordable and safe but dirty, while RE is relatively not affordable, stable but clean. Taking technological innovation of RE and storage into consideration, the EIT might be solved by developing RE in the long term, which also means the solution to tradeoff between economic growth and environmental protection. Therefore, the research objective is to seek for a solution about covering economic loss caused by green energy transition through the RE development with technological improvement.

In **Chapter 2**, based on the past theoretical research, we discuss the impact of carbon tax and subsidy for RE on offset effect of improved RE on economic growth. The LBD of RE can be accelerated by environmental policies because reduction of fossil fuel consumption but increase in RE consumption will enhance LBD effect, leading to greater RE cost reduction. Although carbon tax always leads to GDP loss induced by markup on fossil fuel, the replacement is likely to offset such negative impact because RE at lower price can fully substitute thermal power in long term. This part indicates the advantages of policy mix that combining carbon tax and subsidy would be far better than single policy since it facilitates LBD effect on RE, leading to significant GDP growth. In addition, we also find that higher carbon tax leads to more environmental and economic benefits due to more significant LBD effect. The LBD effect on RE leading to feasible energy structural transition achieves greater GDP development with less carbon emission, in other words, the offset effect of improved RE is enlarged by these environmental policies. The improved RE at low cost ensures energy affordability of EIT.

In **Chapter 3**, we further discuss the impact of RE storage on economic and environmental benefits based on **Chapter 2**. Although environmental policies on supply side can enhance LBD

effect on RE to achieve energy structural transition in long term, it is necessary to take storage into account when RE is installed at large scale for carbon neutrality. Therefore, this chapter is going to probe the conflict between rapid development of RE and backward RE storage that whether RE development will be decelerated by expensive storage in long term. Furthermore, to ensure 25% non-fossil fuel consumption goal by 2030, we discuss electrification as effective method to prompt China's energy structural transition. Our results demonstrate that demand-side regulation, electrification, has overwhelming positive impact on LBD acceleration compared supply-side policies. The accelerated LBD significantly stimulates improvement on RE and storage. Similar to **Chapter 2**, the policy mixing carbon tax, subsidy and electrification presents the best performance in economic and environmental aspects. In scenarios with only supply-side policies, the expensive RE storage restricts demand for RE, thereby leads to less RE development. However, it is needed to point out that single electrification can greatly leads to carbon emission produced by thermal power in short term compared to BaU without any policies. The improved storage for RE guarantees energy security of EIT.

In **Chapter 4**, we further explore the sectoral impact of differentiated carbon tax based on **Chapter 2 and 3**. The uniform carbon tax ignores the industrial heterogeneity induced by various factors, for example, energy-intensive industries such as coke industry and tertiary industries can show totally different attitude to energy price fluctuation. To embody the heterogeneity, this chapter designs an environment-prior differentiated carbon tax that carbon tax on non-energy intensive industries will be two third of energy-intensive industries (same with uniform one). By evaluating sectoral carbon productivity (CP) rather than emission intensity, we measure the sectoral green economic growth pathway against carbon mitigation. The results indicate slight difference between uniform carbon tax and differentiated carbon tax both in economic and environmental aspects. Different from past studies, we find that uniform carbon tax performs better than differentiated carbon tax in environmental aspect. The stricter carbon tax ensures further improvement on all industries, leading to higher energy efficiency which offsets the negative

impact of carbon tax. While looser carbon tax indeed prompt more economic activity but also more carbon emission with lower energy efficiency compared to strict one. The higher energy efficiency prompted by stricter carbon tax further enhances energy affordability, security and less pollution of EIT through RE development during green energy transition.

In **Chapter 5**, we draw the conclusion and discuss the results about various impact of environmental policies and regulation on economic growth and environmental protection, considering LBD effect on RE and storage.

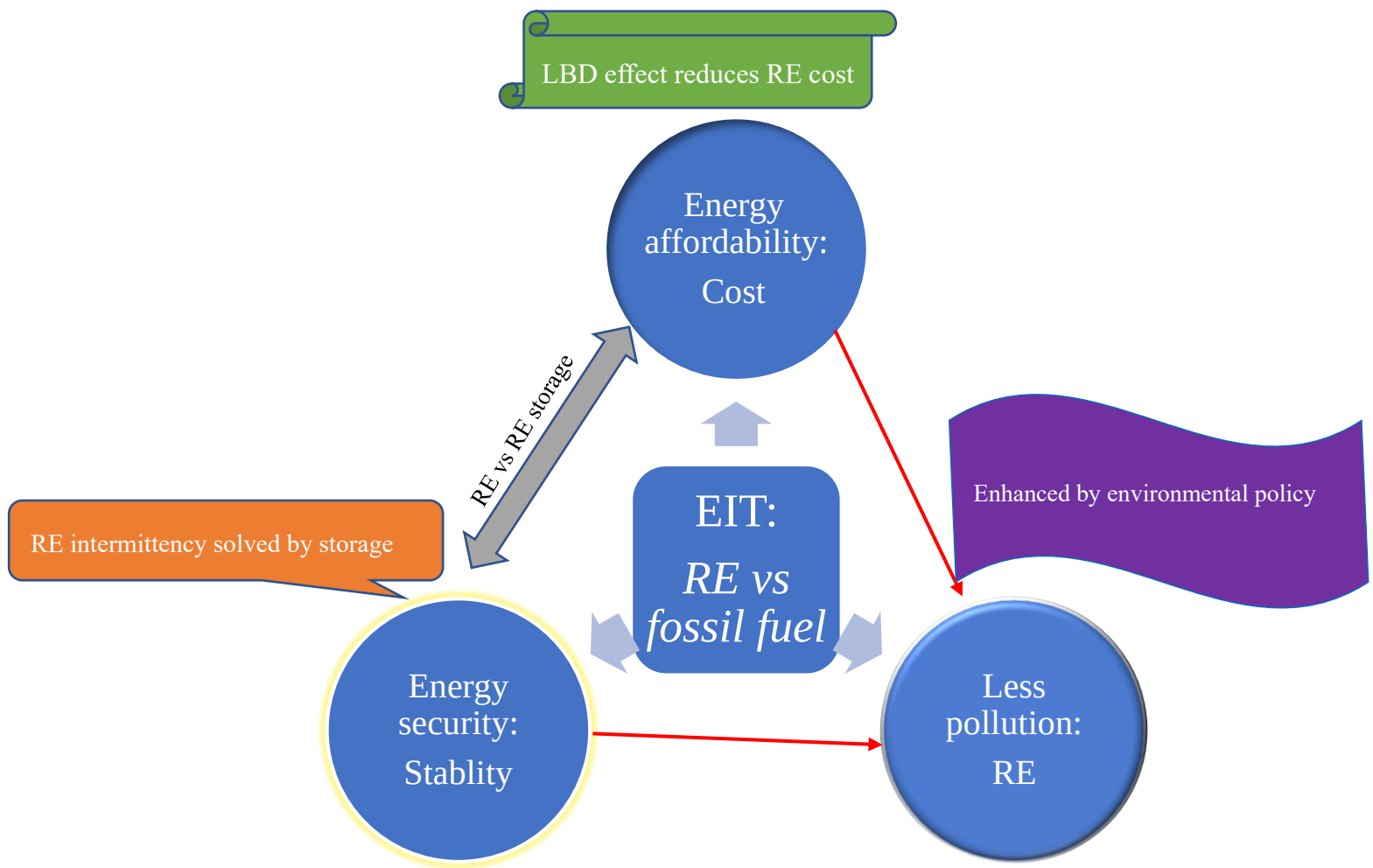


Figure 1.1: Thesis framework

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Chapter 2 Can learning-by-doing offsets negative impacts of carbon pricing?

2.1 Introduction

Owing to the negative impact of carbon emissions globally, many countries have tried to put forth solutions toward reducing it down. Renewable energy (RE) is one of the most promising energy sources for replacing thermal power—the largest source of CO₂. Developed countries have already presented their direction for RE development in the UK (Olabi and Abdelkareem, 2022). Following them, China updated the 2030 nationally determined contributions (NDCs) proposed in the Paris Agreement, which aims to increase non-fossil fuel energy consumption to 25% of the total primary energy consumption and peak carbon emissions. Although the cost of wind and solar power generation has declined significantly in the past decades, it is still higher than that of thermal power generation (National Bureau of Statistics of China, 2021a). As a result, thermal power supply still holds a dominant position in electricity consumption in China. To promote the development of RE to replace thermal power generation, effective policy instruments are necessary to narrow the cost-competitiveness gap between RE and thermal power generation.

Acemoglu and his colleagues suggest that an optimal environmental policy involves carbon taxes and subsidies and will work well when there is high elasticity of substitution between dirty and clean products (Acemoglu et al., 2012). It is well known that carbon pricing is expected to play a substantial role in reducing CO₂ emissions and encouraging RE by internalizing the external cost into fossil fuels (Ramlall, 2017). A subsidy for RE can directly improve the cost competitiveness of RE. Carbon taxes and subsidies are useful regulations for promoting incentives to increase RE share and decrease carbon emissions (Martelli et al., 2020). Acemoglu's work also answers that a single environmental regulation should be temporary rather than further intervention,

that is, just using a carbon tax or subsidy. However, it is not clear whether technological improvement will be maintained without continuous government intervention in the power sector because the homogeneity of electricity on the demand side ensures a high elasticity of substitution for technological improvement in the power sector. Ye et al. (2022) reported that price-based instruments such as subsidies might not be able to provide a continuous incentive for RE power plants to improve technology, but the quantity-based instrument is more effective, that is, learning-by-doing (LBD). However, it remains unclear whether regulators concurrently use subsidies, carbon taxes, and LBD for induced technological change (ITC) in the RE power sector and carbon emission reduction.

The feed-in Tariff (FIT) is one of the most common methods for encouraging RE development by subsidizing RE to reduce the cost of RE power generation. However, there is another barrier to the installation of RE power generation rather than RE resources. For example, (Johnson and Mayfield, 2020; Zander, 2021) investigated the low rate of rooftop solar PV in Australia and the UK and suggested a new FIT for RE development. Furthermore, Hitaj and Löschel (2019) proposed an updated method to improve wind power in Germany. In contrast to the existing cases, in China, the central government implemented the FIT policy by subsidizing wind and solar power generation to narrow the price gap between thermal power and RE, which is called the benchmark price system. However, FIT faces new challenges due to the rapid growth of solar and wind power that has caused a heavy fiscal burden (Zhang et al., 2021; Xia et al., 2020). Policymakers ought to be far-sighted to implement various market-based instruments for the further development of RE. Therefore, Gavard et al. (2019) suggests that subsidies to RE financed by carbon pricing have a positive impact on CO₂ emission reduction and economic growth in the EU.

By April 2022, there are 37 countries implement carbon tax (Aaron et al., 2022). There are five countries started from 1992 and 24 countries levied carbon tax by 2019 (Raghoo and Shah, 2022). For instance, Finland and the Netherlands, carbon tax has been used and researched to effectively reduce carbon emissions (Levi, 2021). Nordic countries levied the highest level of carbon tax, for

example, 130 \$/ton in Sweden (Aaron et al., 2022). There is a case in Sweden of low resistance to carbon tax, even though it has grown gradually to 400\$/ton (with energy and value-added tax) (Ewald et al., 2022). However, the negative impacts of levying a carbon tax on economic growth have a positive correlation with the carbon tax rate: a higher carbon tax rate will lead to higher GDP loss (Nong et al., 2021). It has been proposed that developing countries can rely on carbon tax to achieve carbon peak, even in China, although the excessive burden on industries will affect their competitiveness, which is also likely to yield public resistance (Tong et al., 2022). Moreover, there is a conflict caused by the carbon tax on the industry between the energy cost of RE and thermal power generation. For instance, higher gas price in the US, makes RE costs competitive but higher than industry costs (Ross, 2018). The carbon tax also poses a threat to economic growth unless there is a new carbon pricing policy in the EU (Kiss and Popovics, 2021). Although a carbon tax is likely to yield a fiscal burden, some studies have shown that a combination of different policies can be beneficial to economic growth with carbon reduction (Li and Yao, 2020). Furthermore, the mixed energy policy for RE becomes important to replace the thermal power affected by the carbon tax (Helm and Mier, 2021). The improvement of RE for all countries to cut down CO₂ has played a vital role in CO₂ abatement.

Therefore, some studies illustrate that it is important to decrease energy costs by promoting technological improvement in RE, thereby alleviating economic shocks caused by carbon pricing. (International Renewable Energy Agency, 2022a) shows that the global weighted average cost of RE power has decreased significantly over a decade, which can be explained by the framework of ITC based on endogenous growth theory (Romer, 1990). (Wolfram et al., 2021) shows that technologically improved electricity and battery production in the US can offset the reduced emissions from gasoline combustion in vehicles. Technological spillovers in Norway have significantly facilitated clean structural changes in the industry by optimizing the energy consumption structure (Martinsen, 2011).

Goulder's work suggests that climate policy can affect the knowledge acquisition pathway

through Research & Development (R&D) and LBD. The Optimal pathway of carbon tax and abatement cost for carbon emission abatement is shown by applying R&D to knowledge accumulation that affects ITC in future abatement costs (Goulder and Mathai, 2000). There might be a positive impact of carbon tax on industries' incentives to invest in green technology, e.g., airlines (Dixit et al., 2022). Furthermore, Acemoglu's paper mentions that such ITC of the shift from dirty to clean production is induced by optimal environmental policies, involving a switch of R&D resources to clean production if substitution between dirty and clean products is sufficient (Acemoglu et al., 2012). However, they find an unclear effect of carbon tax on abatement costs endogenously improved by LBD.

Langer's work proposes that increasing subsidies over time should be offset by the cost reduction of solar power induced by technological change; otherwise, substantial subsidies will exert great public pressure on regulators (Langer and Lemoine, 2022). Adding learning curves into a description of the relationship between productivity and price changes in RE affected by the ITC under carbon pricing policies becomes important. Research based on Denmark indicates that LBD-based technological progress might generate a 25% reduction in the cost of RE over the next 25 years (Rasmussen, 2001). Trials have been performed by combining the learning curve of the RE power sector with a computable general equilibrium (CGE) model to explain the positive effect of endogenous technological progress on the deployment of RE in the EU (Ortega et al., 2015). It has also been discussed that the LBD effect with longer working time leads to a higher level of knowledge accumulation for the development of RE (Ortega et al., 2020). In addition, (Meus et al., 2021) strongly suggests capacity-based LBD because manufacturing and construction are the main sources of learning instead of subsequent operations in RE installations, which can be categorized as quantity-based instruments. The LBD module eliminates the shortage of the CGE model on technological influence during production, which shows how producers improved their efficiency to enlarge co-benefits such as environmental and economic impacts (Yang et al., 2021).

This work integrates existing research that carbon tax and subsidy can both facilitate ITC (LBD)

in the power sector, especially RE power generation, which will have a positive impact on RE development and CO₂ emission abatement, with a lower negative impact on economic growth compared to a single carbon tax. A recursive dynamic CGE model that integrates the module of endogenous technological progress based on the LBD mechanism is developed to empirically examine the offset effects using a policy simulation approach. The possible contributions of this study to the literature can be considered as follows. First, based on the theoretical works of Acemoglu et al. (Acemoglu et al., 2012), Ye et al. (Ye et al., 2022), Goulder et al. (Goulder and Mathai, 2000) and Langer et al. (Langer and Lemoine, 2022), this study aims to provide an empirical examination through CGE analysis and reveal the synergistic effects of carbon pricing and subsidy with the LBD mechanism on the RE power sector. Furthermore, this study develops a recursively dynamic CGE model integrated with the LBD and electricity market share allocation mechanisms. The LBD module in this model applies a learning-by-doing mechanism via the accumulation of electricity output, which is different from the existing literature. Finally, this study focuses on the synergistic effects of carbon pricing and subsidies with the LBD mechanism on the RE power sector in China. Because China possesses the largest scale of wind and solar power generation, the results of this study might provide rich soil for developing countries to promote RE via the LBD process.

The remainder of this paper is organized as follows. The second section explains the relevant methodology, including CGE model building (see Appendix) and the LBD module. The third part is scenario design, including business-as-usual (BaU) and other scenario designs. The fourth section presents the results and discussion. Subsequently, a sensitivity analysis of the major parameters was performed. The final section presents the conclusions and policy implications.

2.2 Methodology

2.2.1 The CGE model

In this work, a CGE Model with LBD module that takes a recursive CGE model as the core is

developed based on our previous study (Yuan et al., 2020). The power generation sector is a key part of realizing both carbon and energy targets. Therefore, the model included five power sectors: thermal, hydro, wind, solar, and nuclear technology. The LBD mechanism is incorporated to describe the technological improvement process of power technologies, except for thermal and hydropower. More detailed issues regarding the power sector can be analyzed using the model. Fig. 2.1 shows the framework of the model in this study, in which the dynamic process is via capital accumulation, labor growth, and technological improvement. More details are provided in Appendix A and our previous work (Yuan et al., 2020).

In this study, the base year of the basic database was 2017. Meanwhile, it is dynamic to the long term towards 2060 based on the carbon-zero goal. Additionally, to investigate the effects of carbon tax on energy cost, the module that describes carbon tax and subsidy to the RE power sector was incorporated (see Section 2.2.2). Multiple energy cost indices were constructed (see Section 2.2.3).

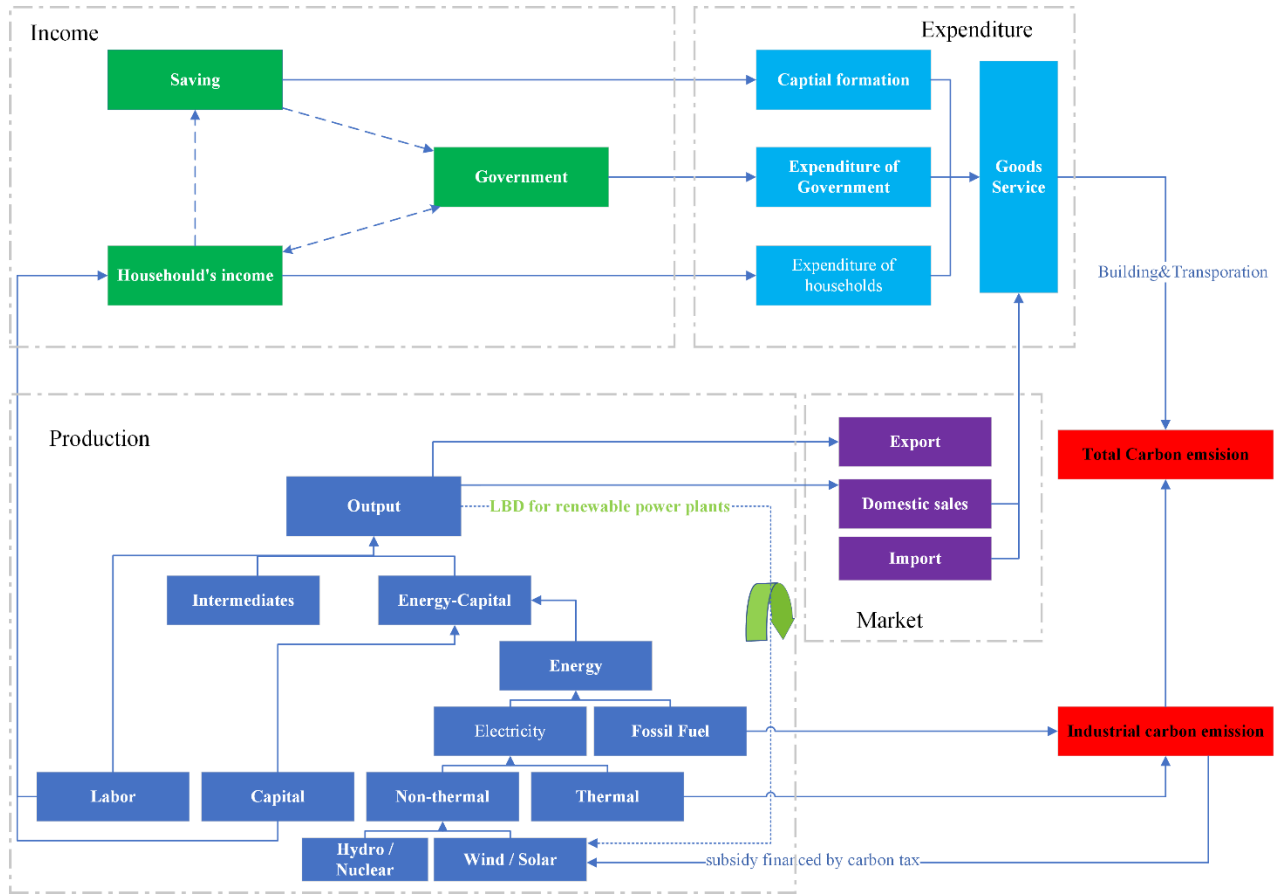


Figure. 2.1: Overall framework of model

2.2.1.1 Production module

This section describes how the suppliers produce commodities. Most of productions employ the constant elasticity of substitution (CES) function, which means that the input of different types of energy (electricity and fossil fuels) can be substituted to a constant extent, depending on the elasticity from existing research. For example, the composite of electricity and fossil fuels in non-energy industries follows the CES function, implying that some fossil fuels function as well as electricity in their energy input processes.

Energy industries, including the power sector, petroleum refinery, coke industry, fossil fuel mining, and gas production and supply, are treated differently because their energy input is not a

CES relationship but a Leontief function. Because the Leontief function is a special form of the CES function, the elasticity of substitution is negative infinity, which means that the inputs are irreplaceable. For example, the coking industry cannot use oil, natural gas, or electricity without coal as the raw material to produce coke. In the power sector, thermal power generation will only consume fossil fuels using the CES function, while RE power generation, including hydro, nuclear, wind, and solar (with other), only consumes less natural gas for heating. Similar to other energy industries, all power generation input energy composites contain electricity as storage and transmission (with loss). The power sector (thermal, hydro, wind, solar, and nuclear) was externally integrated into the CGE model with 35 sectors in this study (Li et al., 2017). All sectors achieved technological improvement by AEEI, except for RE power generation (Li et al., 2017). RE power generation follows the LBD function (see the LBD module section).

Moreover, unlike other types of energy, there is no difference in the electricity generated by fossil fuels, RE or nuclear power. Other industries and end-users only consider electricity consumption because of the homogeneity of electricity on the demand side; there is only a difference on the supply side. This study adds the external production of the power sector module in this CGE model, making, that is, the sum of all kinds of electricity output equals the total electricity output.

$$QX_{c,t} = f_{c,t}(QA_{nec,c,t}, QK_{c,t}, QL_{c,t}, QE_{c,t}) \quad (2.1)$$

$$QX_{c,t} = \alpha_c^{kel} (\delta_c^{kel} QKE_{c,t}^{kel} + (1 - \delta_c^{kel}) QL_{c,t}^{kel})^{1/\rho_c^{kel}} \quad (2.2)$$

The following equations were solved by the Lagrange Theorem using Eqs. (2.1) and (2.2):

$$QKE_{c,t} = \alpha_c^{kel} \rho_c^{kel} \sigma_c^{kel} \left(\frac{\delta_c^{kel} P_{X_{c,t}}}{P_{KE_{c,t}}} \right)^{\sigma_c^{kel}} QX_{c,t} \quad (2.3)$$

$$QK_{c,t} = \alpha_c^{ke} \rho_c^{ke} \sigma_c^{ke} \left(\frac{\delta_c^{ke} P_{KE_{c,t}}}{P_{K_{c,t}}} \right)^{\sigma_c^{ke}} QKE_{c,t} \quad (2.4)$$

$$QL_{c,t} = \alpha_c^{kel\rho_c^{kel}\sigma_c^{kel}} \left(\frac{(1-\delta_c^{kel})PX_{c,t}}{PL_{c,t}} \right) \sigma_c^{kel} QX_{c,t} \quad (2.5)$$

$$QE_{c,t} = \alpha_c^{kep\rho_c^{ke}\sigma_c^{ke}} \left(\frac{(1-\delta_c^{ke})PKE_{c,t}}{PE_{c,t}} \right) \sigma_c^{ke} QKE_{c,t} \quad (2.6)$$

$$QENS_{c,t} = \alpha_c^{ene\rho_c^{ene}\sigma_c^{ene}} \left(\frac{(1-\delta_c^{ene})PE_{c,t}}{PENS_{c,t}} \right) \sigma_c^{ene} QE_{c,t} \quad (2.7)$$

$$QEN_{c,t} = \alpha_c^{en\rho_c^{en}\sigma_c^{en}} \left(\frac{(1-\delta_c^{en})PENS_{c,t}}{PEN_{c,t}} \right) \sigma_c^{en} QENS_{c,t} \quad (2.8)$$

$$QELE_{c,t} = \alpha_c^{ene\rho_c^{ene}\sigma_c^{ene}} \left(\frac{\delta_c^{ene}PE_{c,t}}{PELE_{c,t}} \right) \sigma_c^{ene} QE_{c,t} \quad (2.9)$$

For non-energy intermediates, this model adopts Leontief function:

$$QA_{nec,c,t} = iocif_{nec,c,t} QX_{c,t} \quad (2.10)$$

$$PKE_{c,t} = (QE_{c,t}PE_{c,t} + QK_{c,t}PK_{c,t})/QKE_{c,t} \quad (2.11)$$

$$PE_{c,t} = (QENS_{c,t}PENS_{c,t} + QELE_{c,t}PELE_{c,t})/QE_{c,t} \quad (2.12)$$

$$PENS_{c,t} = \sum_{ecc} (QA_{ecc,c,t}PQ_{ecc,t})/QENS_{c,t} \quad (2.13)$$

$$PL_{c,t} = distort_c * wage \quad (2.14)$$

2.2.1.2 Final Demand, Import and Export

The consumption propensity of households and government are following:

$$QH_{c,t} = \alpha_{c,t} YH_t (1 - htax) (1 - MPSH) / (PQ_{c,t} (1 + tdom_c)) \quad (2.15)$$

$$YH_t = \text{lin} \sum PL_{c,t} QL_{c,t} + k * \sum QK_{c,t} PK_{c,t} + GtoH_t \quad (2.16)$$

where c is the commodity, QH is the consumption of household, PQ is the price of commodity, $\alpha_{c,t}$, YH , $htax$, $MPSH$, $tdom$ are the propensity of consumption, income, tax rate, rate of saving of households, and domestic excise tax, respectively, which are calibrated by the input-

output (IO) table from the China Statistical Yearbooks.

$$QG_{c,t} = \beta_{c,t}(YG_t(1 - MP_{SG}) - GtoG_t - GtoH_t)/(PQ_{c,t}(1 + t_{dom_c})) \quad (2.17)$$

$$YG_t = \sum tp_c PX_{c,t} QX_{c,t} + htax * YH_t + \sum tm_c PWM_{c,t} QM_{c,t} EXR + GtoG_t \quad (2.18)$$

We obtain a similar consumption function for the government. The $GtoG_t$ and $GtoH_t$ are subsidies from the central government to local governments and transfer payment in year t , respectively. Household income comes from capital and labor, for example, rent and wages. The income of the government comes from the taxes.

$$GDPR_t = \sum [PE_{c,t} QE_{c,t} - QM_{c,t} PM_{c,t} + (QIV_{c,t} + QIT_{c,t} + QG_{c,t} + QH_{c,t}) PQ_{c,t}] \quad (2.19)$$

Where $GDPR$ is real GDP and PE, PM, PQ are the prices of exports, imports, and domestic goods, respectively. QE, QM, QIV, QIT are the quantities of export and import goods, fixed capital, and stock, respectively.

This model applies to the Armington assumption for the export and import modules. The Armington assumption suggests that a similar type of export or import goods cannot be categorized as the same because of the brand. The rich might prefer to buy better and more expensive cars rather than cheap cars, while common people prefer to buy cheap cars, which affects their export and import strategies. Thus, it is possible to employ constant elasticity of transformation (CET) to describe the behavior of exporting goods and the CES function for imported goods (Hosoe et al., 2010), where the CET function is similar to the CES function, which describes the transformation between domestic and export goods.

$$QM_{c,t} = (\frac{\delta_c^m}{\delta_c^{dm}} * PD_{c,t}/PM_{c,t})^{\sigma_c^m} QD_{c,t} \quad (2.20)$$

$$QQ_{c,t} = a_c^m (\delta_c^m QM_{c,t}^{\rho_c^m} + \delta_c^{dm} QD_{c,t}^{\rho_c^m})^{1/\rho_c^m} \quad (2.21)$$

$$PM_{c,t} = (1 + tm_c) EXR * PWM_{c,t} \quad (2.22)$$

$$PQ_{c,t}QQ_{c,t} = PD_{c,t}QD_{c,t} + PM_{c,t}QM_{c,t} \quad (2.23)$$

$$QEX_{c,t} = \left(\frac{\delta_c^{dex}}{\delta_c^{ex}} * \frac{PEX_{c,t}}{PD_{c,t}} \right) \sigma_c^{ex} QD_{c,t} \quad (2.24)$$

$$QX_{c,t} = a_c^{ex} (\delta_c^{ex} QEX_{c,t}^{\rho_c^{ex}} + \delta_c^{de} QD_{c,t}^{\rho_c^{ex}})^{1/\rho_c^m} \quad (2.25)$$

$$PEX_{c,t} = (1 + te_c) EXR * PWE_{c,t} \quad (2.26)$$

$$PX_{c,t}QX_{c,t} = PD_{c,t}QD_{c,t} + QEX_{c,t}PEX_{c,t} \quad (2.27)$$

2.2.1.3 Market share and Relative price

The cost of power generation affects the price of electricity; therefore, cheap thermal power dominates China's electricity market. To develop RE, the Chinese government proposed the on-grid price and benchmark price for thermal power and RE power generation, respectively. The government subsidizes RE power producers depending on the gap between the benchmark price and on-grid price, where the on-grid price is always unexpensive than the benchmark price due to the difference in their costs, and both prices are controlled by the government based on the average cost of power plants. We then introduce the relative price (RP) of thermal power to the RE electricity price to show the competitiveness of each power generation in the electricity sector (Yuan et al., 2020):

$$RP_{ren,t} = PXF_t / PX_{nt,t} \quad (2.28)$$

where the PXF_t is the on-grid price of thermal power in year t and $PX_{nt,t}$ is the benchmark price of RE power generation in year t . The initial level of RP was calibrated using the average price of all electricity in 2017 from (National Energy Administration (NEA), 2018). When the benchmark price of RE is decreasing, in other words, the RP gets larger, RE electricity producers will get more market share compared to thermal power plants, as follows:

$$MS_{ren,t+1} = MS_{ren,t} + (s_{ren} - MS_{ren,t})(RP_{ren,t+1} - RP_{ren,t}) \quad (2.29)$$

where s_i is the upper bound for the share of RE and nuclear power generation in the total primary energy consumption and $s_{nt} \in (0,1)$, and market share is determined by. The market share of thermal power generation is equal to:

$$MSF_{thermal,t} = 1 - \sum_{ren} MS_{ren,t} \quad (2.30)$$

The model then demonstrates a system of developing RE in China's electricity market with LBD: (1) The LBD curve will decrease the cost of RE power. (2) A lower cost leads to a lower output price of RE power owing to profit zero. (3) A greater RP leads to more MS for RE power. (4) MS provides more knowledge. We then return to (1). Thermal power generation will exogenously improve energy efficiency by AEEI.

2.2.1.4 Investment

$$TQIV_t * invsha_{c,t} = INV_{c,t} \quad (2.31)$$

$invsha_{c,t}$ refers to the allocation parameter of investment to sector c . Historical data from 2017 to 2021 are from (National Bureau of Statistics of China, 2021a). Investment is endogenously driven by savings from residents and the government. The sum of each power generation investment share is equal to the total power sector.

2.2.1.5 Market-clearing condition and Macro closure

This part ensures total demand equals to total supply:

$$QD_{c,t} + QM_{c,t} = QQ_{c,t} = QA_{c,t} + QG_{c,t} + QH_{c,t} + QIV_{c,t} + QIT_{c,t} \quad (2.32)$$

$$TQL_t = \sum_c QL_{c,t} \quad (2.33)$$

$$PK_{c,t} = distortk_c * TPK_t \quad (2.34)$$

$$TQK_t = \sum_c QK_{c,t} \quad (2.35)$$

This study adopts the closure as follows: (1) the savings of government are endogenous and tax rates are exogenously calibrated by data. (2) The international balance of payments is determined by the exogenous exchange rate and endogenous international trade surplus. (3) Saving from households abroad and the government are driven by exogenous investments in all sectors.

$$FSAV_t = \sum_c (PWM_{c,t} EXR QM_{c,t} - PWE_{c,t} QEX_{c,t} EXR) \quad (2.36)$$

$$\sum_c mpsh * YH_t (1 - htax) + mpsg * YG_t + FSAV_t = \sum_c PQ_{c,t} (QIV_{c,t} + QIT_{c,t}) + WALRAS_t \quad (2.37)$$

2.2.2 Carbon tax and subsidy to RE

A carbon tax is levied on all emission polluters on the supply side. Production is constructed based on the profit-zero condition. See Eq.2.38-2.40.

$$PX_{c,t} * QX_{c,t} (1 - tp_{c,t}) = PL_{c,t} * QL_{c,t} + PK_{c,t} * QK_{c,t} + \sum_{ECC} QA_{ecc,c,t} * PQ_{ecc,t} + \sum_{NEC} PQ_{nec,c,t} * QA_{nec,c,t} + tco_t * \sum_{ECC} ENCO2_{ecc,c,t} \quad (2.38)$$

$$ENCO2_{ecc,c,t} = QE_{ecc,c,t} CO2F_{ecc,c,t} \quad (2.39)$$

$$CTax_{c,t} = tco_t * \sum_{ECC} ENCO2_{ecc,c,t} \quad (2.40)$$

Where:

$$T = \{2017 - 2060\} \text{ and } t \in T,$$

$$C = \{\text{all the sectors}\} \text{ and } c \in C \text{ and } i \in C,$$

$$ECC = \{\text{all the energy sectors}\} \text{ and } ecc \in ECC;$$

$NEC = \{all\ the\ non - energy\ sectors\}$ and $nec \in NEC$

$ELE = \{Thermal, Hydro, Nuclear, Wind, Solar\}$ and $ele \in ELE$

$NELE = \{non - electricity\ energy\ sector\} = ECC - ELE$ and $nele \in NELE$

$NT = \{Wind, Solar\}$ and $nt \in NT$

$REN = \{Wind, Solar, nuclear, hydro\}$ and $ren \in REN$

$LBD = \{Wind, Solar, nuclear\}$ and $lbd \in LBD$

$PX_{c,t}$, $PL_{c,t}$, $PK_{c,t}$ and $PQ_{c,t}$ are the domestic sale price, labor price, capital price, price of domestic and import goods composite of sector c in year of t respectively. $QX_{c,t}$, $QL_{c,t}$, $QK_{c,t}$ and $QA_{i,c,t}$ are the output, labor input, capital stock, and input i of sector c in year of t respectively. $tp_{c,t}$ is the indirect (production) tax rate. $ENCO2_{ecc,c,t}$, $QE_{ecc,c,t}$, $CO2F_{ecc,c,t}$ are carbon emissions, energy ecc combusted and CO₂ emission factor of sector c at the year of t . tco_t is carbon tax rate at the year of t and $CTax_{c,t}$ is the carbon tax that sector c should pay at t .

The total subsidy equals the sum of the carbon tax revenue from all sectors. The subsidy is paid only for wind and solar power generation. Unlike the traditional FIT price, which narrows the price gap between RE and thermal power, this study adopts more market-based methods. The share of subsidy to two RE power producers is determined by the reciprocal of their market share that non-thermal power with lower competitiveness will gain more subsidy, as shown in Eq. (2.41) and Eq. (2.42) shows:

$$subsidy_{nt,t} = \left(\frac{1}{MS_{nt,t}} \right) * \sum_C CTax_{c,t} / \sum_{NT} (1/MS_{nt,t}) \quad (2.41)$$

$$PX_{nt,t} * QX_{nt,t} (1 - tp_{nt,t}) = PL_{nt,t} * QL_{nt,t} + PK_{nt,t} * QK_{nt,t} + \sum_{ECC} QA_{ecc,nt,t} * PQ_{ecc,t} + \sum_{NEC} PQ_{nec,nt,t} * QA_{nec,nt,t} + CTax_{nt,t} - subsidy_{nt,t} \quad (2.42)$$

$MS_{nt,t}$ and $subsidy_{nt,t}$ is market share of wind and solar power, and subsidies given to non-thermal power nt at time t .

2.2.3 Energy Cost Indicators

According to the hypothesis proposed in Section 1, the cost of electricity is affected by the LBD. Therefore, this study adds cost indicators to illustrate the impact of LBD on technological improvements in the power sector. Multiple real energy cost indicators were constructed for the 2017 price level. $AVC_{ele,t}$, $AVC_{ecc,t}$, $AVCELE_t$, $AVCNT_t$ and $AVCE_t$ represent the average costs of sector of ele , ecc , power sector, non-thermal electricity and primary energy at year t , respectively (See Eq. (2.43)-(2.47)).

$$AVC_{ele,t} = \frac{(PL_{C,2017} * QL_{C,t} + PK_{C,2017} * QK_{C,t} + \sum_{ecc} QA_{ecc,ele,t} * PQ_{ecc,2017} + \sum_{nec} PQ_{nec,2017} * QA_{nec,c,t})}{QX_{ele,t}} \quad (2.43)$$

$$AVC_{ecc,t} = (PL_{ecc,2017} * QL_{ecc,t} + PK_{ecc,2017} * QK_{ecc,t} + \sum_{ecc} QA_{ecc,ecc,t} * PQ_{ecc,2017} + \sum_{nec} PQ_{nec,2017} * QA_{nec,ecc,t}) / QX_{ecc,t} \quad (2.44)$$

$$AVCELE_t = \sum_{ele} AVC_{ele,t} * QX_{ele,t} / \sum_{ele} QX_{ele,t} \quad (2.45)$$

$$AVCNT_t = \sum_{NT} AVC_{nt,t} * QX_{nt,t} / \sum_{NT} QX_{nt,t} \quad (2.46)$$

$$AVCE_t = (\sum_{NELE} AVC_{nele,t} * QX_{nele,t} + \sum_{NT} AVC_{nt,t} * QX_{nt,t}) / (\sum_{ECC} QX_{ecc,t} + \sum_{NT} QX_{nt,t}) \quad (2.47)$$

2.2.4 LBD Module

The LBD function for RE in this study is a decreasing function of the cost to the stock of knowledge:

$$AVC_{lbd,t} = lb_{lbd} KS_{lbd,t}^{-lx_{lbd}} \quad (2.48)$$

Where $AVC_{lbd,t}$ is the average generation cost of RE in year t in the 2017 price level, lb_{lbd} is the parameter of the learning curve, which is calibrated using a power balance table (National Bureau of Statistics of China, 2018b), $KS_{lbd,t}$ is the stock of knowledge, and $-lx_{lbd}$ is the indicator of learning (Zhu et al., 2015). The knowledge stock increases with cumulative power generation:

$$KS_{lbd,t} = KS_{lbd,t-1}(1 - \delta_{lbd}) + MS_{lbd,t} * e_{lbd,t} \quad (2.49)$$

where δ_{lbd} is the depreciation of knowledge, $MS_{lbd,t}$ is the market share of RE (see Section A.1.4) in the electricity market, and $e_{lbd,t}$ is the output of power generation in year t . Nuclear power applies to LBD even though it is not RE power. Hydropower does not apply to LBD because of its limited potential (McDonald and Schrattenholzer, 2001). To show the limitation of hydropower, it is controlled by autonomous energy efficiency improvement (AEEI) as other sectors and the low upper-bound of the market share of hydropower in Eq. (2.29).

2.3 Data

The basic database is China's social accounting matrix table (2017) which includes 35 industrial sectors, household consumption, government expenditure, fixed capital formation, exports, and imports. The production of the power sector is divided into five electricity technologies, as mentioned previously, based on cross-industrial data from (National Bureau of Statistics of China, 2018b). The emission factors are provided in (National Development and Reform Commission, 2015).

The model includes endogenous technological change in the power sector, but the total factor productivity (TFP) improvement in other sectors is exogenously given by referring to (Li et al., 2017). The power generation costs for non-fossil fuels are abstracted from (International Renewable Energy Agency, 2022b), and the real electricity price data refer to (National Energy

Administration (NEA), 2018). The parameters of power generation, newly added installed capacity, and electricity investment were based on President Xi’s statement at the UN Climate Ambitious Summit in December 2020. The parameters of learning rates and substitution capability for different non-fossil technologies are described in (Yuan et al., 2020).

2.4 Scenario design

A business-as-usual scenario as well as four policy scenarios were developed in this study.

2.4.1 Business as Usual

The LBD was incorporated in the BaU scenario. The TFP is calibrated by exogenously setting GDP growth rates that are shown in Table 2.1 (Yuan et al., 2020). The labor growth rate refers to (National Bureau of Statistics of China, 2021b), and this study considers a conventional population decrease based on (He et al., 2022) which decreases by 0.1% by 2039 and 0.03% by 2060. The AEEI of thermal and hydropower is assumed according to (Li et al., 2017). The growth rate of investment from 2017 to 2020 is given in reference to (National Bureau of Statistics of China, 2021a), and the growth rate of total investment after 2020 is endogenously determined. The investment share of each sector from 2022 to 2060 is based on historical data with reference to the 14th and 15th five-year plans.

Table 2.1: Changes in average GDP growth rate and TFP

	2021-2030	2031-2040	2041-2050	2051-2060
GDP	5.09%	3.26%	2.06%	0.95%
TFP	1.79%	1.77%	1.5%	0.82%

Note that this study uses existed data from 2017 to 2020 in this model.

Fig. A.2.2 shows GDP growth and CO₂ emission under scenario BaU. Under BaU, CO₂

emission will peak in 2032 which is devoted by rapid growth of non-thermal power with LBD effects and then will decrease to 8.18 billion tons of CO₂ emission by 2060. On the other hand, GDP grows smoothly over all periods, from 8.2 billion CNY to 29 billion CNY at 2017 price level.

Fig. A.2.3 presents the growth potential of non-thermal power generation in long-term. Wind power shows huge potential in replacing thermal power that LBD effectively reduces cost of wind power generation, but solar power increases much less than wind power. Hydro power still plays key role in provision of RE power generation, though its development is controlled by AEEI. Share of nuclear power generation declines even though nuclear power generation keeps increasing until 2060. Nuclear gets markup on generation cost. Because low rate of learning curve given by (Zhu et al., 2015) and insufficiency of raw material of nuclear power plants might occur in the future, operation cost and safe reinforcement for nuclear power plants will increase (Stewart and Shirvan, 2022). Wind power will be the most cost-competitive among non-thermal powers until 2060. Therefore, wind power and hydro power will be the most important RE power generation in BaU. Nevertheless, LBD mechanism fosters RE power generation by reducing their cost, thereby, CO₂ emission will get significant abatement in long term.

2.4.2 Carbon pricing and subsidy scenarios

Under policy scenarios, all fossil fuel consumption that generates CO₂ emissions will be levied on the carbon tax since 2022, including all sectors and household consumption. The initial carbon tax rate in 2022 was 40 CNY/ton and was increased gradually. The tax rates of Low and High are the same until 2030. After 2030, according to (Cao et al., 2021), the carbon tax rate under scenario High increases faster than that under scenario Low, which are 1113 CNY/ton and 548 CNY/ton in 2060, respectively. The carbon tax in this work is fairly higher than in other countries, and related studies show the offset effect of LBD because a low carbon tax does not exert a significant impact on GDP loss and CO₂ abatement. For instance, the carbon tax in British Colombia, Canada (Arcila and Baker, 2022). The carbon tax rate in the scenario of this study increases over 25 times, from

40 CNY/ton to 1113 CNY/ton during 2022-2060. This is similar to the carbon tax implemented in several countries globally. For example, Finland introduced a carbon tax for the combustion of fossil fuels (except wood industry) at 1.12 euro/ton in 1990 and increased it to 66.2 euro/ton in 2013, nearly 60 times higher (Nachmany et al., 2015). The study adopts a national and uniform carbon tax. During the "Fourteenth Five-Year Plan" period, the institutional coordination between local and national carbon pricing will be strengthened to avoid market fragmentation, maintain market integrity, and promote the "one game" of the national carbon market (Yuan, 2021).

Furthermore, this study discusses the combination of other potential and low-carbon instruments. The green finance approach, such as green investment, has a leading effect on carbon tax to optimize the allocation of capital and environmental resources, which enhances the carbon tax on CO₂ abatement (Tong et al., 2022). Therefore, investment in non-fossil fuel power generation (hydro, nuclear, solar, and wind) increases, while thermal power generation decreases.

2.4.3 Carbon tax revenue to subsidy

Furthermore, it is also highlighted that carbon tax revenue might generate a positive impact when it enters the cycle of economic system (Brown et al., 2020). In addition, this study set policy scenarios in which carbon tax revenue is used as a subsidy to wind and solar power, denoted as R_High and R_Low, respectively, because (Rasmussen, 2001) points out the potential of subsidy on knowledge spillover of RE power. Table 2.2 shows the details of the four policy scenarios. It should be noted that the carbon tax rate in this study is higher than that in existing literature.

Table 2.2: Carbon pricing and subsidy Scenarios

Scenario	High carbon tax	Low carbon tax	To RE	To government	LBD
BaU					✓
R_Low		✓	✓		✓
Low		✓		✓	✓
R_High	✓		✓		✓
High	✓			✓	✓

2.5 Results and Discussions

2.5.1 Scenario Low and High (carbon tax revenue collected by government)

Fig 2.2 shows the long-term changes in the GDP under different scenarios. It is found that the GDP loss under Scenario High is less than that under Scenario Low. Compared to the results of GDP loss in the existing literature, such as 2.43% GDP loss at a lower carbon tax rate than scenario Low in 2050 (Yuan et al., 2020), the results in this study present less GDP loss. For example, the GDP loss at 191 CNY/ton carbon tax in 2030 is only 0.098% under the low and high scenarios, and the GDP loss in 2050 even decreases.

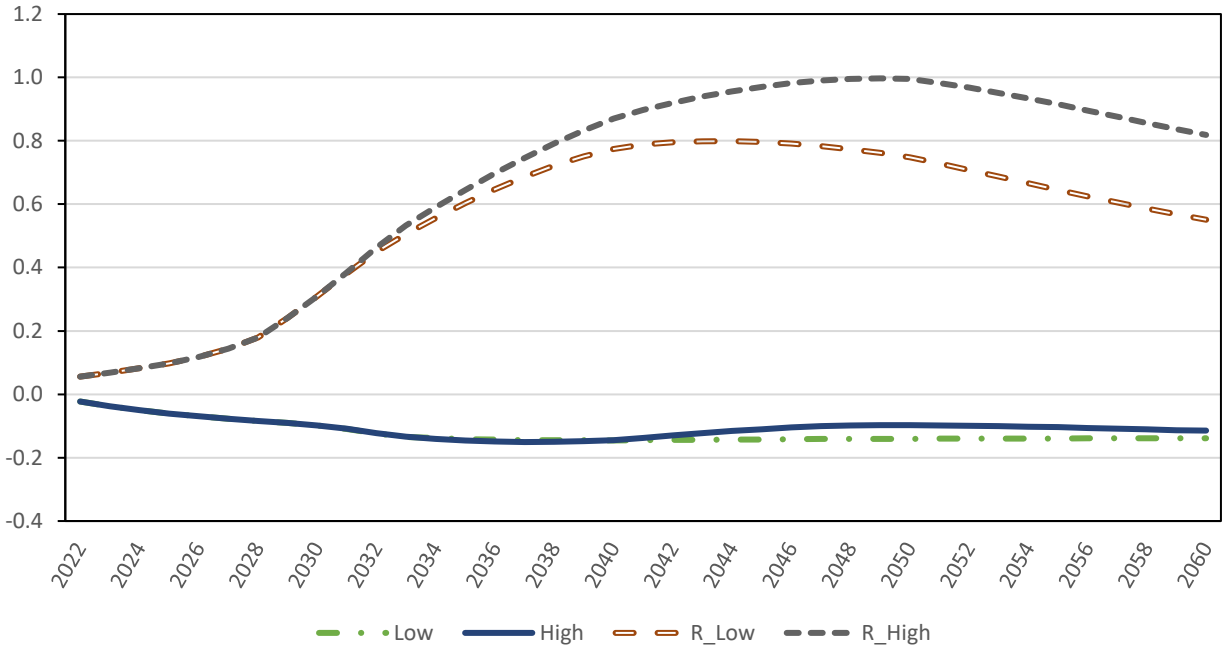
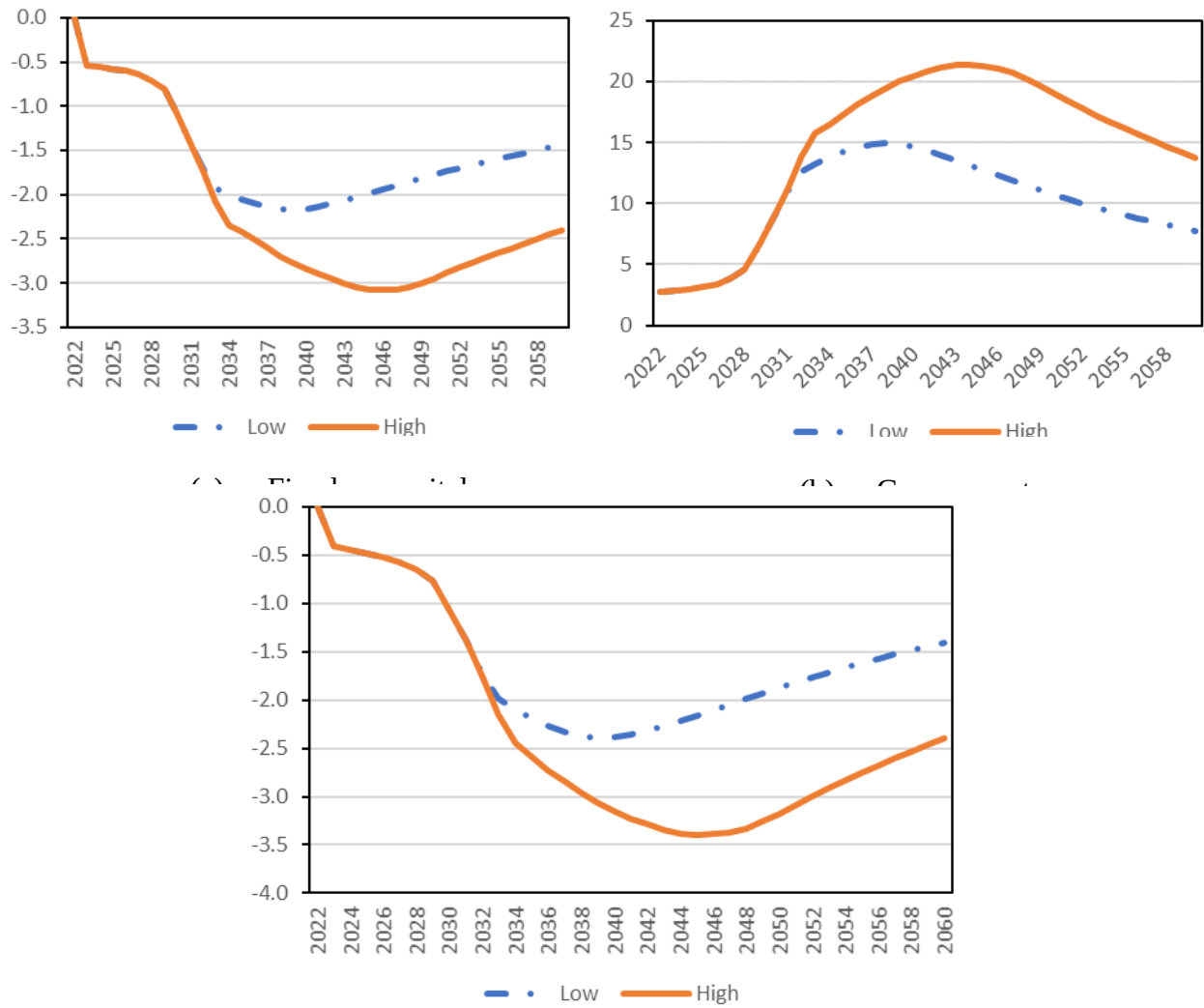


Figure. 2.2: GDP change rate (%) compared to scenario BaU

There are relatively mild impacts on economic growth in the medium term under the Low and High scenarios. However, surprisingly, since 2040, the GDP loss under the High scenario becomes less than the loss under the scenario Low. To further understand how LBD affects GDP, this study decomposed GDP, as shown in Fig.2.3 under scenario Low and High from 2022 to 2060. Most importantly, fixed capital formation is affected by an increase in the carbon tax rate. The impact on fixed capital formation under the high scenario is more serious than that under the low scenario. Fixed capital formation usually refers to physical assets such as devices, machines, vehicles, and buildings. Construction and tertiary industries without transportation will be affected most significantly, accounting for 74.8% of the total loss of fixed capital formation under the Low and High scenarios in 2060. In addition, the capital-intensive industry faces a decline in fixed capital formation, which accounts for 18% of the total fixed capital loss under the Low and High scenarios in 2060. Usually, capital-intensive industries and construction are susceptible to carbon tax because their production relies heavily on fossil fuel inputs or energy-intensive products, which generate CO₂ emissions during the life cycle. Carbon tax directly affects the output price of energy-

intensive products and attracts less investment in relative sectors.

Government expenditure will increase with an increase in the carbon tax rate under scenarios Low and High because substantial carbon tax revenue will be used for government expenditure. Higher carbon tax rates and revenues will increase government income and expenditure, as shown in Fig.2.3. However, household consumption will suffer from the markup of products induced by the carbon tax, and a reduction in household consumption will lead to GDP loss. The reduction in household consumption under Scenario Low will be less than that under Scenario High. There is only one exception: household power consumption will increase in the High and Low scenarios in the long term. The reason for this is the positive impact of carbon tax on the reduction in electricity price. In addition to fixed capital formation, household consumption, and government expenditure, carbon pricing also affects net exports. However, net exports change slightly when the carbon tax is implemented, which has only a trivial negative impact on GDP loss.



(c) Household Consumption

Figure. 2.3: Change rate of Fixed capital formation, government expenditure and household consumption (%)

Although the range of increase in government expenditure is much greater than the loss of fixed capital formation and household consumption, a greater increase in government expenditure induced by the carbon tax can offset the reduction in fixed capital formation and household consumption under scenario High. This is the reason why the GDP loss under scenario High is less than that under scenario Low in the long term. Furthermore, the carbon tax prompts industrial structural shifts because there is less fixed capital formation loss in the long term. Scenario Low obtains a mature low-carbon industrial structure faster than High; however, the benefits of a higher

carbon tax are larger than in Scenario Low, as shown in Fig. 2.2 Therefore, carbon tax will yield energy structural change because it might affect the cost competitiveness of RE power and foster expansion of RE power in Fig. 2.4 Intuitively, a higher carbon tax will not only decrease fossil fuel consumption and thermal power generation, but will also significantly increase the market share of RE power generation in the long term compared to the BaU scenario.

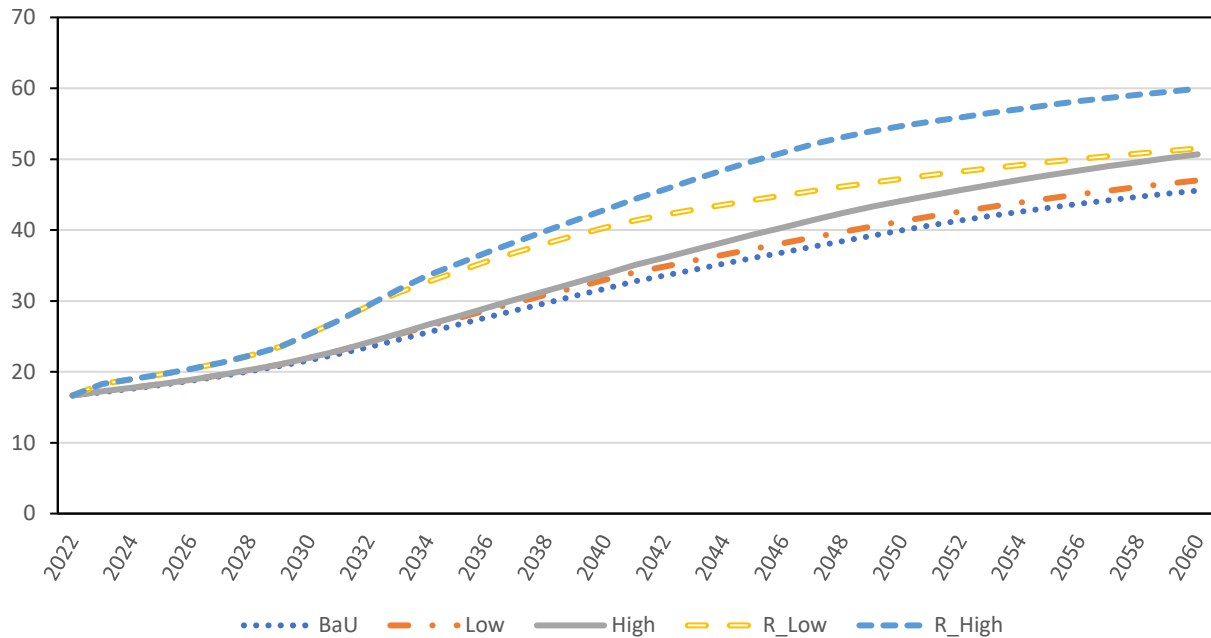


Figure. 2.4: Share of RE in total primary energy consumption (%)

Consequently, structural changes in energy can significantly reduce CO₂ emissions. As Fig. 2.5 shows that CO₂ emissions in 2060 under scenario Low and High will decrease by 8% and 19%, respectively, compared to BaU. This implies that it is realistic to substantially reduce CO₂ emissions by promoting energy transition by implementing carbon pricing. In addition, the power sector contributes to more than 90% of the CO₂ emission reduction under scenarios Low and High over all periods. This means that carbon pricing might bring about substantial abandonment of thermal power plants, which also makes a significant contribution to CO₂ emission abatement.

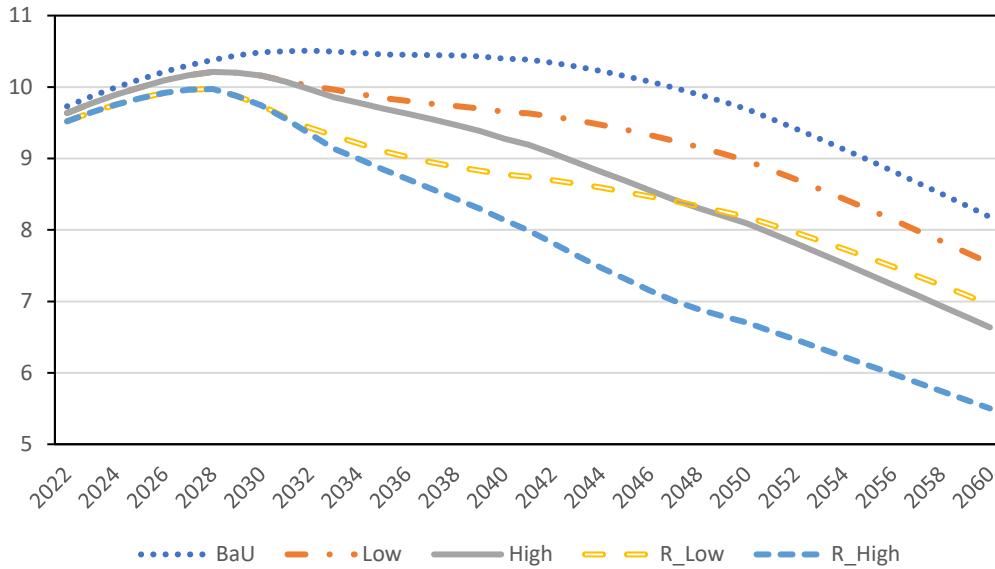


Figure. 2.5: CO₂ emission (billion ton)

Such a significant exit of thermal power in the electricity market brings changes in the weighted average cost of power generation, as presented in Fig. 2.6. In the medium term, the differences in the cost of power generation were not significant under the Low and High scenarios. However, after 2050, the cost of power generation under scenario High becomes lower than that under scenario Low, which means that a higher carbon tax might bring about better benefits in terms of cost reduction in the long term. The synergistic effect of carbon pricing and the LBD mechanism are likely to be taken into consideration. Compared to 50 billion Kwh of thermal power generation under BaU, the carbon tax will reduce thermal power generation in 2060 to 41 billion Kwh and 25.8 billion Kwh under scenarios Low and High, respectively. Meanwhile, a carbon tax can enlarge the market share for RE power, which might accelerate the cost reduction of RE power generation through the LBD process. Because the LBD effect depends on the learning curve of RE power and accumulation of RE power generation, a larger market space for RE power exerted by carbon pricing will further strengthen the LBD effect over time. As a result, the LBD effect increases as carbon tax increases. This leads to a substantial decline in the cost of power generation in the long term. Table 2.3 lists the cost of each type of electricity under different scenarios for 2040 and 2060. The synergistic effect of carbon pricing and the LBD mechanism drives the cost

reduction of RE power generation. The costs of wind and solar power generation under scenario High and Low are significantly lower than those under BaU. A higher carbon tax can be more beneficial. The substantial decline in the cost of power generation improved by LBD could offset the negative impacts on energy costs induced by carbon pricing to a great extent.

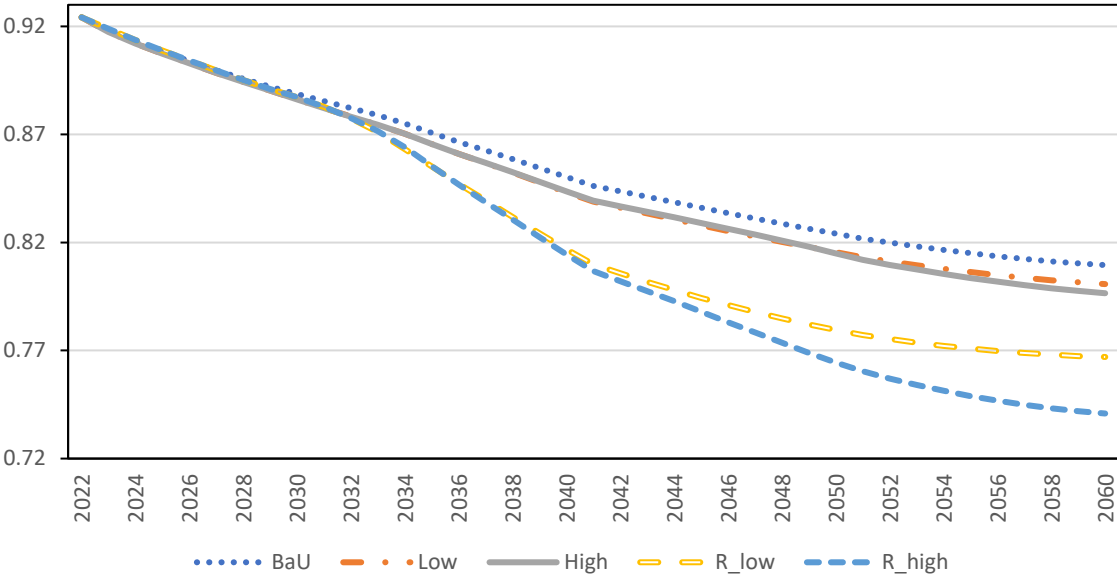


Figure. 2.6: Weighted average electricity generation cost

Note: Vertical axis is indicator rather than real price

Table 2.3: Electricity cost in 2040 and 2060

2040	BaU	Low	High	R_Low	R_High
Hydro	0.8369	0.8362	0.8359	0.8507	0.8526
Thermal	0.8326	0.8176	0.8176	0.8374	0.8584
Nuclear	1.0240	1.0233	1.0230	1.0251	1.0250
Wind	0.8842	0.8788	0.8767	0.7922	0.7826
Solar	0.8046	0.7987	0.7965	0.708081	0.6972
2060	BaU	Low	High	R_Low	R_High
Hydro	0.8195	0.8169	0.8125	0.8533	0.8543
Thermal	0.8157	0.8010	0.8382	0.8303	1.2865
Nuclear	1.1302	1.1258	1.1163	1.1378	1.1221
Wind	0.7884	0.7803	0.7626	0.7126	0.6752
Solar	0.6944	0.6843	0.6628	0.6022	0.5574

Note: cost here is indicator to show the change of them.

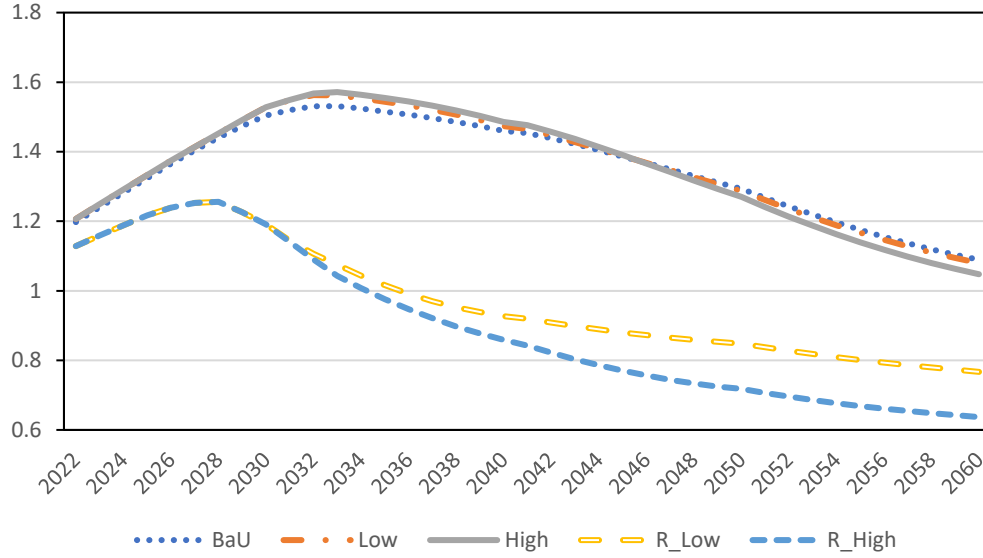


Figure. 2.7: Output price of electricity

Note: vertical axe is indicator rather than real price

The changes in the output price of electricity shown in Fig. 2.7 provide collateral evidence of the offset effect. Because carbon tax might cause an increase in energy cost, the output price of electricity until 2046 under scenarios Low and High is higher than that of BaU. As electricity is a homogenous product, the difference between each type of electricity exists only on the supply side rather than on the demand side. An increase in the output price of electricity will result in a decline in electricity demand; therefore, carbon tax will lead to a 4% and 9.6% decrease in power generation in 2060 under scenarios Low and High, respectively, compared to BaU. However, since 2046, the output price of electricity under scenarios Low and High has become lower than that of BaU. This indicates that the offset effect of LBD on the energy cost induced by carbon pricing emerges in the long term.

In addition, the technological improvement in thermal power generation is defined exogenously by AEEI in this study. The coal-power conversion coefficient (CPCC) refers to the amount of combusted fossil fuels required for power generation, illustrating the energy efficiency of thermal power generation (Yuan et al., 2020). It is evident that the carbon tax also improves the

energy efficiency of thermal power. A higher carbon tax level will have a more significant effect. The logic behind this is that a spontaneous technological improvement in thermal power generation is needed to maintain its cost competitiveness against RE power generation in the future. Fig. 2.8 shows that the CPCC of thermal power improves more significantly under scenarios Low and High compared to BaU.

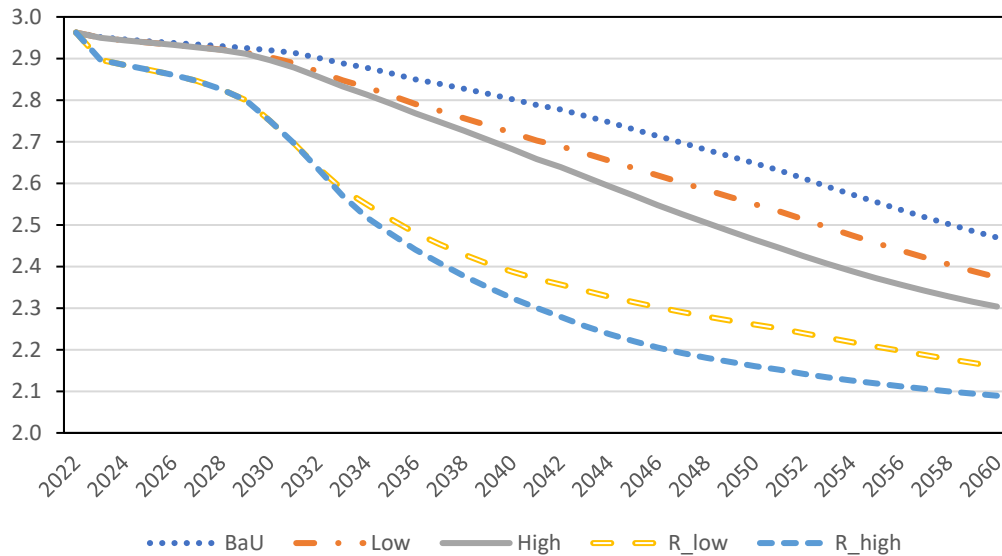


Figure. 2.8: CPCC (100 g of standard coal equivalent/Kwh)

2.5.2 Scenario R_Low and R_High (carbon tax revenue used for subsidy to RE)

Contrary to expectations, if carbon tax revenue is used as a subsidy for RE power generation, carbon pricing can reduce CO₂ emissions significantly with a positive gain in GDP growth, as shown in Fig. 2.2 and Fig. 2.5. A higher carbon tax rate can bring more positive gains in GDP growth as well as a greater reduction in CO₂ emissions by comparing the GDP change rate and total CO₂ emissions under scenarios R_Low and R_High. As mentioned in Section 2.4.1, this section also explains the results from the beginning of the GDP decomposition, as shown in Fig. 2.9. Government expenditure is reduced because carbon tax revenue is used as a subsidy for RE power. Its reduction will turn from an increase to a decrease under scenarios R_Low and R_High, compared to scenarios Low and High. However, household consumption increases substantially,

as shown in Fig. 2.9.

In contrast to government expenditures, household consumption increases under scenarios R_Low and R_High. This is because subsidies to RE power will reduce the price of RE (also average electricity) and stimulate electricity consumption, which accounts for nearly 90% of the growth in household consumption. In other words, unexpensive electricity will stimulate the growth of household consumption of technology-intensive products, such as advanced electric appliances. The negative impacts of carbon pricing on fixed capital formation will be alleviated when carbon tax revenue is used as a subsidy to RE power, although fixed capital formation will still decrease under scenarios R_Low and R_High in the long term. In fact, fixed capital formation will increase until 2031 if RE power is subsidized by carbon tax revenue because subsidies to RE energy will lead to increased investment in power and power-related sectors, such as turbine blades for wind power, monocrystalline solar panels for solar power, and more power plants built by construction. However, total investment will decrease in the long term because the benefits brought by RE power expansion cannot cover the negative impacts of the heavy carbon tax on the whole industrial chain. In addition, there is also a trivial increase in net exports under scenarios R_High and R_Low, which rarely affects GDP.

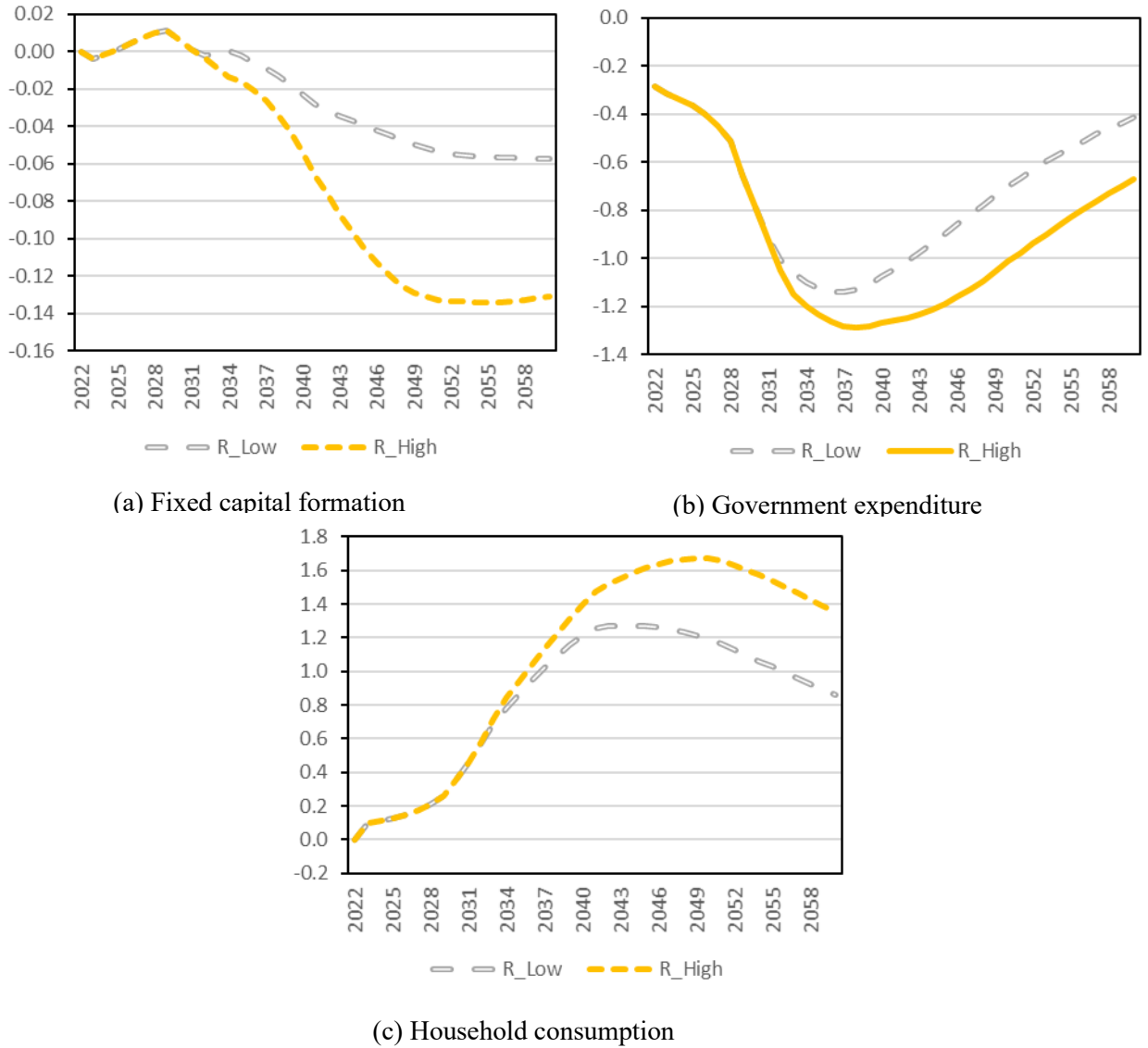


Figure. 2.9: Change rate of Fixed capital formation, government expenditure and household consumption (%)

As the range of increase in household consumption is much greater than the decline in fixed capital formation and government expenditure, a greater increase in household consumption can offset the reduction in government expenditure and fixed capital formation if carbon tax revenue is used as a subsidy to RE power. Consequently, carbon tax combined with subsidies to RE power can have a positive impact on economic growth, as shown in Fig. 2.2. Moreover, subsidies to RE power will foster a more rapid growth of RE power and a more significant energy structural shift,

as proposed by (Langer and Lemoine, 2022). Subsidies to RE under scenario R_High perform better than those under scenario R_Low, as shown in Fig. 2.4 shown. Moreover, the proportion of RE in the total primary energy consumption under scenario R_Low will be higher than that in scenario High.

Therefore, carbon tax combined with subsidy to RE power can provide a more significant effect on CO₂ emission reduction compared to the carbon tax used for government expenditure, as shown in Fig. 2.5 shown. The reduction in CO₂ emissions by 2060 under scenarios R_Low and R_High will account for 11.1% and 26%, respectively, of the BaU scenario. The reduction in CO₂ emissions by 2060 under scenario R_Low will be close to that under scenario High. This implies that there is huge potential to realize CO₂ emission reduction by implementing a carbon tax combined with a subsidy to RE power. This also indicates the potential of the carbon neutralization pathway by substantially increasing RE power and replacing thermal power. It is evident that the energy structural shift is prompted by the markdown of electricity.

When carbon tax revenue is used as a subsidy to RE power, a triple superimposition effect of carbon tax, RE subsidy, and LBD mechanism will stimulate a more substantial decline in energy cost in the long term. As expected, the subsidy to RE power will foster a more rapid growth of RE power, and a larger scale of RE power will strengthen the LBD process. However, hysteresis was observed in the triple-superimposition effect. As Fig. 2.6 shows, the difference in the weighted average electricity generation costs between scenario R_Low/R_High and scenario Low/High is not significant until 2031. Since 2032, the weighted average electricity generation costs under scenario R_Low/R_High have become lower than those under the low/high scenario. A higher carbon tax with an RE subsidy can stimulate a stronger LBD effect and drive a more substantial decline in the average electricity cost. Subsidies for RE power can have a direct influence on the change in the output price of electricity. As Fig. 2.7 shows, the average output price of electricity under scenarios R_Low and R_High will be significantly lower than that in scenarios Low and High. A higher carbon tax can provide more subsidy to RE power, which will lead to a lower output

price of electricity in the long term. As a consequence of the decline in the output price of electricity, more electricity consumption is generated under scenarios R_Low and R_High, even when a higher carbon tax is levied.

Simultaneously, the technological improvement of RE power induced by the LBD process will stimulate improvements in the energy efficiency of thermal power. Otherwise, the thermal power sector loses its competitiveness in the electricity market. As Fig. 2.8 shows that the triple superimposition effect of carbon tax, RE subsidy, and LBD mechanism can also promote a more substantial decline in CPCC compared with scenarios Low and High. The reversal of the status between thermal, wind, and solar power proves the significant function of endogenous technological progress induced by the LBD mechanism in energy transition.

However, there are different outcomes in terms of the costs of hydropower and nuclear power generation. The rapid development of wind and solar power has seized the attraction of capital due to subsidies. The increasing cost of hydropower and nuclear power indicates a fierce market in which they might have to hire more labor to replace the function of capital following the principle of the CES function, that is, monitoring and maintenance.

2.5.3 Discussion

In summary, when carbon tax revenue is collected by the government, the increase in government offsets the reduction of investment in heavy CO₂ emitters; however, carbon tax also affects resident consumption, which significantly results in GDP loss in High and Low. When RE power is funded by carbon tax revenue, improved RE power stimulates investment in power-related construction, technology-intensive industries, and resident consumption. As a result, LBD offsets the negative impact of carbon pricing on economic growth in all scenarios, and there is even GDP growth, while carbon tax revenue is converted into subsidy to RE power generation because the benefits of electricity cost cutdown even exceed the negative impact of carbon tax in

the whole industrial chain and demand-supply relationship.

In addition to the supply-side effects, there is also the possibility that carbon tax revenue can be used on the demand side, for example, to help households. Price changes caused by carbon tax are likely to be more effective in reducing transportation consumption than electricity consumption (Saelim, 2019). This effect can be increased in rural areas where transportation is less elastic and alternative options are less available (Harju et al., 2022). Therefore, many studies suggest using carbon tax revenue to fund exemptions on fuel tax to mitigate poverty and welfare loss (Yamazaki, 2017). When carbon tax revenue is returned to households in the form of income tax deductions, it leads to a significant decrease in transport and heavy industry demand, but an increase in the demand for light industry and clean energy (renewable energy) (Li et al., 2020). Deploying carbon tax revenue on the demand side would provide results similar to those of subsidies on the supply side, as seen in this study. According to the results, though carbon tax increases the price of transportation in the short term, the significant reduction in electricity prices will not lead to a rebound effect on carbon tax revenue and emission reduction because renewable electricity is more competitive than fossil fuels not only in transportation but also in other products such as heating and power supply. As both supply-side and demand-side carbon tax revenue recycling will induce similar results, this paper only focuses on the supply side.

The model used in this study is a nation-level CGE model rather than a regional model. There are substantial energy efficiency differences between western and eastern areas in China, mainly caused by low levels of population and energy consumption (Wang et al., 2021). Western areas have lower carbon emissions and a larger abundance of renewable energy resources (National Bureau of Statistics of China, 2018b). The improvement of renewable resources can significantly reduce carbon emissions in the long term (Wang, 2022). The increase in use of renewable energy can also increase carbon productivity (energy efficiency), especially in western China (Meng et al., 2022). According to the results, stricter environmental policy leads to faster technological improvement. In western areas, the use of ITC is more effective than in developed areas due to the

abundance of renewable energy, which mitigates the impact of the carbon tax. Although there is spatial heterogeneity of energy efficiency in China, the complementary relationship between western and eastern areas can cover the carbon tax. Eastern areas can replace fossil fuels and increase the demand for renewable energy, stimulating further ITC in western areas without being significantly affected by the carbon tax. Therefore, this research does not consider regional differences.

The stage characteristic of decarbonization energy system is included in this study. The energy efficiency is set exogenously step by step, with the energy efficiency increasing gradually in this model. Furthermore, the CGE model also incorporates electrification stage by stage, making electricity more attractive while fossil fuels are gradually replaced. This allows for a more realistic representation of the decarbonization process and the changes that occur in the energy system over time.

2.6 Sensitivity analysis

To test the robustness of the CGE model, this study carried out a sensitivity analysis to check the sensitivity of some key parameters to GDP, CO₂ emissions, and energy cost, which shows the importance of parameters in policymaking (Chatri et al., 2018). In the Results and Discussion section, the offset effect of LBD on economic growth focuses on the weighted average electricity cost, which affects investment and consumption directly or indirectly. Thus, this study analyzes the 5% fluctuation of substitution elasticity between electricity and fossil fuels and the learning rate in the LBD process, except for scenario R_High, in which this model designs a unique scenario of sensitivity analysis named LR_0.9. Higher substitution elasticity *sigma* means that producers prefer to use electricity to replace fossil fuels, and a higher learning rate LR means more technological improvement at the same level of cumulative RE power generation.

Table 2.4: Sensitivity analysis (Change compared to each scenario)

Scenario	GDPR(%)			CO ₂ (%)			Average electricity Cost(%)		
	2040	2050	2060	2040	2050	2060	2040	2050	2060
BaU									
sigma0.95	-	-	-	0.02	0.14	0.32	-0.002	0.016	0.050
	0.003	0.009	0.016						
sigma1.05	0.003	0.009	0.015	-	-	-	0.002	-	-
				0.02	0.13	0.32		0.015	0.048
LR_0.95	-	-	-	0.17	0.27	0.26	0.100	0.212	0.318
	0.021	0.033	0.031						
LR_1.05	0.022	0.035	0.031	-	-	-	-0.116	-	-
				0.18	0.28	0.25		0.253	0.378
Low									
sigma0.95	-	-	-	0.02	0.13	0.33		0.02	0.05
	0.003	0.009	0.015				0.0001		
sigma1.05	0.003	0.008	0.015	-	-	-	-	-0.02	-0.05
				0.01	0.13	0.33	0.0001		
LR_0.95	-	-	-	0.20	0.32	0.32	0.10	0.20	0.30
	0.021	0.033	0.031						
LR_1.05	0.024	0.038	0.034	-	-	-	-0.13	-0.29	-0.43
				0.23	0.37	0.34			
High									
sigma0.95	-	-	-	0.01	0.14	0.37		0.03	0.07
	0.002	0.008	0.015				0.002		
sigma1.05	0.002	0.008	0.015	-	-	-		-0.03	-0.07
				0.01	0.14	0.36	-0.002		
LR_0.95	-	-	-	0.24	0.49	0.52	0.10	0.23	0.36
	0.022	0.036	0.035						
LR_1.05	0.025	0.041	0.038	-	-	-	-0.13	-0.34	-0.54
				0.27	0.56	0.56			
R_Low									
sigma0.95	-	-	-						
	0.006	0.010	0.015	0.08	0.24	0.43	0.026	0.035	0.053
sigma1.05				-	-	-		-	-
	0.006	0.010	0.014	0.08	0.24	0.42	-0.025	0.033	0.050

LR_0.95	-	-	-						
	0.033	0.041	0.039	0.30	0.38	0.39	0.317	0.480	0.557
LR_1.05				-	-	-		-	-
	0.038	0.047	0.044	0.35	0.43	0.43	-0.441	0.672	0.781
R_High									
sigma0.95	-	-	-						
	0.006	0.008	0.011	0.08	0.32	0.64	0.039	0.030	0.006
sigma1.05				-	-	-		-	-
	0.006	0.008	0.011	0.07	0.30	0.61	-0.037	0.029	0.006
LR_0.9	-	-	-						
	0.082	0.113	0.111	0.90	1.42	1.42	0.998	1.874	2.312
LR_0.95	-	-	-						
	0.035	0.047	0.046	0.38	0.58	0.57	0.357	0.669	0.825
LR_1.05				-	-	-		-	-
	0.017	0.024	0.024	0.20	0.32	0.32	-0.429	0.805	0.978

Note: *sigma* is the elasticity of substitution between electricity and fossil fuel. *LR* is the learning rate of the LBD process.

Table 2.4 shows the results of the sensitivity analyses for the years 2040, 2050, and 2060. In all scenarios with carbon tax, a higher *sigma* leads to an average electricity cost reduction in 2040; however, it is totally reversed in BaU. In BaU, lower substitution elasticity means relatively less electricity consumption, that is, a low electrification rate for households and industries. Less electricity demand ensures mild technological improvement in RE power, which is similar to other carbon tax scenarios in the long term. When a carbon tax is levied, the LBD process is accelerated to drive RE power generation cost reduction. Table 2.4 shows an explicitly higher reduction of cost in all scenarios in 2060 than in 2050 and 2040. However, substitution elasticity directly affects the consumption of fossil fuels, with lower *sigma* values leading to higher CO₂ emissions in all the scenarios. Less electricity demand also results in less investment in the power sector, which has a negative impact on GDP because the LBD effect is weakened by less consumption of electricity.

On the other hand, as a key parameter in the LBD process, *LR* directly improves technological

improvement in all scenarios, except R_High, where a higher learning rate leads to more cost reduction, CO₂ emission abatement, and GDP growth. The faster LBD process facilitates the growth of investment in the power sector, further accelerating the technological improvement of thermal power and RE power, and vice versa. As Table 2.4 shows, the influence of the learning rate is always stronger than the substantial elasticity in the medium- and long-term because the development of RE power directly affects the cost of electricity, thereby affecting the price of electricity. A higher learning rate not only fosters improvement in the power sector but also promotes investment in related industries and demand for electricity. Unexpensive electricity has further driven the popularization of electronic devices and machines, which has stimulated the development of technology-intensive, tertiary, and transportation industries.

Furthermore, a higher carbon tax with LBD will exert a more positive impact on economic growth and CO₂ emission abatement in all scenarios because a higher carbon tax provides more space for RE power to improve China's power sector. However, our model shows infeasible results for LR_1.05 after 2057, which might be caused by the excessively high learning rate set for solar power generation from (Zhu et al., 2015). From the model aspect, the learning rate in LR_1.05 leads to a negative AEEI for solar power generation to balance the excessive improvement in technology, which results in an infeasible outcome. However, there is no doubt that a higher LR leads to a greater cost reduction compared with all feasible results in scenario R_High. To check the sensitivity of the learning rate, this study designed an LR_0.9 scenarios that means the learning rate decreased by 10%. Obviously, LR_0.9 shows a more negative impact of a lower learning rate on GDP growth, CO₂ emission abatement, and cost reduction compared to LR_0.95. Moreover, the impact on cost reduction is nearly three times larger than that of LR_0.95 in LR_0.9, although the learning rate only decreases by 5.5%. Thus, it was easy to determine the significant sensitivity of the learning rate in the LBD process and cost reduction.

Both sigma and LR have a greater impact on cost and CO₂ emission reduction in the long term, except for GDP. The economic system tends to become balanced in the long term even when there

is an external shock caused by policy instruments because technological improvement becomes more difficult as it develops in the long term.

2.7 Conclusion

This study combined a bottom-up LBD module with a top-down CGE model to investigate the offset effects of endogenous technological progress on the negative impacts of economic growth with the induction of carbon pricing in China. A recursively dynamic CGE model is advantageous for demonstrating in detail how economic impacts are yielded by policy instruments.

The offset effect of ITC on GDP loss caused by the carbon tax on all industries has already been proposed in (Lim and Kim, 2012) in the CGE model. It creates a sector for R&D services and evaluates the economic and environmental impacts of the ITC. However, our study adopts LBD not as a sector, but as a bottom-up module combined with the CGE model. Moreover, the results of our study reveal that only the cost reduction of RE power induced by the LBD mechanism is capable of effectively offsetting the GDP loss caused by carbon tax, compared with all industries that reduce carbon emissions by fuel mix in (Lim and Kim, 2012). In addition, the previous study does not clearly reveal how ITC with carbon tax and subsidy leads to a low-carbon energy structure instead of more carbon emissions with R&D subsidy. Our results illustrate that, in comparison with a lower carbon tax, more CO₂ emission abatement under a more stringent carbon tax is likely to lead to more GDP loss in the long term. Furthermore, RE power funded by carbon tax revenue leads to an increase in RE market share compared to simple carbon tax revenue recycling from the government. Further, more market share supports more RE power generation, which causes greater LBD effects driven by the cumulative generation capacity. Therefore, this study demonstrates more specific results that the offset effect of LBD on RE is significant in reducing GDP loss (even GDP growth) caused by strict carbon tax and carbon emission abatement, leading to a low-carbon energy structure.

The main contribution of this study is that this is the first study connecting LBD, renewable energy, carbon tax and renewable subsidy with CGE model.¹ Our CGE model reveals the synergistic effect of carbon pricing and subsidy with the LBD mechanism on the RE power sector in China. Our results show the LBD mechanism with subsidy can boost technological improvement in RE power generation, and the negative impacts of carbon tax could be offset by endogenous technological progress in the RE power sector.² This study provides a reference for levying a carbon tax in developing countries that are mainly contributed by energy-intensive industries, such as China. China is not only the largest carbon emitter in the world, but also possesses the largest scale of wind and solar power generation that provides rich soil for developing RE via the LBD process, as endogenous technological progress works well with a solid foundation. This work shows substantial ITC in the wind and solar power sector that it is possible to replace thermal power in the future, contributing to the global mitigation of GHG emissions.

The results of this study also indicate that the LBD mechanism is the key factor of the ITC in reducing the costs of RE power. Beneficial LBD effects on the power sector provide explicit policy implications: 1) carbon pricing with subsidies works significantly on 2.68 billion tons of CO₂ emission reduction in scenario R_High compared to BaU in 2060. 2) energy structural shift which shows 31.5% increase in renewable energy consumption in scenario R_High compared to BaU in 2060. 3) slight GDP loss under carbon tax compared to existed research (Yuan et al., 2020) and even GDP growth of nearly 1% to 0.82% during 2022 to 2060 in scenario R_High compared to BaU. An industrial structure change under CO₂ emission constraints optimizes it, and a higher carbon tax is more efficient. Moreover, this study implements a continuous subsidy to RE from carbon tax revenue, even though it is unexpensive than thermal power in the long term because

¹ Our theoretical foundation comes from Acemoglu et al., 2021, Ye et al., 2022, Goulder et al., 2000 and Langer and Lemoine (2022).

² This study developed a recursively dynamic CGE model integrated with the LBD mechanism and electricity market share allocation mechanism. The improved model to policy simulation on the synergic effects of carbon pricing and subsidy with the LBD mechanism on the RE power sector. The LBD module in this model is different from that in Ortega et al. (2015), which applies a learning-by-doing mechanism via the accumulation of electricity output rather than cumulative labor employment. In addition, it is also different from the soft link between exogenous LBD and the CGE model in Lim and Kim (2012) that our work constructs a hard link between the CGE model and endogenous LBD module.

there are incentives for firms to invest in related industries (Helm and Mier, 2021).

The study in this work suggests that by providing alternatives such as unexpensive electricity, the public's resistance to the implementation of a carbon tax caused by lack of public support and commercial opposition might be mitigated to some extent Ewald et al. (2022). The ability for households and industries to switch to unexpensive electricity instead of fossil fuels, such as natural gas, coal, or oil for heating and transportation, might make it easier for residents to accept a carbon tax. This is particularly relevant in China, where the consumption share of gas is lower, and electrification in the future could make it even more viable (Povitkina et al., 2021). Furthermore, there is a big difference between other developed countries and China is that China has a highly centralized government with strong infrastructure, which allows for the effective implementation of state practices to achieve persistence in environmental policy (Lee and Zhang, 2013). For example, the pilot emission trading scheme (ETS) implemented in 2013 has achieved in both economic and environmental improvement, and has potential for national carbon pricing (National carbon pricing market has been launched in 2021) (Zhang and Liu, 2022). The centralized government is able to coordinate political and commercial power, including local governments and enterprises, to implement environmental policy without suffering from poor political understanding or communication. Additionally, the centralized regime can mitigate public resistance to carbon tax. However, we cannot ignore that soft budget constraint is persist in this system (Managi, 2010). Policy enforcement of Top-down centralized regime is more susceptible to effectiveness of policy design. Inefficiency is likely to persist in implementation of nation-level carbon tax in China.

However, this study remains a question and limitation. This research focuses on discussing the price effect on the demand side, which shows long-term beneficial results in final demand, but lacks the impact of the income effect. Since income inequality is likely to be caused by environmental policies, homogenous carbon tax recycling for all labor groups should be avoided (Zhao et al., 2022). Nevertheless, the results show that the potential price effect of LBD on

electricity can cover the negative impact on the markup of traditional thermal power generation, as discussed, more unexpensive electricity in Section 5.2. In addition, this model does not consider the storage of electricity, which can affect the behavior of firms. Nevertheless, if carbon pricing with subsidies was implemented, several billion tons of CO₂ emissions could be mitigated. Overall, a significant contribution to global carbon abatement can be expected by implementing carbon pricing, supported by the offset effects analysis in this study. Further studies might need to consider other low-carbon technologies such as carbon capture, utilization, and storage (CCUS) which can be improved by carbon tax policy at the medium level in areas with well-designed infrastructure (Sun and Chen, 2022). A higher carbon tax of around 350 CNY/ton could result in full implementation of CCUS, which would have a positive impact on its deployment. High carbon tax increases the cost of thermal power generation and make application of CCUS an more economical way for power supplier (Jiang et al., 2020). However, it is uncertain if CCUS will remain competitive as renewable energy (RE) becomes more economic in the power sector. The substantial development of RE might make CCUS less attractive for thermal power supplier since most of carbon emission has already been reduced by exit of thermal power. There is currently a lack of available data to support better policymaking in CCUS.

Appendix A: Supplementary data

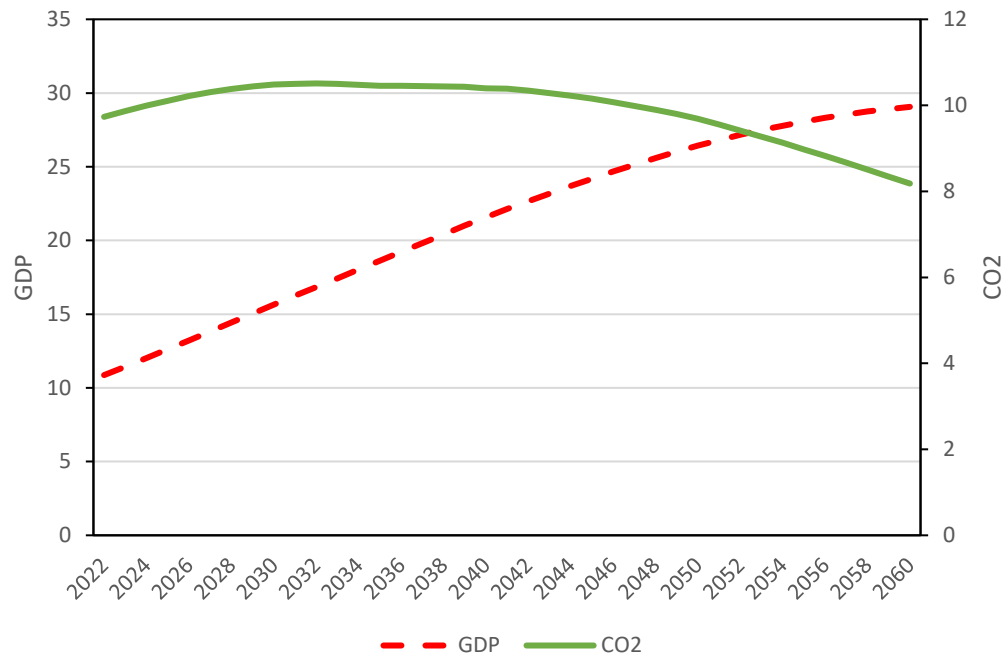


Figure. A.2.1: Real GDP (billion CNY, 2017 price level) and CO₂ emission (billion ton) in BaU

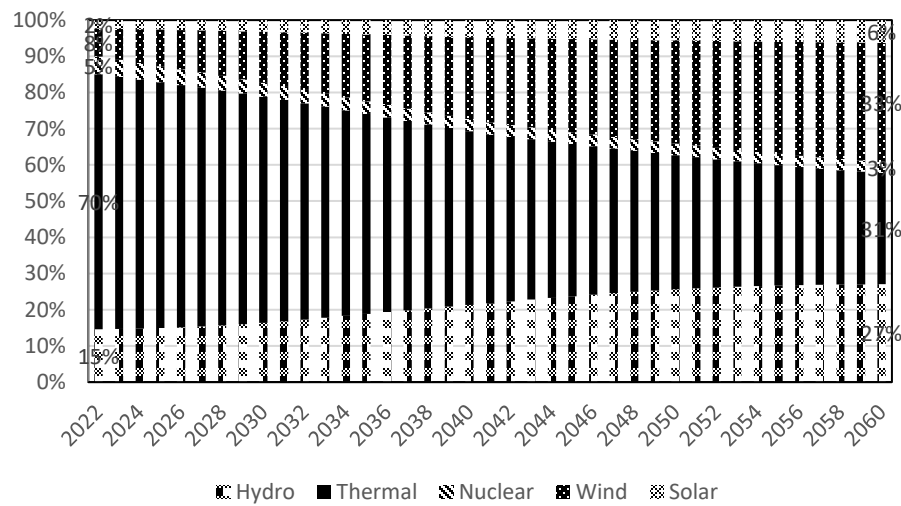


Figure. A.2.2: Ratio of each power generation in power sector

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Chapter 3 Improved renewable energy storage, clean electrification and carbon mitigation

3.1 Introduction

China's decision to develop renewable energy as a way to replace coal-fired power plants is a crucial step towards achieving its nationally determined contribution (NDC). By replacing coal-fired power plants with renewable energy, China can reduce its reliance on fossil fuels and shift towards adopt cleaner and more sustainable sources of energy. Clean electrification is an important strategy for reducing carbon emissions. However, this energy structural transition requires a clean electrification, which is likely to be achieved through the development of renewable energy (RE).

RE and electrification indicate a future interdependence among developing countries (Bamisile et al., 2021), which means RE is essential for energy structural shift. RE can positively affect the promotion of electric vehicles (EVs) if electricity prices are reduced by wind and solar power generation (Keller et al., 2019). However, so far, RE is not capable of providing sufficient electricity for EVs (Sacchi et al., 2022). Industries can benefit from electrification because electrified steel industries supported by solar and wind power can effectively reduce fossil fuel consumption (Toktarova et al., 2022). The soaring demand for EVs in the transportation industry has spurred the development of low-cost battery technologies (Schwarz et al., 2020) and electrification in other industrial sectors (Sorknæs et al., 2022). Moreover, residents' behavior might play a key role in decarbonization through coal-to-electricity (CtE) and gas-to-electricity power generation (Frapin et al., 2022). Therefore, the markdown of RE-powered electricity supply is the centerpiece of clean electrification with economic growth.

Evidence from developed countries has shown that there are barriers to developing RE to

replace thermal power because of its current high cost. Induced technological change (ITC) greatly helps in reducing the cost of RE generation without any government intervention (Acemoglu et al., 2012). Furthermore, some studies have highlighted the positive impact of environmental policy, that is, carbon tax, on ITC, which indicates that learning-by-doing (LBD) or Research and Development (R&D) can be accelerated by government regulation (Lim and Kim, 2012; Goulder and Mathai, 2000; Langer and Lemoine, 2022). The cost of RE has been reducing over the past few years, for example, the cost of photovoltaic power generation has decreased by around 50% from 2010 to 2019 (International Renewable Energy Agency, 2022b). However, RE such as wind and solar power has intermittent and volatile characteristics and may cause instability in the power supply.

Developing large-scale energy storage becomes more and more important in the efficient utilization of RE. The storage of RE is a common and essential method to keep a stable load with more intermittent RE in electricity market. Khan et al. (2018) suggest that endogenous investment in storage and power generation can significantly reduce capacity cost. However, the cost of RE storage is significantly higher than that of power generation (Li et al., 2023). Therefore, in June 2022, the National Development and Reform Commission and National Energy Administration issued the Guiding Opinions on Accelerating the Development of New Energy Storage Technologies (GOADNES).³ The GOADNES encourages the development of independent energy storage market entities and makes policies to promote the development of new energy storage technologies, such as capacity subsidies.

However, there is an argument regarding whether reducing storage costs can lead to renewable energy sharing (Laha and Chakraborty, 2021) or whether further development of RE instead depresses more storage (Liebensteiner et al., 2023). Increasing demand for electricity storage is likely to increase the price of electricity (Nyamdash and Denny, 2013). Using the Computable

³ http://www.gov.cn/xinwen/2022-03/28/content_5681916.htm

General Equilibrium (CGE) model, Dai et al. (2017) have suggested that higher storage costs lead to more GDP loss because of higher electricity prices; however, storage becomes important if the share of the RE power generation is substantial. This conflict between the development and storage of RE poses a challenge to policymaking. Helm and Mier (2021) have suggested that storage subsidies financed by lump-sum taxes should be used to offset electricity markup during electricity storage. More RE generation at a reduced cost allows further subsidizing the storage, especially that of solar and wind power, which may help overcome the obstacle of expensive development and storage of RE and further electrification.

The carbon tax is considered to be one of the most efficient instruments for reducing fossil fuel consumption and it has been implemented across 37 countries as of April, 2022 (Aaron et al., 2022). The development of energy-intensive industries can be severely hindered unless they decide to replace fossil fuels with electricity (Khastar et al., 2020). Helm and Mier (2021) proposes the carbon tax-financed subsidy is an effective method to encourage RE development. As a price-oriented policy, subsidization has its limitation as electrification further develops. However, price-oriented policies play an irreplaceable role in the development of the power sector in its initial stages (Song et al., 2021). For example, subsidy on RE generation can promote EV penetration through the promoted cost competitiveness of electricity (Jiang et al., 2022).

Although carbon tax and subsidy might promote clean electrification, there exists a self-contradiction because carbon tax revenue declines during the electrification of industries and households. This leads to decreased subsidies for RE power generation and storage. Thus, during electrification, the reduced carbon tax revenue transferred as a subsidy because of the decreased fossil fuel consumption is likely to exacerbate the conflict between the soaring demand for cheaper electricity and its expensive storage. However, there is a lack of studies on incorporating storage with endogenous technological improvement in the power sector.

This study develops a CGE model to analyze the conflicts between soaring demand for RE

generation and storage, caused by the urgent clean electrification and expensive storage for RE. The main contributions of this study are as follows: 1) We incorporate the wind and solar power storage industries and thoroughly describe the dynamic path of non-thermal power generation technology by considering the economies of scale and LBD effect of RE and new energy storage technologies in the CGE model. 2) The influence of some policies proposed in the GOADNES is evaluated. 3) The relationships among the development of RE storage, RE, electrification, and carbon mitigation are studied. We also demonstrate the conflict between the exit of thermal power and decreasing subsidies financed by carbon tax revenue. Accordingly, we highlight the importance of technological change for the development of RE and RE storage, clean electrification, and carbon mitigation. Additionally, the conflict between RE storage and RE development is also verified that electricity generation affected by RE and electrification further influences the pathway for storage improvement, leading to economic and environmental benefits and losses in the short term.

The remainder of this paper is organized as follows: Section 2 shows our methodological framework and data sources with an emphasis on ITC in RE and energy storage. Section 3 describes the scenario design and demonstrates the results under the business-as-usual (BaU) scenario. Section 4 presents the main results of the scenarios. Section 5 gives the discussion on limitation. Section 6 provides sensitivity analysis. Finally, Section 7 concludes the study and makes a comparative analysis with other studies.

3.2 Model

3.2.1 Overall framework of the model

We establish a framework in which the LBD in RE and RE storage are incorporated into a CGE model. Electrification increases the demand for replacing fossil fuels with electricity in energy

consumption. The supply of wind and solar energy faces the challenge of the high cost of storage, resulting from the soaring demand for clean electricity under the structural energy transformation. Fig.3.1 demonstrates the overall framework of our model. The basic structure of the CGE model, including income, market, production, and expenditure is based on Yuan et al. (2020)⁴ Furthermore, we include new mechanisms of subsidization, investment allocation, and LBD in the RE storage sector.

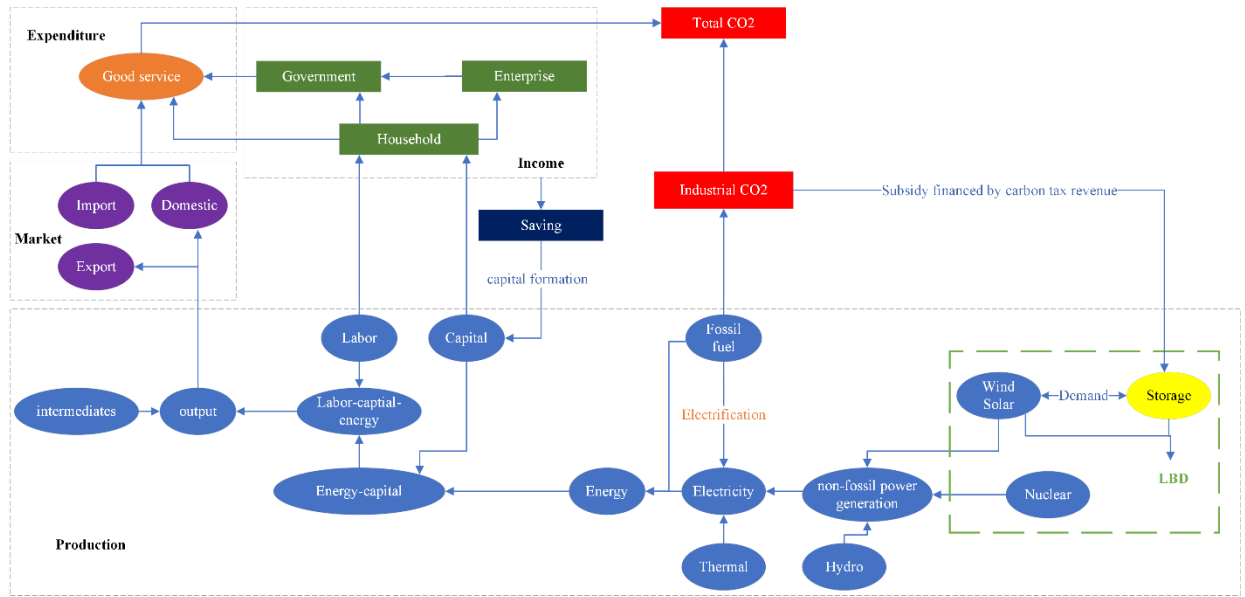


Figure 3.1 Overall framework of the model

3.2.1.1 Power production

We suppose all power plants will achieve zero-profit condition:

$$PX_{elec} * QX_{elec}(1 - tp_{elec}) = PL_{elec} * QL_{elec} + PK_{elec} * QK_{elec} + \sum_{ECC} QA_{ecc,elec} * PQ_{ecc} + \sum_{NEC} PQ_{nec,elec} * QA_{nec,elec} + tco * \sum_{ECC} ENCO2_{ecc,elec} QA_{ecc,elec} \quad (3.1)$$

$C = \{all\ the\ sectors\}$ and $c \in C$ and $i \in C$,

$ECC = \{all\ the\ energy\ sectors\}$ and $ecc \in ECC$;

⁴ We do not show all equations of CGE model in this paper. The authors would respond to request for all equations by email.

$$NEC = \{all\ the\ non - energy\ sectors\} \ and\ nec \in NEC$$

Eq. (3.1) shows power plants' production function under zero-profit condition, where PX is the output price of electricity and PL , QL , PK , and QK are the price and quantity of labor and capital, respectively. PQ and QA are the price and quantity of intermediate inputs, respectively, and tco is the tax rate of carbon emission. $\sum_{ECC} ENCO2_{ecc,elec} QA_{ecc,elec}$ is the carbon emission calculated by the intermediate of fossil fuel combustion in industries.

3.2.2.2 Demand for storage of wind and solar power

The storage cost is determined by the share of variable renewable energy (VRE) generation, as given by Dai et al. (2017):

$$Share = \alpha_{win} * swin^{\beta_{win}} + \alpha_{sol} * ssol^{\beta_{sol}} \quad (3.2)$$

Where α_{win} , α_{sol} , β_{win} , and β_{sol} are parameters estimated for the storage of wind and solar power. $ssol$, $swin$ is the theoretical share of solar and wind power generation and $Share$ is the total share of electricity storage. $swin$ and $ssol$ indicate the share of wind and solar storage capacity in total wind and solar power supply, respectively. Eq. (3.2) shows the relationship between RE supply and its storage demand, in which a higher share of RE generation leads to higher demand for RE storage. β_{win} and β_{sol} are 1.5 and 1.7, respectively, based on Dai et al. (2017), while α_{win} and α_{sol} are calibrated based on historical data from 2017.

3.2.2.3 Market share and investment

We apply the market share mechanism into this model, similar to Williams and Green (2022) because it encourages the entry of competitive electricity producers into the electricity market, and lower price leads to a higher market share in our model.

$$MS_{re} = MS1_{re} + a * MS1_{re} * (\widehat{MS}_{re} - MS1_{re}) * (RP_{re} - RP1_{re}) \quad (3.3)$$

$$re = \{hydro, nuclear, wind \text{ and } solar \text{ power}\}$$

Where MS_{re} , RP_{re} , a , and $\widehat{MS}_{re}$ are market share, relative price, weight parameter, and the upper bound of market share, respectively. Market share is determined based on non-thermal power (price*quantity) and the relative price is a specific price of thermal power divided by price of non-thermal power, which means that the electricity market prefers cheaper non-thermal power. $MS1_{re}$ and $RP1_{re}$ denote the market share and relative prices in the previous year, respectively. Finally, the market share of thermal power is the sum of all remaining sources of non-thermal power.

The investment (installed capacity) in the wind and solar power is positively related to its market share. We use the investment share of total new investments from all sectors to determine the investment in the power sector.

$$INV_{sw} = INV1_{sw} + iva_{sw} * (\widehat{INV}_{sw} - INV1_{sw}) * (MS_{sw} - MS1_{sw}) \quad (3.4)$$

$$sw = \{wind \text{ and } solar \text{ power}\}$$

Where INV_{sw} , iva_{sw} , and $\widehat{INV}_{sw}$ indicate the total investment share, weight parameter, and the upper bound of total wind and solar investment, respectively. The actual investment in the power sector equals the total investment multiplied by the investment share. The investment share in storage is similar to that in Eq. (3.4) but the weight parameter is different. The parameters iva_{sw} are five and nine for total investment share in wind and solar power and nine and eleven for storage. The weight parameter is calibrated by historical data.

3.2.2.4 Learning-by-doing (LBD) in power generation

The LBD is applied for nuclear, wind, and solar power generation as follows:

$$AVC_{nsw} = lb_{nsw} * KS_{nsw}^{lx_{nsw}} \quad (3.5)$$

$$nsw = \{nuclear, wind, and solar power\}$$

Where AVC_{nsw} , KS_{nsw} , and lx_{nsw} are the average cost, knowledge stock, and learning rate, respectively. lb_{nsw} is calibrated by basic data. The knowledge stock is given by the accumulated output of power with a 0.05 depreciation rate. The learning rate based on Zhu et al. (2015) and McDonald and Schrattenholzer (2001) for nuclear, wind, and solar is -0.09, -0.1, and -0.12, respectively. The storage of wind and solar power is the same as given in Eq. (5). The details are given in Section 3.3.2.3.

3.2.3 Battery and endogenous technological change in the wind and solar storage

According to the GOADNES and China's State Council, new energy storage should be developed to regulate power supply and transmission. Accordingly, its efficiency and stability will be enhanced, renewable energy development will be supported based on market power, and ITC becomes important at the carbon peak. Furthermore, it has been pointed out that storage on the supply side should be facilitated by the exit of thermal power plants and entry of storage installation of wind and solar power plants, increasing the ratio of renewable energy in power storage. More importantly, it has been suggested that technological improvement in electrochemical energy storage plays a key role in reducing the cost of commercial (lithium) batteries.

Batteries are one of the most popular methods for storing electricity and comprised nearly 80% of electricity storage in China (except for pumped hydropower) in 2020 (Xiao et al., 2022). Although the current high cost of batteries is not feasible for maintaining the peak load in most European countries, it has been demonstrated that frequent battery-stored power supply is profitable in the electricity market. This is because battery energy storage systems may become more attractive with declining battery costs (Hu et al., 2022). Combining the CGE model with life cycle assessment, Guo et al. (2021) have mentioned that fixed technological progress in batteries significantly contributes to economic growth and carbon emission abatement instead of subsidy,

such as in the EV industry. Existing studies have found that innovation in battery technologies greatly contributes to the technological improvement of energy storage (Feng and Lazkano, 2022). More importantly, it has been proposed that increased electricity prices negatively affect the innovation of storage technologies. Therefore, technological improvement in batteries can represent the ITC in RE storage. To show the negative relationship, in our model, the learning rate of technological storage is affected by electricity prices.

$$AVCST_{sw} = lbs_{sw} * KST_{sw}^{TIE_{sw}/PX_{sw}} \quad (3.6)$$

Where $AVCST_{sw}$, KST_{sw} , TIE_{sw} , and PX_{sw} denote the average cost, knowledge stock, learning rate of storage, and price of solar and wind power, respectively. lbs_{sw} is also calibrated by basic data, and TIE_{sw} is -0.085 based on Guo and Fan (2017). Therefore, policies that can facilitate ITC should play a key role in prompting storage technologies. Cost-efficient investment in the power sector and storage is driven by the learning rates of ITC (Golombek et al., 2022).

3.2.4 Data

The social account matrix for the CGE model is derived from China's national input-output table 2017, energy balance sheet, and power statistical database (National Bureau of Statistics of China, 2021a; National Bureau of Statistics of China, 2018; China Electricity Council, n.d.), which includes 35 industries, two residential households (urban and rural), and three production inputs (labor, capital, and energy). The model is recursively dynamic to 2060.

According to the fourteenth five-year plan of energy development proposed by the National Development and Reform Commission (NDRC), the installed capacity of hydropower should increase by 11% compared to 2020 and that of nuclear power should increase by 75% from 2021 to 2025. Their average growth rates are 2.1% and 7%, respectively. The public attention to and the perception of nuclear power in coastal areas is much higher than that in inland area-based nuclear

power plants. The average annual investment growth rate of nuclear power is estimated to be 2% from 2025 to 2035 and that of installed capacity to be 15.5 GW by 2035 (Gong et al., 2022). We add nuclear power to the LBD because the exogenous investment share of nuclear power only shows the lower limit of nuclear development.

Thermal power continues to dominate the Chinese electricity market, accounting for over 70% of the total electricity consumption in 2022, even though intermittent power storage helps peak loading to an extent. Additionally, given that thermal power is necessary for regulating the peak load, the fourteenth five-year plan has mentioned the complementary sources of wind, solar, hydro, and thermal power. Furthermore, thermal power also plays a key role in mitigating the carbon peak through the technological improvement of combustion efficiency and stable power supply (Wang et al., 2023). For example, solar power can be combined with thermal energy storage to reduce the impact of intermittency (Imran Khan et al., 2023). Moreover, thermal power is also an important source of heat supply because of cogeneration, which may help improve the overall thermal power efficiency and reduce its cost (Imran Khan et al., 2023). Therefore, this study gradually reduces the investment in thermal power until 2032 and maintains the annual investment share of thermal power until 2060 because thermal power may continue to play key a role in the electricity market in the future.

3.3 Scenarios

Seven scenarios are designed, including a BaU scenario and six policy scenarios.

3.3.1 Business as Usual (BaU)

The GDP growth and population growth rates are determined based on previous studies and past data (Yuan et al., 2020; National Bureau of Statistics of China, 2021a; National Bureau of Statistics of China, 2021b). The total factor productivity (TFP) is calibrated by the parameters shown in Table 3.1.

Table 3.1 TFP and GDP growth rate.

	2023-2030	2031-2040	2041-2050	2051-2060
GDP	4.89%	3.21%	2.05%	1.05%
TFP	2.52%	2.31%	1.68%	0.96%

The learning rates of wind, solar, and nuclear power generation are derived from previous studies and recent data on renewable energy (Zhu et al., 2015; International Renewable Energy Agency, 2020). The learning rates for wind, solar, and nuclear energies are 0.1, 0.12, and 0.09, respectively. The learning rate of storage is 0.085 (Guo and Fan, 2017).

The baseline results of our model as shown in Table 3.2. The real GDP in 2060 is 289.8 trillion CNY and peak carbon emission is 10.96 billion tons in 2033. The ITC of renewable energy, including power generation and storage, indicates the greater RE cost-competitiveness, which gradually replaces thermal power. However, achieving the ambition of reaching 25% non-fossil fuel consumption and carbon peaking by 2030 is not possible without policy intervention.

Table 3.2: BaU results

	2030	2040	2050	2060
CO ₂ (billion ton)	10.86	10.73	10.14	8.79
P_s (%)	21.07	30.43	39.41	47.93
Carbon intensity (CNY/ton)	14.31	19.87	25.74	32.96

3.3.2 Carbon tax, subsidy and electrification

Carbon taxes, electrification, and subsidies on energy storage are introduced to analyze the influence of policies and policy mix on economic development, energy structure, and carbon mitigation. Some power storage parameters are changed for sensitivity analysis, such as learning rates of RE storage and elasticity of substitution.

3.3.2.1 Carbon tax

Usually, tax is used to finance subsidies for renewables, including power generation and storage. The carbon tax is a very common environmental taxation method for energy structural transition. As of April 2022, the carbon tax has been levied in 37 countries and the highest carbon tax rate is 137 \$/ton in Uruguay. European countries have levied carbon tax earlier and higher than most countries, for example, it is 130 \$/ton in Sweden and Switzerland, which are the highest carbon tax rates in Europe (Aaron et al., 2022). Previous research has proposed tax energy storage as long as fossil fuel contributes to storage because storage can raise the price of electricity, which makes fossil fuels more profitable (Helm and Mier, 2021). However, this study only considers RE storage because of its intermittency. Therefore, storage taxation is not included in our scenarios. In our model, the carbon tax is levied on all sectors emitting carbon, especially the power sector and energy-intensive industries. In industries where fossil fuels are used as raw materials such as oil refineries or the coke industry, less carbon tax may be levied because most oil and coal are processed to make gasoline and coke instead of combustion (National Bureau of Statistics of China, 2018b). The initial carbon tax rate is 60 CNY/ton in 2023 and gradually increases to 938 CNY/ton in 2060, which is closer to that levied in Europe. We do not take other tax such as direct or indirect taxes into consideration that the carbon tax recycling for RE subsidy are best accepted in empirical evidence from previous studies (Bourgeois et al., 2021; Helm and Mier, 2021). In addition, the tax

recycling including income tax (direct tax) and fuel tax (indirect tax) is likely to cause less government income, thereby affects transfer payment that leads to negative impact on investment, consumption and production (Kim, 2021).

3.3.2.2 Subsidy for RE storage

The subsidy is commonly considered to be essential to overcome the expensive storage of RE for stable grid (Chen et al., 2019). Subsidies on production-based incentives are not suitable for our study because they only focus on power generation and neglect the role of RE storage (He et al., 2023). For example, large production tax credits on wind farms in the U.S. might show the negative impact of stimulating market transactions on power storage and generation (Liu et al., 2022). However, the investment tax credit levied on solar power storage installation in Hawaii reduces the high cost of storage and overcomes barriers to battery storage deployment (Retna Kumar and Shrimali, 2021). The investment tax credits are given on federal tax paid by enterprises. These credits deduct a certain percentage of eligible investments from their taxes, which can up amount to up to 30% for five years. Such investments include purposes such as battery charge for RE. Additionally, through reverse auction feed-in tariff, Australia has collected this revenue from electricity payments for fixed capacity (Martin and Rice, 2021). In this study, the subsidy is financed by carbon tax revenue recycling. A previous study has pointed out that subsidies can be financed through tax revenue for storage, which is more important than RE generation because market penetration of RE raises following a decrease in its prices (Helm and Mier, 2021).

The decrease in the price of RE power generation attributes to the LBD of RE and policy support in this research, including the exit of thermal power because of the carbon tax. However, there is a divergence of opinions between capacity and price subsidies for RE storage. Capacity subsidy is given on investment in energy storage such as battery, while price subsidy is applicable on the cost of storage. It has been found that the price subsidy on storage is more cost-effective for

achieving the short-term RE target, that is, a 25% share of non-fossil fuel consumption in total primary energy consumption of China by 2030; however, the investment subsidy provided based on storage capacity is more effective for reducing technological costs and further improving capacity installation in the long term (Özdemir et al., 2020). Additionally, subsidies on renewable technologies are more efficient if provided on investment than price such that the upfront investment in new technology can be more cost-effective than future price subsidies (De Groote and Verboven, 2019). Therefore, this study adopts investment subsidy provided on total carbon tax revenue and allocated by investment share (installed capacity) of RE storage.

3.3.2.3 Electrification

We design basic electrification rates for households in all scenarios involving developed countries and different electrification progress for urban and rural areas (Aklin et al., 2018; Statistics of Japan, 2019). China's electrification rate is estimated to be the same as that of Japan by 2050. The electrification policy is determined by the goal that 25% of the total primary energy consumption in China will be sourced from hydro, wind, solar, and nuclear power by 2030. Therefore, in scenarios with electrification, all industrial sectors and households increase their electricity consumption share in CES function because electricity is more competitive than coal, oil, and natural gas, regardless of the price of energy as shown in following equation

$$QENS_{c,t} = \alpha_c^{ke} (\delta_c^{ke} QEN_{c,t}^{\rho_c^{ke}} + (1 - \delta_c^{ke}) QELE_{c,t}^{\rho_c^{ke}})^{1/\rho_c^{ke}} \quad (3.7)$$

Where $QENS_{c,t}$, $QEN_{c,t}$ and $QELE_{c,t}$ are quantity of energy composite input of sector c , quantity of fossil fuel composite input in sector c and quantity of electricity input in sector c . ke indicates energy composite. For parameters α, δ and σ , which are scale, share and substitution parameter for CES production function, respectively. In addition, $\rho = 1 - 1/\sigma$. By increasing elasticity of substitution of electricity, the producers will prefer to use electricity rather than fossil

fuel. For household, we increase the propensity of electricity consumption and decrease the willingness of consuming fossil fuel, where the propensity and willingness of household's consumption is determined by ratio of energy consumption to total household consumption in 2017.

3.3.3 Demand and learning rate of power storage

GOADNES has pointed out that energy storage requires great technological improvement to meet the demand of RE. Additionally, high safety, low cost, high dependence, and long lifespan are the main aspects of storage innovation. Policies to promote the development of energy storage such as R&D can quicken the LBD process, which increases the learning rate of new technologies. Moreover, the guidance has also indicated flexible regulation of power storage for a stable power supply. The harsh carbon mitigation goals require rapid development of RE, which may require fast growth of demand. Furthermore, climate change will not stop until carbon emissions are neutralized, which is likely to induce severe natural disasters during the upcoming decades, such as floods (Chen et al., 2023). Therefore, to further enhance the durability of storage, we add scenarios such as CTSEL and CTSEB (see Table 3.3). The former refers to an increase in the demand for power storage, while the latter is the increase in the learning rate of energy storage. These two scenarios are more like sensitivity analysis of learning rate and energy demand parameters. Given that these two parameters have important policy implications, we regard them as policy scenarios.

3.3.4 Scenario design

All scenarios, including BaU, apply LBD for RE generation and storage (via the battery industry). CT levies carbon tax on all sectors and carbon tax revenue is collected by the government. CTS levies carbon tax on all sectors and carbon tax revenue is recycled to subsidize wind and solar power storage. CTSE adds electrification based on CTS. CTSEB enhances the role of storage, β_{win} and β_{sol} for 5% based on CTSE. CTSEL increases by 5% of the learning rate of storage,

TIE based on CTSE. Table 3.3 summarizes the scenario design. For scenario ELE, we only add the electrification rate in CTSE based on BaU without any other policies to check the effects of the policy combination.

Table 3.3: Scenario design.

Scenarios \	BaU	CT	CTS	CTSE	ELE	CTSEB	CTSEL
Carbon tax		√	√	√		√	√
Subsidy			√	√		√	√
Electrification				√	√	√	√
High storage demand						√	
Higher learning rate							√

3.4 Results

3.4.1 GDP

The single carbon tax implementation (CT) leads to a GDP loss across all terms, as shown in Fig. 3.2. The S-shaped change in GDP for CT before 2030 is negatively affected by the gradually increasing carbon tax from 2023 to 2030. However, for ITC in RE and the reduced supply of thermal power in the power market, there is a decrease in GDP between 2031-2047. The heavy carbon tax prompts exit of thermal power plants and dirty industries, which also leads to reduced carbon tax revenue, as shown in Fig. 3.3. This affects the government's expenditure and increases GDP loss after 2047. However, the total GDP loss is not very high compared to previous studies

because of the learning effects of the power sector (Cao et al., 2021).

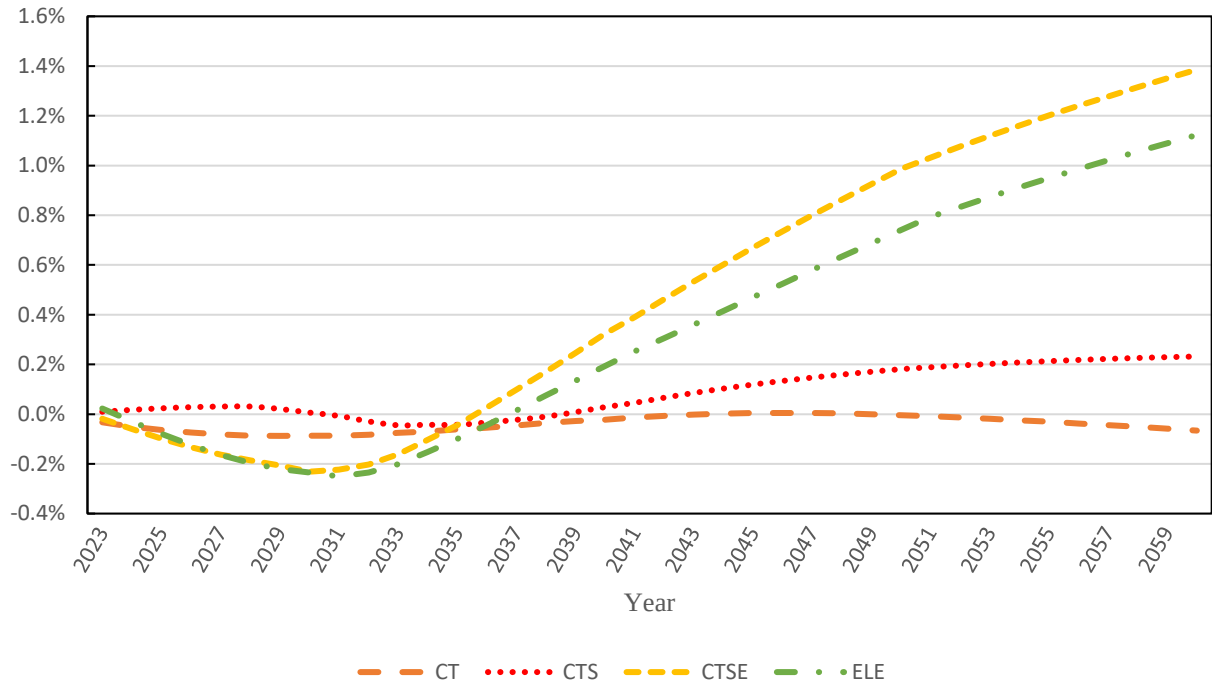


Figure 3.2: GDP change rate of CT, CTS, ELE, and CTSE compared to BaU

When carbon tax revenues are recycled to subsidize energy storage in CTS, there is a positive impact on economic growth in the early stage. This is because the subsidy can cover the increase in RE cost to an extent. The changes in GDP during 2030-2038 are negative but the GDP loss is always less than that in CT., which is benefited by subsidy-accelerated ITC accelerated in the power sector. After 2038, the GDP change is positive and grows with time, which is benefited by replacing thermal power with technologically improved RE. Compared with CT, CTS benefits economic development because there exist “double dividends” of carbon tax revenue tax recycling. Basically, the slight GDP loss in CT and CTS contributes to ITC accelerated by carbon tax. The carbon tax reduces market share of thermal power and increase RE in electricity market. The increasing output of RE thereby enhance LBD both in RE generation and RE storage. In CTS, such enhancement is further improved by subsidy to RE storage. Similarly, the GDP gain in CTS in long term is attributed to improved RE, replacing thermal power and mitigating negative impact

of carbon tax. Therefore, we get slight GDP change rate as Fig. 3.2 shown.

When the electrification rate increases for CTSE, compared with CTS, electrification increases GDP loss in the short run but causes great GDP growth in the long run. This is because the LBD of RE generation and storage reduces the total RE price. The soaring demand for RE caused by the carbon tax and electrification distorts the electricity market because expensive RE affects electricity prices, which results in a GDP loss. Fig. 3.3 also shows a self-contradiction because aggressive electrification may speed up the reduction of fossil fuel consumption, resulting in reduced carbon tax revenue collection. However, less subsidy financed by carbon tax revenue leads to more GDP growth in the long term, where the ITC of storage plays a key role in the energy structural shift. Compared with CTS, the significant GDP growth in CTSE suggests that the demand-side power and technological innovation in RE for energy structural shift can bring economic and environmental benefits (see next section), however, it might lead to a short-term negative shock caused by intensive energy structural shift. Compared with the ELE scenario, CTSE shows a similar GDP change trend but leads to lower losses and higher gains. This shows a positive cumulative policy interaction effect between electrification and carbon tax policy with revenue recycled to subsidize carbon.

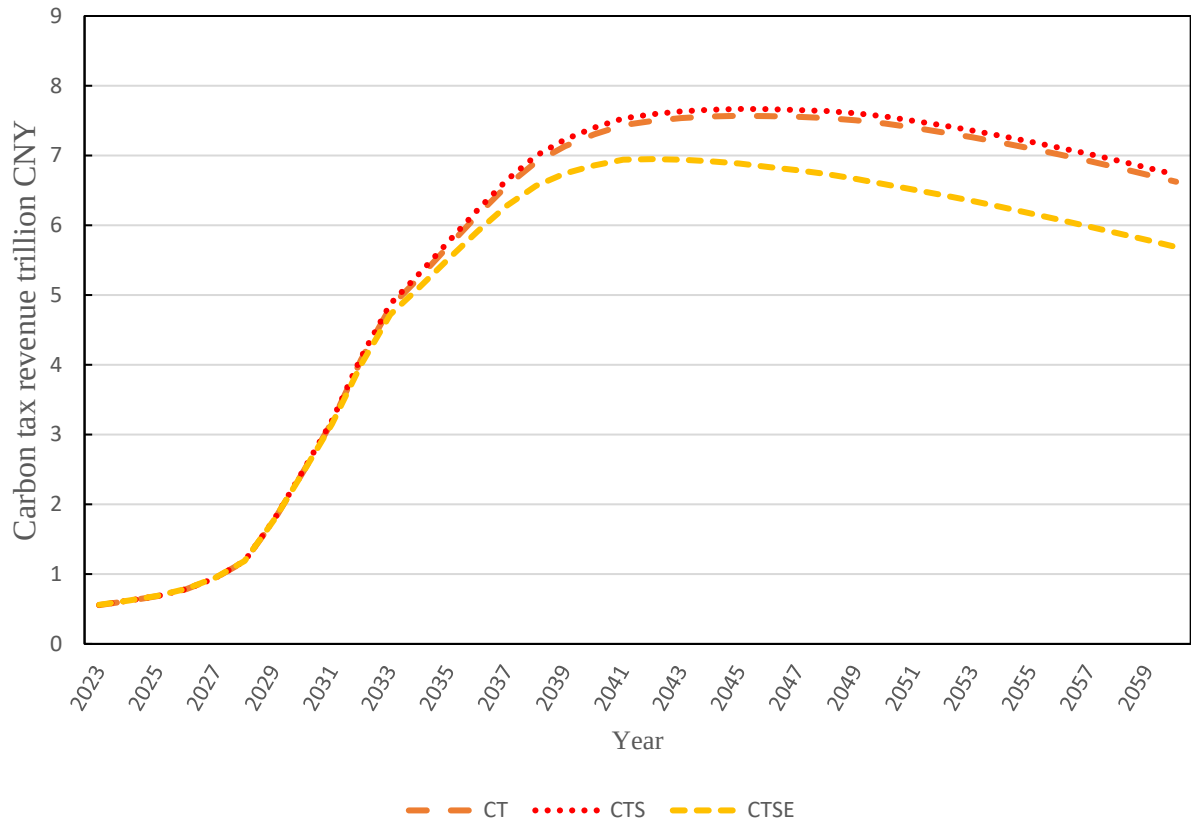


Figure 3.3: Total carbon tax revenue in trillion CNY.

3.4.2 Carbon emission

Compared to BaU, all scenarios with environmental policies are cleaner, as shown in Fig. 3.4. Carbon tax effectively decreases the consumption of fossil fuels. However, the carbon emission in CTS is slightly more than that in CT because of the higher fossil fuel consumption (see explanation in section 3.4.1.4). The higher fossil fuel consumption in CTS is caused by the rebound effect of thermal power because more RE leads to a higher total average weighted electricity price before 2040. Therefore, industries consume more fossil fuel in CTS than in CT. Additionally, subsidy for storage increases the competitiveness of RE, which enhances the efficiency of thermal power (see Fig. A3.1) and subsequently leads to more thermal power generation in CTS compared to CT. However, the non-fossil fuel consumption rate continues to be larger in CTS than CT (see Fig.

A3.2) because subsidy increases RE power generation to a further extent than fossil fuel consumption (see next section).

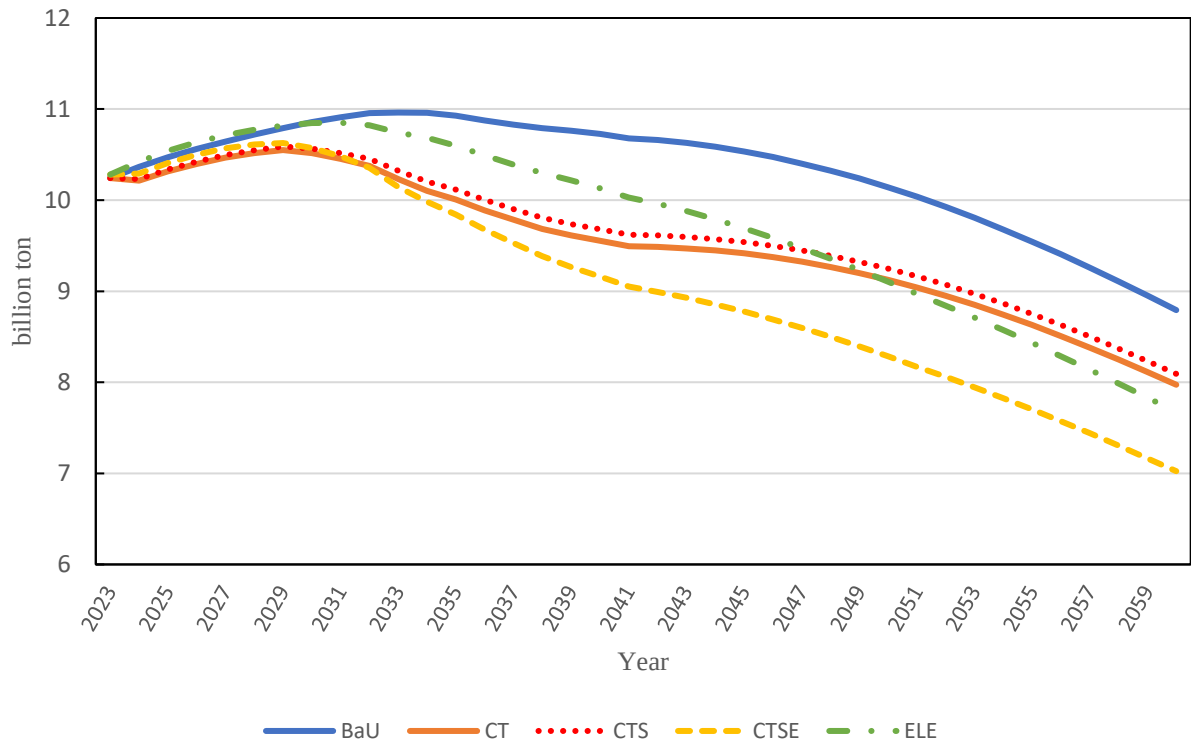


Figure 3.4: Total carbon emission in billion ton.

Electrification with carbon tax and subsidy achieves significant carbon emission abatement. Comparing CT, CTS, ELE, and CTSE, RE plays a key role in carbon emission abatement. Although carbon emissions are significantly reduced in CTSE, the carbon emission in CTSE is more than that in CTS before 2030, which is likely because of more thermal power generation (see next section).

Electrification will increase the electricity demand and the cost of RE and RE storage cannot be reduced in the short run. Therefore, significantly more thermal power would be produced to meet the electricity demand, which would result in further carbon reduction (here refers to market competition shown in section 3.2.2.3). The carbon emissions are lower in CTSE than that in ELE. This means that the development of RE and RE storage should be consistent with that of

electrification; otherwise, it may result in greater GDP loss and more carbon emissions. In the long run, given the LBD in RE and energy storage, the cost of RE power supply will greatly decrease and become more competitive than that of thermal power, which will benefit economic development and carbon mitigation.

3.4.3 Power generation output

As one of the biggest emission sources, the power sector greatly affects carbon emissions. From Fig. 3.5, we can determine that a single carbon tax can substantially reduce thermal power and slightly encourage wind and solar power generation. Conversely, CTS shows more wind and solar power (also hydro and nuclear power, see Table A3.1) encouragement but also less thermal power generation reduction. The improved RE also facilitates the improvement of thermal power because its efficiency is enhanced in CTS compared to that in CT (see Fig. A3.1). Fig. 3.4 explains more CO₂ emissions in CTS than CT because thermal power reduction in CTS is less than that in CT. This is because all types of power generation increase in CTS, including hydro, nuclear, thermal, wind, and solar power generation (also see Fig. A3.2).

Electrification with policy mix (CTSE) greatly facilitates the power sector. Given the soaring electricity demand in CTSE, total power generation is significantly higher than that in BaU. The increase in thermal power by 2030, as shown in Fig. 3.4, shows the difference between the demand and supply for electricity, that is, the power is homogenous on the demand side but heterogeneous on the supply side. Therefore, despite the carbon tax, thermal power generation will increase to meet the soaring demand for electricity by 2030. This is because thermal power has the biggest market share and consequently is the most competitive source of electricity at the early stage. Therefore, such ambitious energy structural shift leads to a GDP loss that is significantly higher than that in CTS during 2023–2037, as shown in Fig. 3.2. Comparing CT and CTS to ELE, we can find that single electrification does not restrict the increase in thermal power because there is no

carbon tax. RE increases more in ELE than in CT and CTS because it has a more significant impact on the demand side of ITC for RE storage than supply-side policies. However, compared with CTSE, single electrification is less effective than the policy mix because a carbon tax is a necessary regulation for restricting thermal power generation under electrification. Moreover, Fig. 3.5 underlines that there is a synergic effect of policy mix on ITC acceleration when comparing CTSE and ELE. Moreover, the increase in total power generation in ELE is induced by the increase in thermal power.

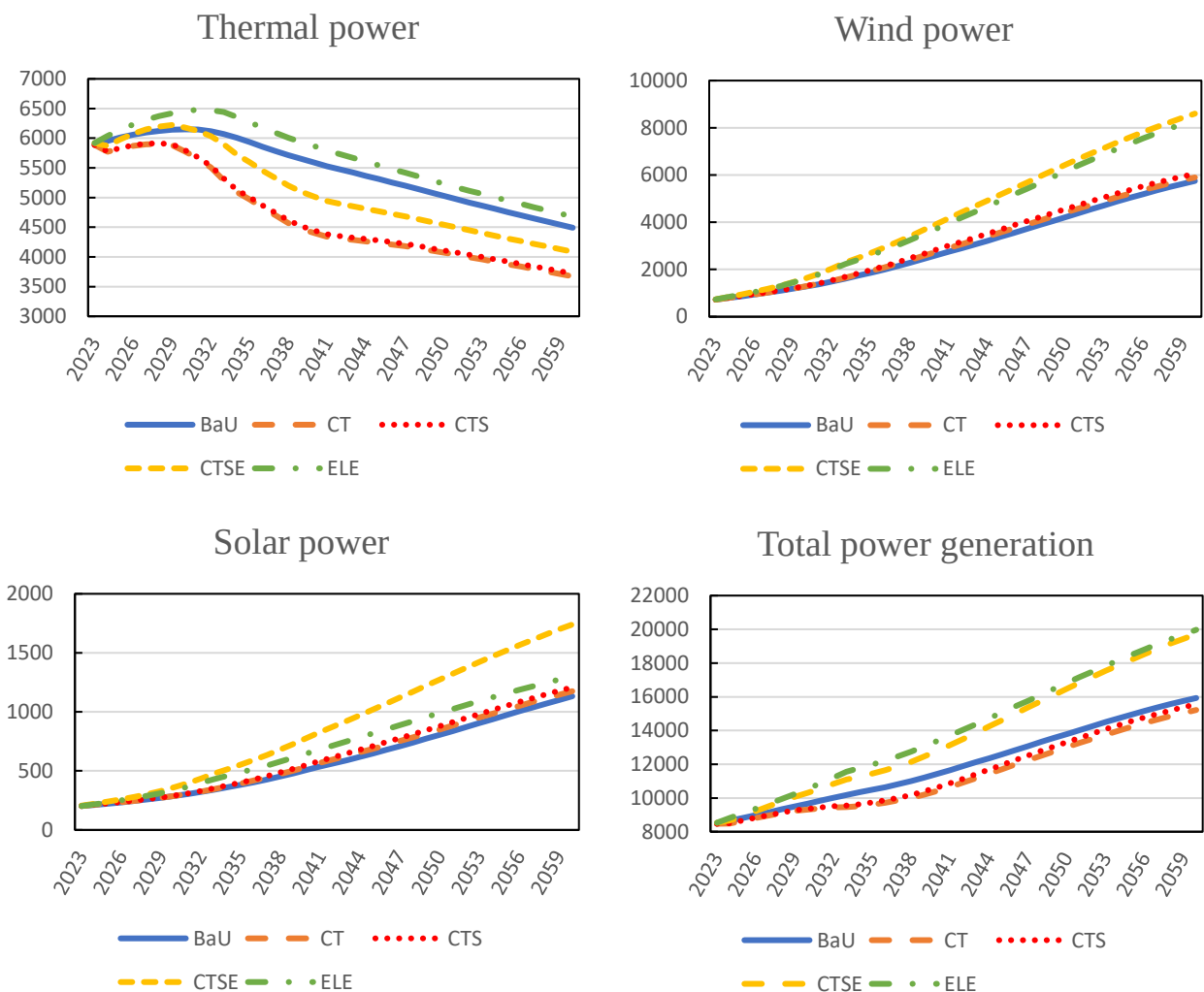


Figure 3.5: Wind, thermal, solar, and total power consumption (Twh) in BaU, CT, CTS, ELE, and CTSE.

Note: Horizontal axis is Year

3.4.4 Non-fossil fuel consumption ratio

Table 3.4 demonstrates the rate of change of the non-fossil fuel consumption ratio in CT, CTS, ELE, and CTSE compared to BaU. For example, in 20205, CT's non-fossil fuel consumption increases by 1.25% compared to BaU. The increase in such ratio shows positive impact of carbon tax on reducing fossil fuel consumption. Above is similar to CTS that it increases by 2.65% compared to BaU. The combination of carbon tax and subsidy is more efficient than single carbon tax policy. The supply-side environmental instruments increase the ratio of clean energy consumption by reducing fossil fuel consumption. Therefore, there is a positive but marginal growth in CT and CTS. Compared to scenarios with electrification, carbon tax only restricts fossil fuel consumption, and subsidy does not play key role in RE development at early stage because demand of electricity is not high. Although thermal power decreases less in CTS than in CT, the energy structural shift in CTS goes further than that in CT, which means that the ITC in RE plays a key role in RE development. While CTSE shows great potential on the demand side, electrification with ITC in RE drives significant clean energy structural transition compared to CT and CTS. Additionally, as mentioned in Section 3.3.2.3, CTSE achieves the 25% goal by 2030 while CT and CTS do not (see details in Fig. A3.2).

Furthermore, the 25% non-fossil goal is not achieved in ELE even though the electrification rate is the same as that in CTSE. The better performance of CTSE than ELE further emphasizes the advantages of the policy mix, and electrification plays a vital role in achieving the non-fossil energy goal when comparing CT and CTS with ELE.

Table 3.4: Change rate of non-fossil fuel consumption ratio in CT, CTS, ELE, and CTSE compared to BaU

	2025	2030	2040	2050	2060
CT	1.25%	2.17%	6.41%	3.29%	2.01%
CTS	2.65%	3.53%	7.75%	4.58%	2.84%
ELE	5.73%	16.90%	27.10%	27.83%	25.37%
CTSE	6.89%	18.82%	32.66%	31.05%	27.35%

3.4.5 Price and cost of wind and solar power

Although carbon tax greatly affects carbon abatement, subsidy on power storage does not significantly affect the markdown on wind and solar power. We find that the price of wind and solar power in CTS is higher than that in CT until 2038. Moreover, the decline in the cost of wind and solar power is faster in CT after 2038, as shown in Fig. 3.6. The subsidy increases wind and solar power generation (Fig. 3.4), but the total increase in RE generation also leads to an increased demand for storage at the early stages when ITC is not fully functional for cost reduction and subsidies do not fully cover the markup in RE. In addition, the implementation of carbon tax also increases cost of RE and storage cost since the cost of intermediates also increases. Therefore, the total wind and solar price in CTS is higher than that in CT, which also leads to lower ITC in RE storage. However, the markdown of RE in CTS is faster than that in CT, demonstrating the effectiveness of ITC in RE. Fig. 6 further explains carbon emissions and thermal power in CTS and CT, as shown in Fig. 3.4 and 3.5. The subsidy on RE storage increases wind and solar power generation through lower storage costs (Fig. 3.6 shows the average cost of storage without subsidy). However, the increased wind and solar energy prices make them less competitive than thermal power in CTS than in CT. Thus, the rebound effect of subsidy shows the strong competitiveness

of thermal power in the electricity market in the short term.

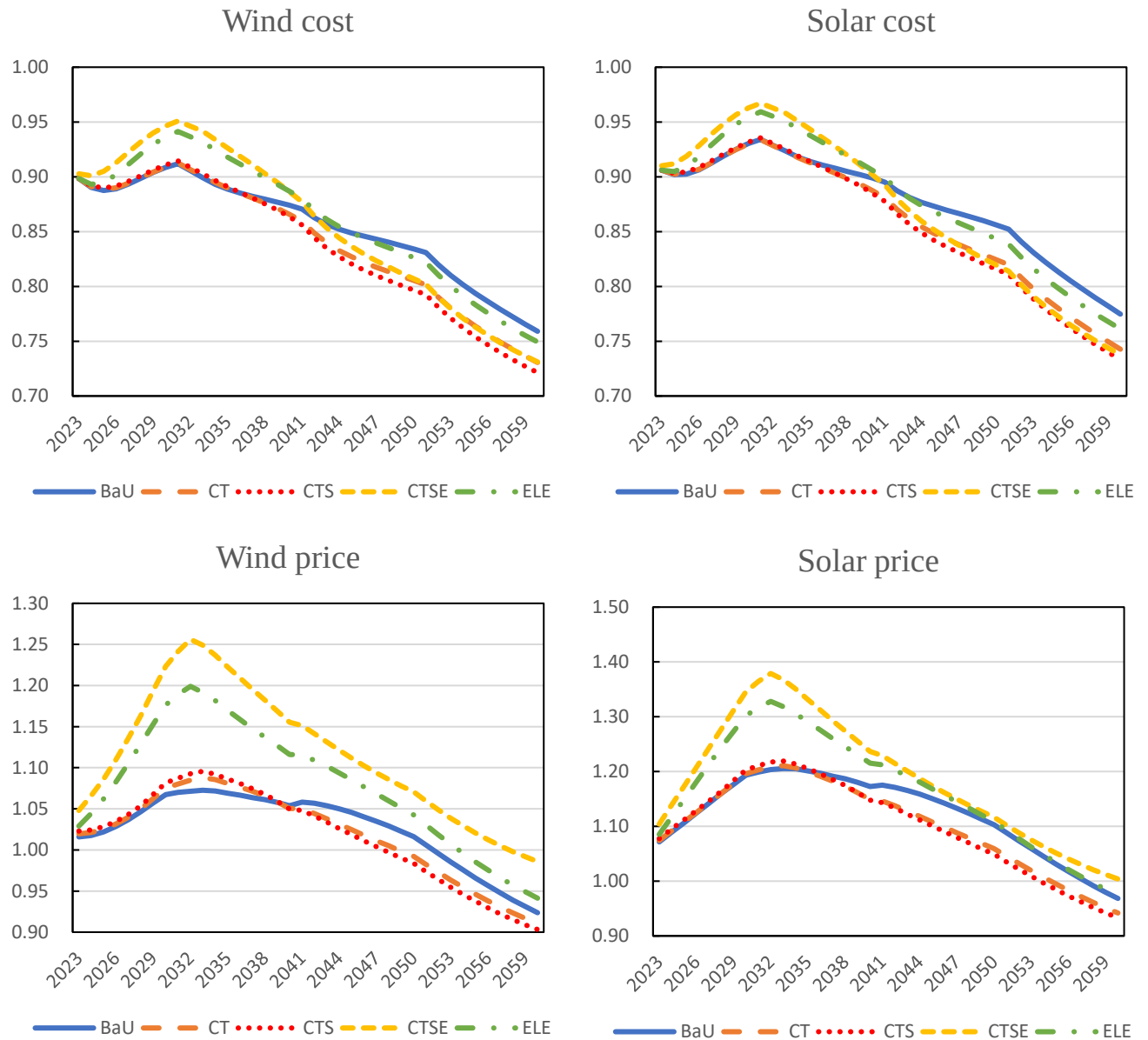


Figure 3.6: Average cost of wind storage(a), solar storage (b), price of wind (c), and solar (d).

Note: Vertical axis is not the real price or cost but an indicator which is levelized to 1 in 2017.

Horizontal axis is year.

To achieve a 25% of non-fossil fuel consumption ratio by 2030, power suppliers in the CTSE

scenario will be urgently forced to produce not well-prepared renewable energy, leading to more expensive wind and solar power in the market. Consequently, expensive total weighted electricity prices will be driven by the soaring demand of RE, which will affect ITC in RE storage. After the intensive energy structural shift, solar and wind power will gradually resume quick technological improvement, decreasing the price of electricity in the long term. The markdown of storage is much faster than that of RE, which is shown in Fig. 3.6. With further electrification, cheaper RE shows a greater and positive impact on GDP growth, carbon reduction, and energy structural shift. Therefore, short-term clean energy structural shift will slow down the normal ITC (compared to BaU, CT, and CTS) of wind and solar power, thereby affecting the ITC of RE storage.

Moreover, comparing CTSE with ELE, there are smaller negative impacts on solar and wind price markup in ELE. There are also smaller positive impacts of wind and solar storage on cost reduction. The subsidy for RE storage increases the output of RE and storage demand (Fig. 3.5), which weakens the negative impact of electricity markup in CTSE. Hence, the encouragement in CTSE eventually produces better results than that in single electrification (scenario ELE).

3.5 Discussion

3.5.1 Policy implications given by scenarios

Considering the environmental and economic aspects, a single carbon tax is not a perfectly viable option for carbon emission abatement. This is because precise social marginal damage cannot be estimated and a first-best carbon tax cannot be designed (GE Metcalf, 2009). Furthermore, the single carbon tax is also likely to cause carbon leakage, which only reduces local carbon emissions and increases global emissions (Kruse-Andersen and Sørensen, 2022). Therefore, the policy mix is considered to be more appropriate if both economic and environmental aspects are considered (Li and Yao, 2020; Zhao et al., 2020). Although CTS shows negative economic

shock during 2030-2038, the ITC accelerated by subsidy continues to reduce GDP loss and even leads to GDP growth in the long term. This result is better than that in CT if we trade off the economic and environmental impacts.

In CTSE, intensive electrification encourages expensive RE in the short term. Such encouragement further leads to slower ITC in RE storage given the higher electricity price due to more demand for expensive storage. However, electrification also stimulates great RE demand because it brings significant GDP gain in the long term. Thus, electrification forces the rapid development of wind and solar power, which accelerates their ITC, including storage. Electrification increases the demand for electricity; however, it is not easy to achieve a low-carbon economy without a carbon tax, which is proved in ELE. Without environmental regulation, electrification will further enlarge the development of thermal power because it possesses the largest market share. The bigger the market share occupied by thermal power, the more the competitiveness in our model (see Section 3.2.2.3). The carbon tax restricts further market share acquisition of thermal power, and ITC accelerated by environmental policy helps RE replace thermal power to a great extent. Although short-term and aggressive clean electrification causes GDP loss, demand-side intervention plays a key role in further renewable energy development in the long term. The higher share of RE is shown in Fig. 3.5, and the higher electricity price and the average cost of storage in Fig. 3.6 address the argument proposed in the introduction section. Accordingly, increased RE development decreases storage improvement because of the lower learning rate caused by higher electricity in the short term. However, the increased output required by clean electrification also prompts RE development and storage. This brings far more economic and environmental benefits, as shown in Fig. 3.2 and 3.4.

Additionally, comparing CTSE and CTS, RE storage only guarantees lower RE development. This is because cheaper storage does not significantly affect RE development as storage is not important until RE develops further. However, electrification greatly stimulates RE demand (under carbon tax), which yields a synergic effect between electrification and ITC in RE storage. This

synergic effect also illustrates the comparison between CTSE and ELE. The policy mixing of demand and supply side presents better performance than single-demand (ELE) or supply-side (CT) regulation. Moreover, further economic and environmental gains in ELE, as compared to CT, show that the soaring demand for RE is stimulated by electrification. This effectively facilitates the ITC in RE (storage) than supply-side policies (CT and CTS) in the long run. Therefore, this study shows the higher efficiency of policy mixing in comparison to single environmental policies such as carbon tax.

3.5.2 Further discussion and limitation

This paper only considers the carbon tax at same rate in all scenarios, which means the effect of ITC can be changed under different carbon rate. Numerous studies and empirical researches have already shown the negative impact of carbon tax on economic growth but also positive impact on reducing fossil fuel consumption. Chien et al. (2023) suggests that the positive relationship between low-carbon transition and enforceable carbon tax in developing countries. However, the increasing carbon tax is likely to induce more GDP loss and degenerate economic activities (Khastar et al., 2020). The effect of carbon tax on energy storage can be fluctuant because it depends on grid's electricity generation portfolio (Freeman et al., 2017). It suggests that even high carbon tax (\$250/t which is over 1700 CNY/ton at 2023 price) is unlikely to create sufficient incentives to encourage storage technology unless electricity become unexpensive and accessible.

Although subsidy to RE storage in this paper will be enriched by increased carbon tax, the higher carbon tax also increase cost of RE storage attributed to markup of intermediates which also affects RE generation. As forementioned in Section 3.2.2.2, the negative impact of RE generation will directly reduce demand of RE storage. In addition, the increased cost of RE caused by higher carbon tax also increase RE and total electricity price as shown in Fig. 3.6, thereby development of RE storage will be deterred from demand and LBD aspects (see section 3.2.3). In

other words, higher carbon tax might be not helpful for subsidy to RE storage to accelerate ITC. Therefore, it is difficult to ascertain the impact of increasing carbon tax on ITC of RE storage in this paper.

Moreover, the carbon neutral not only attributes to RE development, but also needs carbon capture, utilization and storage (CCUS) to increase economic value of carbon mitigation (Han et al., 2023). Liu et al. (2023) find positive relationship between CCUS and energy storage in low-carbon electricity. The soaring demand of RE requires improvement on storage for stable power supply, however, CCUS is a promising solution to carbon abatement avoiding exacerbating volatile grid. Furthermore, due to decreasing competitiveness compared to RE with ITC, the exit of thermal power from electricity market will encourage investment in CCUS technology to maintain competitiveness (thermal power is necessary for peak load). Besides, the lower barriers to technology development is likely to increase knowledge spillover effect of CCUS, where the lower barriers can be achieved by adoption of other green technology such as energy storage (Bae et al., 2020; Jiao et al., 2020). Therefore, RE storage might be better for policy makers to take into consideration for CCUS development.

3.6 Sensitivity analysis

We conduct CTSEB and CTSEL based on CTSE scenario to examine the role of storage under electrification. β_{win} and β_{sol} increase by 5% and TIE also increases by 5% in CTSEB and CTSEL, respectively. The results are shown in Table 3.5.

Table 3.5: Change rate of parameters compared to CTSE.

Scenario	Parameter	2025	2040	2060
CTSEB	GDP	-0.00002%	-0.0011%	-0.0029%
	Price	0.0038%	0.0562%	0.1107%
	CO ₂	0.0002%	0.0019%	0.0009%
	ps	-0.0006%	-0.0075%	-0.012%
	Price (solar)	0.0018%	0.0181%	0.2381%
	cost (solar)	0.0083%	0.0446%	0.0502%
	Output (solar)	-0.0104%	-0.0994%	-0.1080%
CTSEL	GDP	0.00015%	0.0001%	0.0008%
	Price	-0.0221%	-0.008%	-0.0209%
	CO ₂	-0.0020%	-0.0011%	-0.0019%
	ps	0.0110%	0.0011%	0.0023%
	Price (solar)	-0.1029%	0.0021%	-0.0934%
	Cost (solar)	-2.328%	-0.7535%	-2.1276%
	Output (solar)	0.1482%	0.0179%	0.1332%

Note: *ps* is the ratio of non-fossil fuel consumption, *Price* is the total (weighted) price of electricity, *price (solar)* is the price of total solar price, and *cost (solar)* is the storage cost of solar power. We do not demonstrate wind power because it is similar to solar power.

The GDP loss yields more carbon emissions in CTSEB. The higher storage demand leads to

less wind and solar power generation but more thermal power generation, which negatively affects the ITC in RE power sector and carbon emissions even under electrification. Thus, the electricity price and carbon emissions in CTSEB are higher than that in CTSE. Furthermore, the markup of electricity prices also affects ITC in RE storage because the average cost of solar storage is higher than that in CTSE. The reduced power generation also imposes a negative impact on electrification because industries have to use fossil fuels to replace electricity, which also leads to less energy structural transition in CTSEB compared to CTSE.

For CTSEL, the higher learning rate of ITC in storage leads to an increase in GDP. The greater ITC induced by higher learning rate lowers both cost and price, prompting further clean electrification in CTSEL because the ps is higher than that in CTSE. Therefore, the acceleration of ITC in RE power directly affects clean energy structural shift and cheaper RE replaces thermal power at a lower cost than in CTSE because more GDP growth is gained. However, during 2040–2042, there is an increase in solar (wind) prices in CTSEL, compared to CTSE. The cost, price, and output of solar (wind) power show (inverted) U-shape curves because the ITC in the middle term is weak. This may be caused by the decrease in the electrification rate after 2030 because the achievement of the ambitious 25% goal by 2030 leaves small leeway to further electrification, which leads to less improvement in RE during 2031–2040, as compared to 2023–2030. The higher learning of storage in CTSEL leads to fewer carbon emissions and carbon tax revenue for subsidies (several billions of CNY), while the same electrification rate in CTSEL and CTSE are not significantly benefited by the cost reduction in storage because the reduction in subsidy cannot cover the decreasing cost reduction of subsidy in CTSEL. Hence, over-developed RE storage induces a fiscal burden on maintaining subsidization for storage. Consequently, this sensitive analysis shows the importance of ITC in RE storage. It demonstrates that faster technological innovation will bring both environmental and economic benefits. However, when the demand of storage increases given the same generation output, expensive storage negatively affects environmental and economic growth. Energy storage may hinder the development of on-grid

supply of wind and solar power. Therefore, knowing how to design the development pace of energy storage under higher demand for power is very important. It requires a balance between low carbon emissions, economic development, energy transition, and energy safety.

3.7 Conclusion

This study aims to find out the key role of power storage and clean electrification in energy structural shift and carbon mitigation in China by applying the CGE model with ITC bottom-up module. Previous studies have suggested that fluctuation in variable renewable energy cannot be ignored and incorporated storage into the CGE model (Dai et al., 2017). As the production of RE is getting less expensive because of technological innovation (Acemoglu et al., 2012), Helm and Mier (2021) have proposed that subsidies financed by the carbon tax on storage are better than those financed by generation. De Groote and Verboven (2019) have indicated that investment subsidies are more effective than price subsidies, while Özdemir et al. (2020) have suggested that capacity subsidies could be more effective if LBD is included in RE.

This study considers market share mechanisms with five types of electricity sources to test how RE is cost-competitive with subsidy on storage. We design a subsidy financed by carbon tax revenue that more capacity investment in storage can receive more subsidy in line with market share. The more cost competitive RE is, the more market share it will have. This will lead to more subsidies for its storage. Moreover, this study also explains that ITC in RE generation and storage is important because RE develops better in CTSE than in CTS under less subsidy financed by carbon tax revenue. Additionally, this study also provides a solution for the argument mentioned in the introduction, according to which electrification increases the price of electricity and affects ITC in storage. This further affects the total development of RE in the short term. However, ITC plays a crucial role in the improvement and development of RE and storage in the long term. To the best of our knowledge, our study is the first to discuss how ITC in storage plays a key role in

energy structural shift. This is because a reduction in subsidy caused by supply-side and demand-side policies can create further economic and environmental benefits in the long term, showing great potential for RE storage with ITC.

The primary findings of this study are as follows: 1) single carbon tax policy is not an appropriate instrument for pursuing both environmental and economic gains against CO₂ abatement and energy structural transition. 2) To achieve the ambitious energy structural shift goal by 2030, carbon tax and subsidy to storage on the supply side have to be encouraged because RE is not sufficient. The subsidy for storage is useful for accelerating ITC but the share of storage is restricted by the lower market share of RE production at the early stage. This results in a slight negative effect in the short term but a positive effect in the long term. For example, compared to BaU, CTS can reduce 9.74% of carbon emissions at most by 2060 but can increase non-fossil fuel consumption shares by 2.2% by 2030. 3) A policy mix that considers electrification with carbon tax and subsidies can greatly increase the demand for electricity. This makes it possible to achieve the ambitious goal of a 25% share of non-fossil fuel energy sources in China by 2030. It also shows better results than the single electrification scenario (ELE). However, the short-term intensive energy structural shift not only hurts economic growth but also has a rebound effect. This is because more thermal power (as well as CO₂) is required to meet the soaring demand. RE requires time to become technologically improved and yield economic growth. For example, compared to BaU, CTSE creates a 0.36% GDP loss in 2030 but 0.7% GDP growth in 2060. 4) Comparing CTS and CTSE, even though there is nearly a 20% difference in the carbon tax revenue in 2060, ITC exerts a great impact on economic and environmental benefits. The improved storage also contributes to the ITC in RE generation because electrification guarantees the demand for electricity. This shows the significant synergic effect of policy mix (CTSE) when compared to single regulation (CT and ELE). 5) The increase in learning rate brings greater economic and environmental benefits, while more storage demand results in the opposite outcome. The greater performance of CTSEL shows the importance of encouraging further technological improvement

in RE storage.

This study also finds a rebound effect through which a subsidy financed by a carbon tax on storage might increase electricity prices and fossil fuel consumption, resulting in a marginal increase in carbon emissions. This can be likely solved with a higher carbon tax. This study lacks discussion on urbanization and electrification of households given that residents in the urban and rural areas have different propensities of consumption and fossil fuels are being gradually replaced by electricity. Therefore, more consumption without urbanization might lead to an overestimation of carbon emissions from the rural areas, which may stay at the 2017 level. Furthermore, this study also suggests that clean electrification driven by carbon tax and subsidies is conducive to carbon neutralization. This is because RE with ITC becomes more cost-competitive than fossil fuel when considering storage. In addition, this study main focus on impact of electrification and environmental policies on ITC of RE and storage rather than carbon tax. Therefore, it also lacks discussion on effect of higher or lower carbon tax on ITC acceleration. Furthermore, this paper also provides a possibility that improved RE storage might be helpful for CCUS in the future.

Appendix

Table A3.1: Hydro and nuclear power generation in CT and CTS (Twh).

		2025	2030	2040	2050	2060
Hydro (Twh)	CT	1330.3	1561.6	2302.9	3156.6	3886.7
	CTS	1333.2	1566.9	2343.3	3229.5	3972.8
Nuclear (Twh)	CT	394.2	395.2	445.8	519.8	586.7
	CTS	394.6	395.7	451.7	532.6	603.0

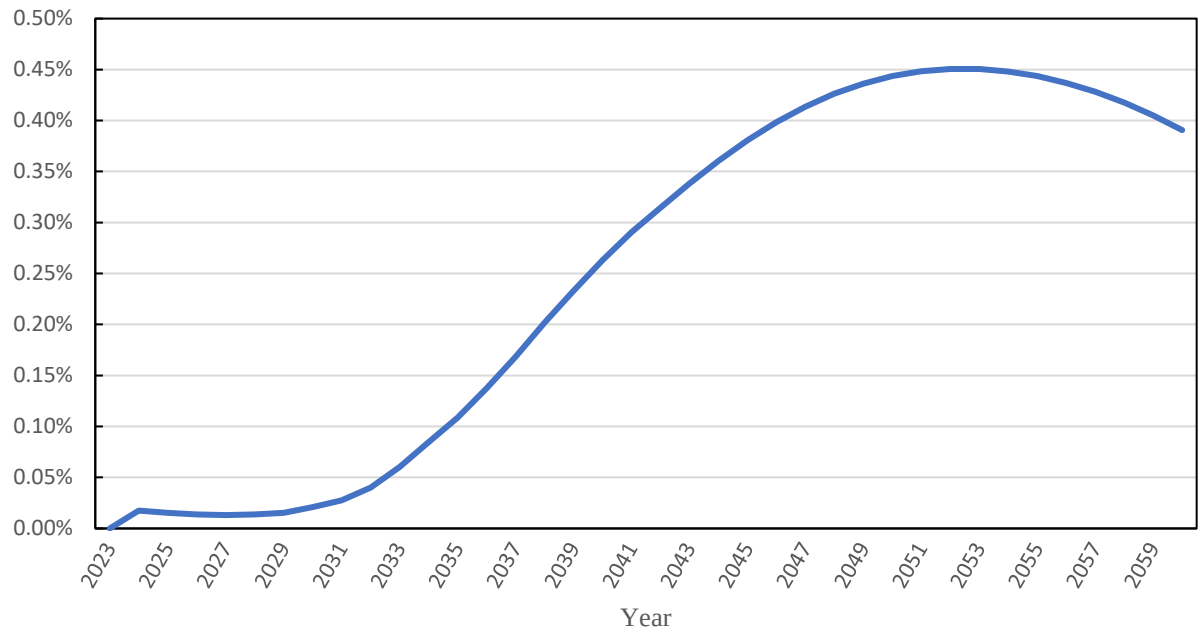


Figure A3.1: Thermal power efficiency of CTS compared to CT (%)

Note: caculated by coal-power coversion coefficient (100g/Kwh)

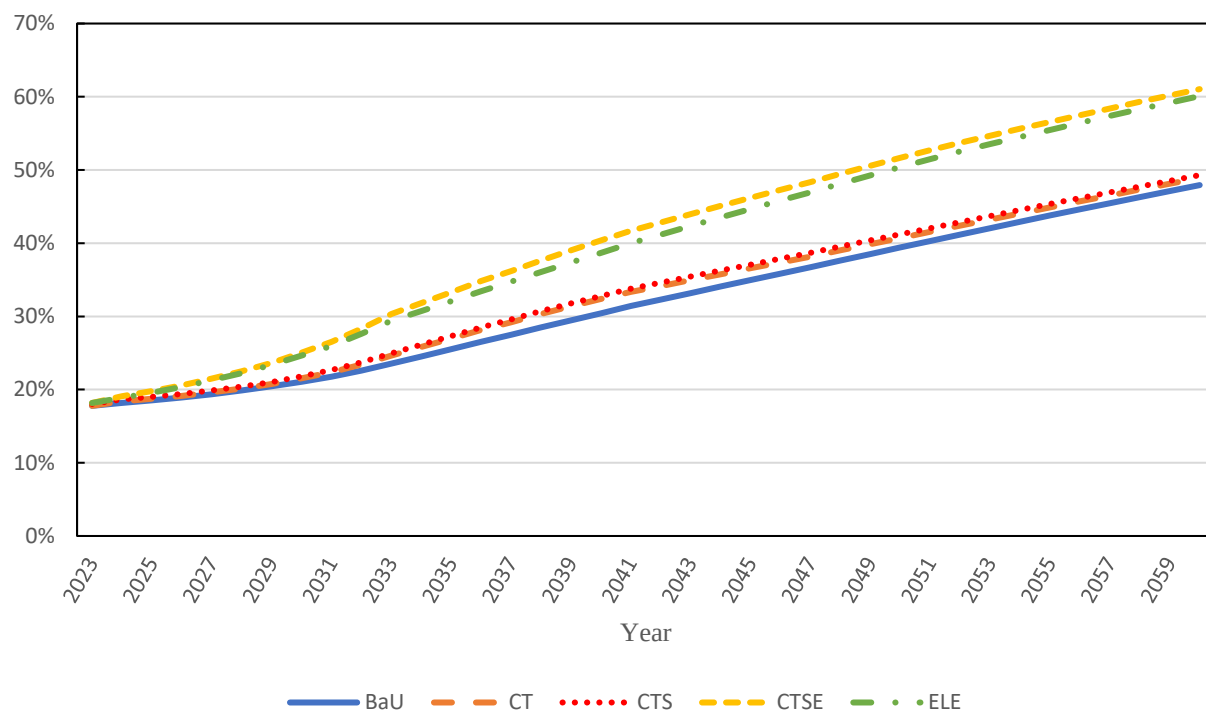


Figure A3.2: Non-fossil fuel consumption ratio in BaU, CT, CTS, ELE and CTSE

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Chapter 4 Evaluating impact of carbon tax stringency on sectoral carbon productivity

4.1 Introduction

Since the nationally determined contributions (NDCs) are proposed, the Chinese government pledged to achieve a carbon peak by 2030 and improve the ratio of non-fossil fuel consumption to total energy consumption structure to 25% in the same year. Towards this goal, the increasing cost to replace fossil fuel with renewable energy is a major hindering factor.

Towards this goal, the increasing cost to replace fossil fuel with renewable energy is a major hindrance. To further this urgent process, carbon pricing has been introduced. Carbon pricing essentially indicates a shadow pricing of emissions. Apart from labor and capital, carbon shadow price (CSP) can also be taken as a type of input serving for industrial output (Silva & Magalhães, 2023). Higher CSP or stricter carbon pricing is thus needed for improving its technology efficiency so as to reach higher-level productivity (Cui et al., 2022). The implementation of low-carbon policy could lead to green technological innovation, enhancing energy efficiency and productivity (C. Zhu & Lee, 2022). Essentially, CP can be regarded as a measurement of a green economic growth pathway of the industry (Coderoni & Vanino, 2022). The improvement on CP could be the good way to achieve carbon peak and carbon neutrality in China that high energy efficiency indicates clean economic development (Xiong et al., 2021).

Given that energy consumption patterns are significantly different between sectors, with the secondary sector taking the biggest share of carbon emission, the major energy-intensive industries thus show greater potential in improving the CP compared with the tertiary sector (Wu and Han, 2020). Due to different technological efficiency and carbon intensity across the energy-intensive

industries, the industrial behaviors are unclear under the carbon tax, which can impose either a positive or negative impact on carbon emission. Furthermore, the stringency of environmental policy shows positive relationship with energy efficiency and carbon emission abatement that stricter carbon tax tends to gain more environmental benefits (Saqib & Usman, 2023). On the one hand, carbon tax is likely to lead to high energy efficiency by motivating technological advancement. On the other hand, it might result in more carbon emissions by stimulating increasing industrial output with higher energy efficiency (Ofori et al., 2023). As a result, the unexplicit impact of carbon tax on industries is possible to incur a rebound effect on carbon mitigation. Therefore, the carbon-abatement pathway of energy-intensive industries cannot be commonly applied to i.e., steel and medicine industry (Tang et al., 2022).

China has launched the national carbon emission trading market in June 2021. It is considered to be enlarged from only electric power sector to all energy-intensive sectors in the near future, resulting into a uniform carbon emission trading market. The expansion of the national carbon emission trading market will account for more than 70% of the total carbon emissions in China (National Bureau of Statistics of China, 2021b). It means a differentiated carbon pricing scheme will be formed. One is the uniform carbon pricing for the national carbon emission trading market. The other is carbon pricing for the rest of industries that have not entered the national carbon emission trading market. The uniform carbon tax ignoring the inter-industrial heterogeneity is proven to be not as conducive as a differentiated carbon tax in balancing carbon emission and economic growth, which even adversely affects the development of low energy-consuming industries due to their high marginal cost in improving CP (Liu et al., 2022; N. Zhu et al., 2020). Therefore, the differentiated carbon tax for those industries consuming less fossil fuel might reduce economic burden on these industries. To reduce the extra payment on the carbon tax, industries can promote electrification on the demand side and increase energy storage capacity deployment, and renewable energy markdown on the supply side (Ringkjøb et al., 2018). However, the economic and environmental performances of the uniform carbon tax and the differentiated carbon

tax have not been compared under the introduction of forementioned possible solutions.

Furthermore, the differentiated carbon taxes are divided into environment-based and economic-based taxes that former one proposes lower carbon tax on energy-intensive industries since their abatement cost is far higher than non-energy-intensive industries such as electronic devices industry. The latter one focuses on energy structural transition that energy-intensive industries should be levied on higher carbon tax than low energy-consuming industries since industrial carbon emission is mainly generated by them such as thermal power. However, the stringency of differentiated carbon tax would be lower than uniform carbon tax in this study, which is likely to cause less sectoral innovation on energy efficiency (Martínez-Zarzoso et al., 2019). Additionally, Acemoglu et al. (2012) suggests that the elasticity of substitution between dirty and clean inputs will affect industrial technical change. Therefore, the looser carbon tax on non-energy-intensive industries might lead to less CP improvement compared to uniform carbon tax, thereby worse economic and environmental performance.

As the non-fossil fuel consumption ratio only reaches 18% in 2020 (National Bureau of Statistics of China, 2021b), it is the key point of energy structural transition in China to encourage RE development and replace thermal power, which remains one of the biggest sources of carbon emission (China Electricity Council, n.d.). However, the RE penetration might induce a markup on electricity prices due to its higher costs than thermal power at the current stage (International Renewable Energy Agency, 2020). Therefore, it is a new perspective to force RE development from the demand side and its technological related side, as RE development can be considered as a result of induced technical change (ITC) and then serve as the source of energy structure transition (Acemoglu et al., 2012).

On the demand side, electrification ensures higher electricity consumption that can stimulate the demand for RE power, and thus can also induce the endogenous technology development of RE (Shi, Yuan, & Managi, 2023). On the technological-related side, the REs development of wind

and solar power are recognized as the least-cost decarbonization pathway under the interaction of competing energy storage technologies, including battery electric vehicles, electrolyze, heat pumps, and battery storage (Misconel et al., 2022). The subsidy to RE storage financed by carbon tax revenue is effective for energy structural transition (Helm & Mier, 2021). Given that electrification and increasing energy storage capacity deployment tends to have stimulating effects on the endogenous technological development of RE and its markdown, this paper intends to fully consider such inducing relationships and selects China as the case study to evaluate the respective performance of uniform and differentiated carbon tax on improving the CP of energy-intensive industries. Therefore, we evaluate the impact of differentiated and uniform carbon tax on industrial CP, introducing the electrification and LBD effect on RE and its storage, to show how policy-influenced innovation of sectoral energy efficiency affects energy structural transition and economic growth.

4.2 Model

To further figure out the possible external shocks of environmental policies on sectoral CP variation, this study adopts computable general equilibrium (CGE) model with its novelty of fully considering the inducing effect of electrification and increasing energy storage capacity deployment on the learning-by-doing (LBD) of RE.

4.2.1 Production

We suppose all industries will achieve zero-profit condition:

$$PX_c * QX_c(1 - tp_c) = PL_c * QL_c + PK_c * QK_c + \sum_{ECC} QA_{ecc,c} * PQ_{ecc} + \sum_{NEC} PQ_{nec,c} * QA_{nec,c} + tco * \sum_{ECC} ENCO2_{ecc,c} QA_{ecc,c} \quad (4.1)$$

$C = \{all\ the\ sectors\}$ and $c \in C$ and $i \in C$,

$ECC = \{all\ the\ energy\ sectors\}$ and $ecc \in ECC$;

$NEC = \{all\ the\ non - energy\ sectors\}$ and $nec \in NEC$

where PX is the sectoral output price and PL , QL , PK , and QK are the price and quantity of labor and capital input in each industry, respectively. PQ and QA are the price and quantity of intermediate inputs, respectively, and tco is the tax rate of carbon emission. $\sum_{ECC} ENCO2_{ecc,c} QA_{ecc,c}$ is the carbon emission calculated by the intermediate of fossil fuel combustion in industries. The emission factor of fossil fuel in each industry is calibrated by historical data (National Bureau of Statistics of China, 2021a).

4.2.2 Carbon productivity with value-added

Carbon productivity (CP) is introduced in this paper to describe and access the relationship between industrial gain and environmental protection in the studied industry (Yang et al., 2021). Compared with the carbon intensity, another common-used instrument to examine the industrial efficiency on carbon mitigation, CP has the advantage of accurately illuminating the economic gain. By introducing the CP, this paper can examine whether high carbon intensity is impotent to green growth sustainably (value added) (Gazheli et al., 2016).

In definition, the sectoral CP for each industry is the ratio of sectoral value-added to sectoral carbon emission (Bagchi et al., 2022; Jung et al., 2023; Yang et al., 2021), where the value-added equals to sum of labor wage, capital, and production tax in an input-output table. Thus, CP is more than an informative indicator but also an effective instrument for guiding the sectoral carbon mitigation pathway against a carbon peak and carbon neutrality in China. According to the CP value, the industry can adjust its green growth strategy, as the lower CP in the industry implies the

need for more effort on improving its energy efficiency (Gazheli et al., 2016).

In this paper, CP is used as a standard to evaluate the overall economic and environmental performance of the uniform carbon tax and the differentiated carbon tax in different designed scenarios, with the REs-related subsidy and electrification introduced respectively. It aims at examining and comparing whether and how the CP of energy-intensive industries can be facilitated by the carbon tax in different forms and under different situations.

4.2.3 RE and storage

The storage for RE is determined by RE generation penetration in the electricity market, as given by (Dai et al., 2017):

$$Share = \alpha_{win} * swin^{\beta_{win}} + \alpha_{sol} * ssol^{\beta_{sol}} \quad (4.2)$$

Where *Share* is the total share of electricity storage that larger share of wind and solar power penetration leads to more demand for storage. α_{win} , α_{sol} , β_{win} , and β_{sol} are parameters calibrated by (Dai et al., 2017), showing the level of storage that depends on the role of wind and solar power. *swin* and *ssol* indicate the share of wind and solar storage capacity in total wind and solar power supply, respectively. β_{win} and β_{sol} are 1.5 and 1.7, respectively, based on (Dai et al., 2017), while α_{win} and α_{sol} are calibrated based on historical data from 2017 and our past study.

The LBD is applied for nuclear, wind, and solar power generation as follows (Shi, Yuan, Shi, et al., 2023):

$$AVC_{nsw} = lb_{nsw} * KS_{nsw}^{lx_{nsw}} \quad (4.3)$$

$$nsw = \{nuclear, wind, and solar power\}$$

Where AVC_{nsw} , KS_{nsw} , and lx_{nsw} are the average cost, knowledge stock, and learning rate,

respectively, and lb_{nsw} is calibrated by basic data. The knowledge stock is given by the accumulated output of power with a depreciation rate of 0.05. The learning-by-doing rate introduced into this model is based on the results of (L. Zhu et al., 2015) that nuclear, wind, and solar are 0.09, -0.1, and -0.12 respectively.

Not only the LBD of REs but also that of the energy storage for wind and solar power are considered in this model due to China's guidelines for new energy storage development that battery energy storage will play a key role in RE storage (Xiao et al., 2022). The endogenous technology development of energy storage batteries with lower cost can bring substantial economic benefits to REs development (Sacchi et al., 2022). Considering that the learning-by-doing of energy storage batteries is susceptible impeded by the ascending electricity price (Feng & Lazkano, 2022), the learning rate of the storage battery for wind and solar power is thus divided by the electricity price in this paper.

4.3 Data

The social account matrix for the CGE model is derived from China's national input-output table 2017, energy balance sheet, and power statistical database (National Bureau of Statistics of China, 2021b)(China Electricity Council, n.d.), which includes 35 industries, two residential households (urban and rural), and production inputs (labor, capital, and energy) (Shi, Yuan, Shi, et al., 2023). The sectoral Autonomous Energy Efficiency Improvement (AEEI) is similar to (N. Li et al., 2017). The data of renewable energy is from (International Renewable Energy Agency, 2021; National Energy Administration (NEA), 2018).

4.4 Business as Usual and Scenarios design

4.4.1 Business as Usual

The BaU scenario is derived by the basic data and the total factor productivity is calibrated by the historical GDP growth (National Bureau of Statistics of China, 2021b, 2021a), (Shi, Yuan, Shi, et al., 2023) and (Yuan et al., 2020).

Table 4.1: BaU results

	2025	2030	2040	2050	2060
GDP					
(Trillion CNY)	123.5	155.4	213.1	261.1	289.8
Carbon emission					
(Billion ton)	10.47	10.86	10.73	10.14	8.79
Carbon					
productivity	11.8	14.3	19.9	25.7	33.0
(CNY/kg)					

The BaU scenario has not any environmental policy and regulation included but only considers the endogenous technological development of RE and energy storage (wind and solar power). In the BaU, the GDP growth rate refers to (Cao et al., 2021) and is used as an exogenous development factor to calibrate the total factor productivity. It can be observed that the gross energy efficiency and the gross CP keep increasing and reach a carbon peak in 2033 and then present a declining trend until 2060. In this process, CP can decline faster in the long term than in the short term, indicating that the increasing energy storage capacity deployment and the LBD of RE play crucial

roles in industrial carbon abatement under no implementation of environmental policies restricting fossil fuel consumption.

4.4.2 Carbon tax

The carbon tax is commonly used in nearly 40 countries (regions) and has been set to be the highest of 137\$/ton in Europe, due to its efficiency in carbon abatement (Aaron et al., 2022). (Chang et al., (2022) figure out the adverse economic impact of the carbon tax by 2030 and find that the financial loss can be mitigated if the responsibility for carbon emission reduction is only taken by high carbon-emission industries, in which carbon reduction is more cost-effective and economically efficient. Consequently, as the extra cost of fossil fuel consumption, carbon tax tends to negatively impact the industrial outputs of energy-intensive industries in developing countries especially. The differentiated carbon tax on energy-intensive industries is introduced by (Liu et al., (2022) into a revenue recycling system, where the carbon rates of energy-intensive industries (60 CNY/ton) is 1.5 times bigger than that of other industries (40CNY/ton).

This paper intends to systematically evaluate the economic and environmental performance of the carbon tax in either uniform or differentiated form under some specific environments, on the basis of overcoming the limitations of the aforementioned literature, including (1) not taking the external impact of the policy environment into consideration and assuming the price levels of the studied sector to always be constant, (2) not accounting for different input-output elasticity between sectors and assuming them to be the same. The differentiated carbon tax defined in this paper, follows the principle of energy-intensive industries undertaking more responsibility than low energy-consuming industries. For these purposes, the scenarios of CT, CTS and CTSE are designed for evaluating the performance of uniform carbon tax and the scenario of DCTSE is designed for the differentiated carbon tax. Specifically, under the differentiated carbon tax, the studied energy-intensive industries only refer to petroleum refinery, coke, basic chemical raw

material (chemical), other chemical industry such as fertilizer, fabric and plastic, cement, other non-metallic such as tile, ceramic and glass, steel and non-ferrous metal industry and thermal power sector.

4.4.3 Subsidy to storage

The Guiding Opinions on Accelerating the Development of New Energy Storage Technologies⁵ was proposed by the National Development and Reform Commission(NDRC) and National Energy Administration(NEA), to serve for the target of raising non-fossil fuel consumption accounting for 25% of total energy consumption by 2030. As the related and supporting technology of RE, energy storage acts as an increasingly important role in the energy structural transition (Hu et al., 2022). Energy storage mainly refers to battery storage for wind and solar power in this paper.

According to (Özdemir et al., (2020)), it is a strategy to allocate the subsidy to energy storage, comparing with a direct subsidy to REs. Furthermore, the subsidy can serve as a more effective instrument in the long run, if it is based on the installed capacity of energy storage rather than the electricity generation of RE or its electricity price (De Groote & Verboven, 2019). The capacity-based subsidy can form a virtuous circle that the capacity installation for energy storage can receive more subsidy for its further deployment (Guo et al., 2021). Considering the cost-effectiveness of allocating the subsidy on the capacity deployment of energy storage, this paper designs the scenarios of CTS, CTSE and DCTSE in which the subsidy for energy storage is fully financed by carbon tax revenue based on the installed capacity of wind and solar power storage.

⁵ http://www.gov.cn/xinwen/2022-03/28/content_5681916.html

4.4.4 Electrification

The carbon tax on the energy-intensive industry can be implemented with the promotion of electrification. Specifically, it can serve as a constant driver for the replacement of fossil fuels with REs, by stimulating electricity consumption (Barrett et al., 2020). In other words, the consumption propensity of electricity increases for the end-users tends to be along with the decline of fossil fuel consumption. In this regard, the economic and environmental performance of the uniform carbon tax and the differentiated carbon tax should be evaluated with the electrification considered.

According to (Acemoglu et al., (2012), the technical change can be directed by environmental regulations to promote the energy structural transition. As such, the substitution of REs for fossil fuels can be improved by electrification under the effective policy intervention. Given that the mixed policy has been proven to perform better than a single policy on furthering electrification (X. Li & Yao, 2020), this paper designs the CTSE and DCTSE scenarios with an aim at further assessing the economic and environmental performance of the differentiated carbon tax under the context of policy packages conducted for electrification promotion. It assumes that a series of strong regulation on electrification promotion can increase the propensity of electrification assumption in the energy-intensive industries and reduce their reliance on fossil fuel. In the analysis, the initial propensity of energy consumption, including petroleum, gas, coke and electricity, is calibrated by historical data.

4.4.5 Scenario design

This paper intends to evaluate the economic and environmental performance of uniform and industry-differentiated carbon taxes under different scenarios as shown below.

Table 4.2: Scenario design

	Uniform Carbon tax	Subsidy	Electrification	Differentiated carbon tax
BaU				
CT	√			
CTS	√	√		
CTSE	√	√	√	
DCTSE		√	√	√

4.5 Results

4.5.1 CT and BaU comparison: The economic and environmental performance of the uniform carbon tax

The results justify the effectiveness of carbon tax on abating sectoral carbon emissions. Table 4.3 shows the change rate of carbon emission between the BaU and the CT scenario over the year. With the implementation of a uniform tax, the carbon emission in thermal power has declined most significantly and other energy-intensive industries also achieve significant carbon mitigation, except for the Non-Ferrous metal and the Other Chemical industries. The change-rate trajectories with negative values indicate the positive effect of a uniform carbon tax on carbon abatement while that with positive values signify the opposite effect. It is observed that, compared with other energy-intensive industries, the Non-Ferrous Metal industry and the Other Chemical industry are highly dependent on fossil fuel consumption that cannot be substituted by electricity at this stage.⁶

⁶ To avoid difficulty, we do not display the output here but the industrial output of both the Non-Ferrous Metal and the Other Chemical in CT is lower than CT, which means the increase in carbon emission is not caused by more production but by more fossil fuel consumption (Yong et al., 2022).

Table 4.3: The change rate of sectoral carbon emission in CT compared with BaU

	2025	2030	2040	2050	2060
Petro	-0.32%	-0.66%	-2.07%	-2.45%	-2.35%
Coke	-0.54%	-1.43%	-5.47%	-5.18%	-4.41%
Chemical	-0.36%	-1.76%	-8.66%	-7.87%	-6.68%
Other chemical	0.52%	0.64%	1.18%	0.58%	0.80%
Cement	-0.05%	-0.18%	-0.74%	-1.59%	-1.31%
Other non-metallic	-0.09%	-0.34%	-1.04%	-1.46%	-1.19%
Steel	-0.73%	-1.60%	-5.03%	-4.58%	-3.76%
Non-ferrous	0.72%	0.97%	0.93%	-0.41%	-0.32%
Thermal	-3.17%	-6.79%	-25.52%	-24.70%	-24.02%

The implementation of the uniform carbon tax not just significantly increases the cost of fossil fuel consumption but also induces the markup of electricity. Under this scenario, the power sector takes the most share of total carbon emission reduction as shown in Table.4.3. On the contrary, for the Non-Ferrous metal industry, the uniform carbon tax does not result in more electricity consumption in the short term but more coal consumption for smelting non-ferrous metal, i.e., thermal power generators. As an important industry that provides technology-intensive industries with raw materials, including lithium, copper, and aluminum, it maintains a thermal power-dominant energy consumption pattern (Chen et al., 2022). Similarly, for the Other Chemical industry, a uniform carbon tax leads to more fossil fuel consumption and thus more carbon emission in the short term. It is on the ground that carbon tax tends to stimulate the industry to

reuse phosphogypsum in the fertilizer industry (Z. Wang et al., 2023). However, such a situation may reverse in the long term. It is shown that the uniform carbon tax can lead to carbon abatement in the long term, especially the Non-Ferrous Metal industries.

Table 4.4: The change rate of sectoral electrification rate in CT compared with BaU.

	2025	2030	2040	2050	2060
Petro	-0.82%	-1.78%	-1.45%	0.63%	0.78%
Coke	-1.19%	-2.55%	-2.72%	-0.15%	-0.23%
Chemical	-0.79%	-1.57%	-0.78%	1.41%	1.15%
Other chemical	-0.42%	-0.91%	-0.85%	0.18%	0.10%
Cement	-1.14%	-2.46%	-2.69%	-0.29%	-0.36%
Other non-metallic	-1.25%	-2.66%	-2.85%	-0.13%	-0.24%
Steel	-0.95%	-2.10%	-2.57%	-0.43%	-0.48%
Non-ferrous	-0.73%	-1.58%	-1.78%	-0.21%	-0.27%
Thermal	-1.14%	-2.42%	-2.51%	-0.04%	-0.11%

Note: the electrification rate refers to sectoral ratio of electricity consumption to total energy consumption

The effect of the uniform carbon tax on the electrification rate is observed to vary until 2060, from non to negative and then to positive, as shown in table 4.4, which are completely different from its effect on carbon abatement. Generally, the trade-offs between expensive electricity and the increasing cost of fossil fuel brought by the uniform carbon tax are presented at any stage for energy-intensive industries. It is shown that the ratio of electricity consumption to total energy

consumption is stable as a constant by 2028. At this stage, thermal power still takes up the dominant position in the energy consumption pattern, on the ground that the LBDs of RE only exert a small function on its cost reduction in the short term. Since then, it presents a steep declining trend until 2033, which can be explained as the negative effect of the uniform carbon tax. With the carbon tax reaching the threshold (124 CNY/ton), the energy-intensive industries would trade-off to consume more fossil fuel rather than electricity, as electrification is not considered as a cost-effective choice. However, the electrification rate presents an increasing trend since 2033 with the carbon tax rising to 528.7 CNY/ton. This process reflects that, the increasing uniform carbon tax can improve the cost competitiveness of electricity to be higher than fossil fuel in the medium- and long term.

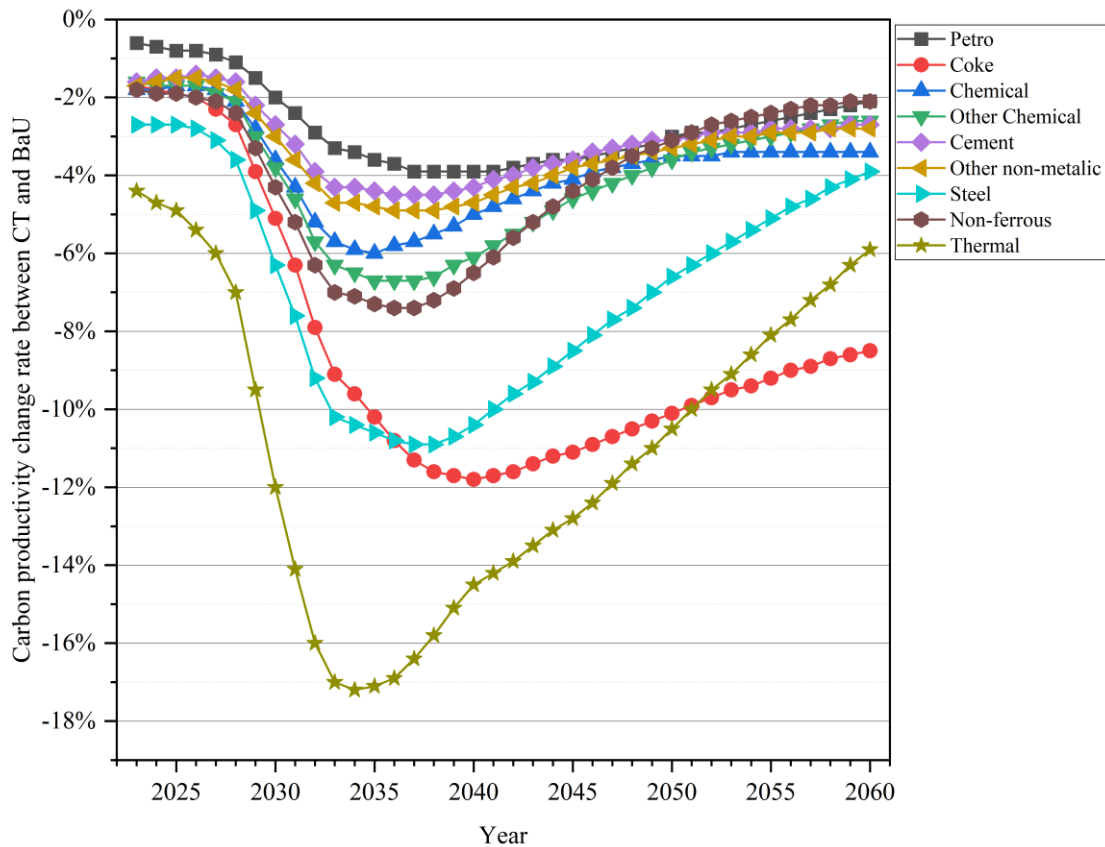


Figure. 4.1: The change rate of CP in CT compared with BaU

Fig. 4.1 clearly demonstrates the negative impact of a uniform carbon tax on increasing the CP of energy-intensive industries over the years, as the change rates of CP between CT and BaU are always negative across the studied energy-intensive industries until 2060. During this period, the CPs of the Thermal power industry witnesses a dramatically declining trend until 2034, reflecting the increasingly adverse effect of a uniform carbon tax on their energy efficiency improvement. Other studied energy-intensive industries also suffer the adverse economic effects of the uniform carbon tax but are significantly fewer than the aforementioned one. However, we also find that the rebound effect of carbon tax on CP of thermal power industry is earlier than other energy-intensive industries that the former improves its CP in 2035 and the latter increases commonly in 2038, while the petroleum refinery and coke industry does not get any CP enhancement until 2039 and 2040, respectively.

Two reasons are behind this situation. In one aspect, the introduction of a uniform carbon tax inflicts an extra cost of fossil fuel consumption and leads to a sharp increase in the coal price, which is sensitive to energy-intensive industries. In the other aspect, the thermal power can still not be replaced by REs due to its less cost competitiveness in short and medium term. Under the interactive effect of increasing coal consumption cost and no other good substitute, the synergism between carbon emission reduction and CP reduction in the thermal power industry should be explained by both the increased energy efficiency shown in Fig.A4.1 and the reduced industrial output. The negative effect of the uniform carbon tax on the CP of energy-intensive industries has been mitigated since 2035, when the CSP (carbon tax) reaches a threshold. Combining the results shown in Table 4.5 and Fig.4.1⁷, the energy-intensive industries incline to electrify their production rather than keep reliance on fossil fuel consumption in the long term, under the motivation of the uniform carbon tax. In this long-term process, the costs of RE and energy storage tend to decline

⁷ The electricity consumption in the power sector is regarded as power transmission and loss during production and transmission. Fig. A1 shows improvement in energy efficiency of thermal power in CT that it unit electricity production increases with less unit coal consumption. Also, the improvement in thermal generators such as thermal storage systems might lead to an increase in electricity consumption.

with their capacity deployment due to the function of learning by doing. The cost-reduction of RE can to a large degree improve its substitution for fossil fuel, which would result in CP improvement in energy-intensive industries. In this regard, the environmental performance of the uniform carbon tax can be coordinated with its economic performance attributing to the LBD of REs. In addition, the earlier CP improvement in thermal power is also benefited by fierce competition in electricity market, while other energy-intensive industries suffer from tradeoff between fossil fuel and electricity during 2033 to 2038 that their curves become flat as shown in Fig. 4.1. The later CP enhancement in petroleum refinery and coke industry indicates hysteresis of upstream industry that coke and petroleum are massively consumed in downstream industries until 2038. Given that other energy-intensive industries suffer less economic shock compared with the thermal power industries, it can at a large level justify that the uniform carbon tax tends to have more substantial and far-reaching implications on the energy structural transition of the traditional energy power industry.

To summarize the economic and environmental performance of the uniform carbon tax, it is different across the studied energy-intensive industries and has an immense effect on releasing the carbon-abatement potentials of the traditional power sector. The energy-intensive industry, especially the thermal power industry, tends to be motivated to improve the energy efficiency of fossil fuel and reduce their industrial output so as to offset the extra cost of per-unit fossil fuel consumption introduced by the uniform carbon tax (Meng et al., 2023). In the short term, the environmental performance of the uniform carbon tax in these energy-intensive industries is achieved at the cost of their industrial output. But in the long term, the uniform carbon tax can promote the electrification and the endogenous technological development of REs and their storage, which ensures its environmental and economic performance to be achieved eventually.

4.5.2 CTS and CT comparison

Different from the CT scenario in which the economic and environmental performance of the uniform carbon tax is evaluated under no specific policy intervention, the CTS scenario is designed to conduct such evaluation based on considering the impact of subsidy on the capacity installation of energy storage for REs. The subsidy financed by carbon tax revenue to energy storage is proposed by (Helm & Mier, 2021), and is recognized to be a possibly effective instrument to improve the LBD of RE for its cost reduction with capacity deployment and thereby accelerate the substitution of REs for fossil fuels in the energy-intensive industry (Acemoglu et al., 2012). In Fig.4.2, the change rate of CP in CTS compared to that in the CT reflects the function of the energy storage-based subsidy on the economic and environmental performance of the uniform carbon tax.

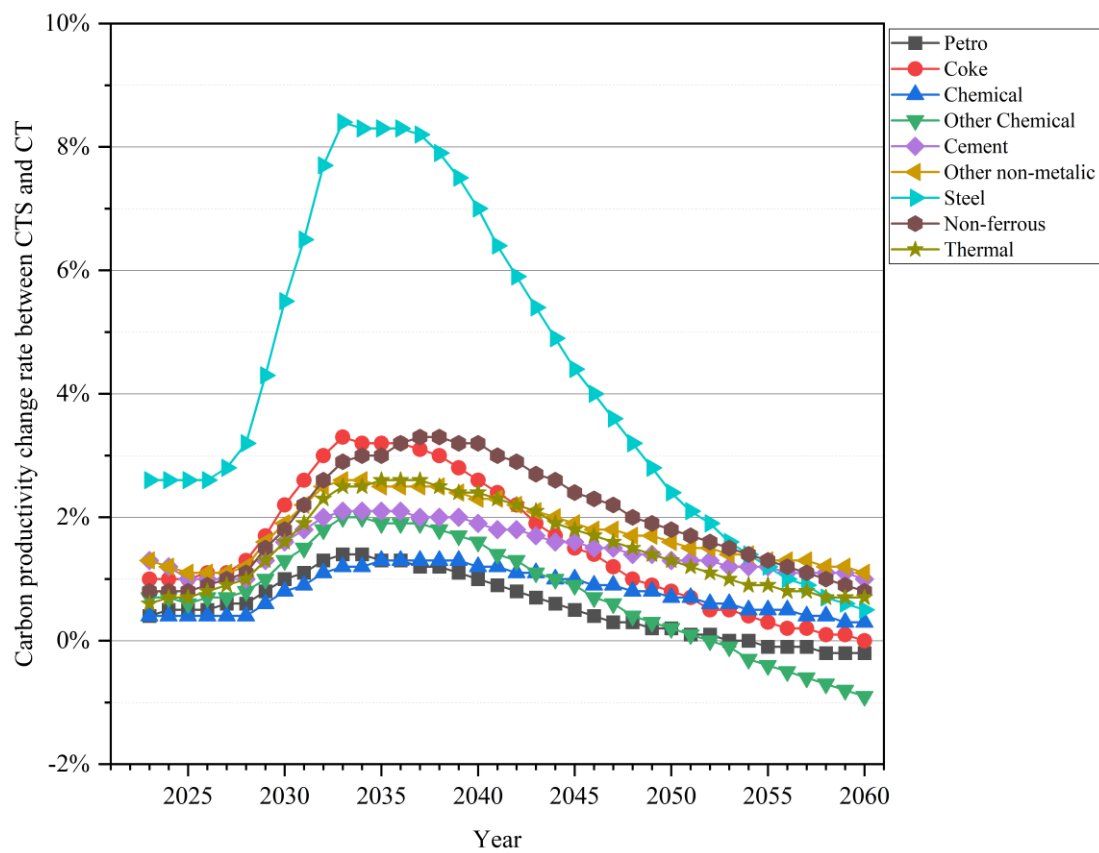


Figure. 4.2: The change rate of CP in CTS compared with CT

As shown in Fig.4.2, the subsidy for the capacity installation of energy storage tends to improve the economic and environmental performance of the uniform carbon tax on the energy-intensive industries at the initial stage, especially for the steel industry. As a typical energy-intensive industry, the steel industry is highly susceptible to the fluctuation of electricity price and is thus most sensitive to the cost-reduction of REs caused by the subsidy for REs storage (Qu et al., 2022). Combining Fig.4.1 with Fig.4.2, it could be found that the economic and environmental performance of the uniform carbon tax remain negative in the studied energy-intensive industries, even though they are at different level improved by the energy storage-based subsidy.

The lower CP in CT and CTS comparing BaU discloses that fossil fuel levied on the uniform carbon tax remains more competitive than electricity consumption. And the increased CP in the CTS scenario compared with that in the CT scenario reflects that the positive effect of subsidizing the REs storage capacity installation can to some degree offset the negative effect of the uniform carbon tax on the CP of energy-intensive industries. The positive effect of subsidizing the REs storage capacity installation is generated by that it forces the exponent reduction of REs cost along with its increasing deployment. Facing the markup of fossil fuel caused by the uniform carbon tax and the increasing cost-competitiveness of REs supported by the relevant subsidy, the consumption of fossil fuel not only can be reduced through increasing energy efficiency of fossil fuel in the energy-intensive industries but also can be replaced by the REs attributing to its lower price and increasing capacity deployment in the electricity market, as shown in Table 4.5.

Specifically, in both CT and CTS scenarios, the increasing energy efficiency of fossil fuels in energy-intensive industries can be explained on the supply side and the demand side respectively. On the supply side, thermal power tends to have less penetration in the electricity market, due to the decreasing industrial output of the thermal power industry and the increasing cost of thermal power consumption under the uniform carbon tax. On the demand side, the technological level of the energy-intensive industry tends to be improved, forced by the increasing consumption cost of fossil fuel (X. Wang et al., 2023).

Table 4.5: Non-fossil fuel consumption rate in CT and CTS. (Unit: %)

	2030	2040	2050	2060
CT	21.5	32.4	40.7	48.9
CTS	21.8	32.8	41.2	49.3

However, as shown in Table.4.6, the increased CP in CTS is along with more sectoral carbon emission in the long run, especially in the energy-intensive industries of non-metallic, steel, coke, and petroleum refinery. More carbon emission can be explained by the higher CSP threshold for transiting from relying on fossil fuel to electricity (Shi, Yuan, & Managi, 2023). This increased threshold in CTS compared with that in CT is mainly attributed to the markup of electricity with increasing REs penetrations in the electricity market under the REs-storage-based subsidy. As such, it tends to be more cost-effective for energy-intensive industries to improve the energy efficiency of fossil fuels rather than electrification. The improved energy efficiency of fossil fuels on the demand side can offset the effect of the uniform carbon tax on reducing the supply of fossil fuel and increasing its cost. The higher reliance on fossil fuels but not the electricity generated by REs inevitably results in the increased carbon emissions (Goulder & Mathai, 2000). This process discloses that, the positive relationship between CP improvement and carbon emission in the short run can rebound to a negative one in the long run with the introduction of the uniform carbon tax under the REs-storage-based subsidy that RE is fully improved for replacing fossil fuel (Meng et al., 2023).

Table 4.6: The change rate of sectoral carbon emission in CTS compared with CT

	2025	2030	2040	2050	2060
Petro	0.29%	0.55%	1.44%	1.84%	2.09%
Coke	0.42%	0.88%	2.29%	2.15%	2.19%
Chemical	-0.13%	-0.10%	0.05%	0.46%	0.69%
Other chemical	0.02%	0.21%	0.83%	1.05%	1.14%
Cement	1.10%	2.02%	4.33%	3.58%	3.24%
Other non-metallic	0.86%	1.66%	3.72%	3.24%	2.98%
Steel	0.80%	1.47%	3.20%	2.46%	2.28%
Non-ferrous	-0.01%	0.15%	0.74%	1.04%	1.32%
Thermal	0.09%	0.26%	0.70%	0.47%	0.84%

Different from the increased CP in the energy-intensive industry, the CP of most technology-intensive and tertiary industries tend to be lower with the introduction of the uniform carbon tax under the REs-storage-based subsidy, as shown in Fig.A4.4. It reflects the negative effect of the REs-relevant subsidy on the economic and environmental performance of the uniform carbon tax. It is on the ground that the markup on electricity induced by the uniform carbon tax and RE penetration tends to demotivate the energy structural transition of most high-tech and tertiary industries, as they are inclined to consume more fossil fuel and less electricity in the short term. However, with the decreasing electricity price, the CP would increase gradually except for the transport industry. Taking the transport industry as an example, the traditional fuel cell vehicle replaced by the electrical vehicle as a structural transition process would be slowed down with the

markup of electricity. Given the energy structural transition is stagnant, the reduced CP is along with the increased carbon emission (Du et al., 2022).

However, the economic and environmental performance of the uniform carbon tax for electrical machinery, battery, electronic equipment, and instrumentation industries, tends to be improved by the introduction of the REs-storage-based subsidy. These technology-intensive industries are all highly related to REs development. In these industries, the increased CP is due to the endogenous technological development of REs motivated by the subsidy. With increasing REs penetrating the electricity market, LBD can endogenously function in coordination between the industrial output increase and carbon abatement (Rasool et al., 2022). The increased CP in these high-tech industries is together with the increased sectoral carbon emission, attributing to more industrial output of these industries forced by more demand under the increasing REs penetration in the electricity market.

To summarize the impact of REs-storage-based subsidy on the economic and environmental performance of the uniform carbon tax, it is observed to be positive on increasing CP of the studied energy-intensive industries and the REs-related high-tech industries, but imposes a negative effect on that of other studied high-tech industries. Furthermore, the increasing RE penetration induced by the uniform carbon tax and the REs-relevant subsidy would result in more carbon emissions emitted from both the energy-intensive industry and the high-tech and tertiary industries. For most energy-intensive industries, it is a strategy to stabilize their industrial output by increasing fossil fuel consumption. For the REs- and storage-related high-tech industry, it is necessary to consume more fossil fuels to meet the increasing demand for REs and storage during the energy structural transition, especially battery industry. During this process, the trade-offs between energy efficiency improvement of fossil fuel and electrification always exist. The higher threshold caused by more RE penetration for transiting from improving energy efficiency to promoting electrification in CTS than that in the CT, reflects the additional effect of the REs-storage-based subsidy on hindering the industrial electrification. Given that electrification is a key part of the energy structural transition

but its impact on the economic and environmental performance of the uniform carbon tax remains unclear, the mandatory electrification scenario of CTSE is designed further in this paper.

4.5.3 CTSE and CTS comparison

On the basis of CTS, electrification in the industry has been further introduced in the CTSE. Electrification is assumed to be mandatorily promoted under the mixed policy package, which can effectively force all end-users and prosumers to adjust their energy consumption patterns from a fossil-fuel-dominant one to an electricity-based one. The change rate of CP in CTSE compared with that in CTS as shown in Fig.4.3, reflects the impact of electrification on the economic and environmental performance of the uniform carbon tax.

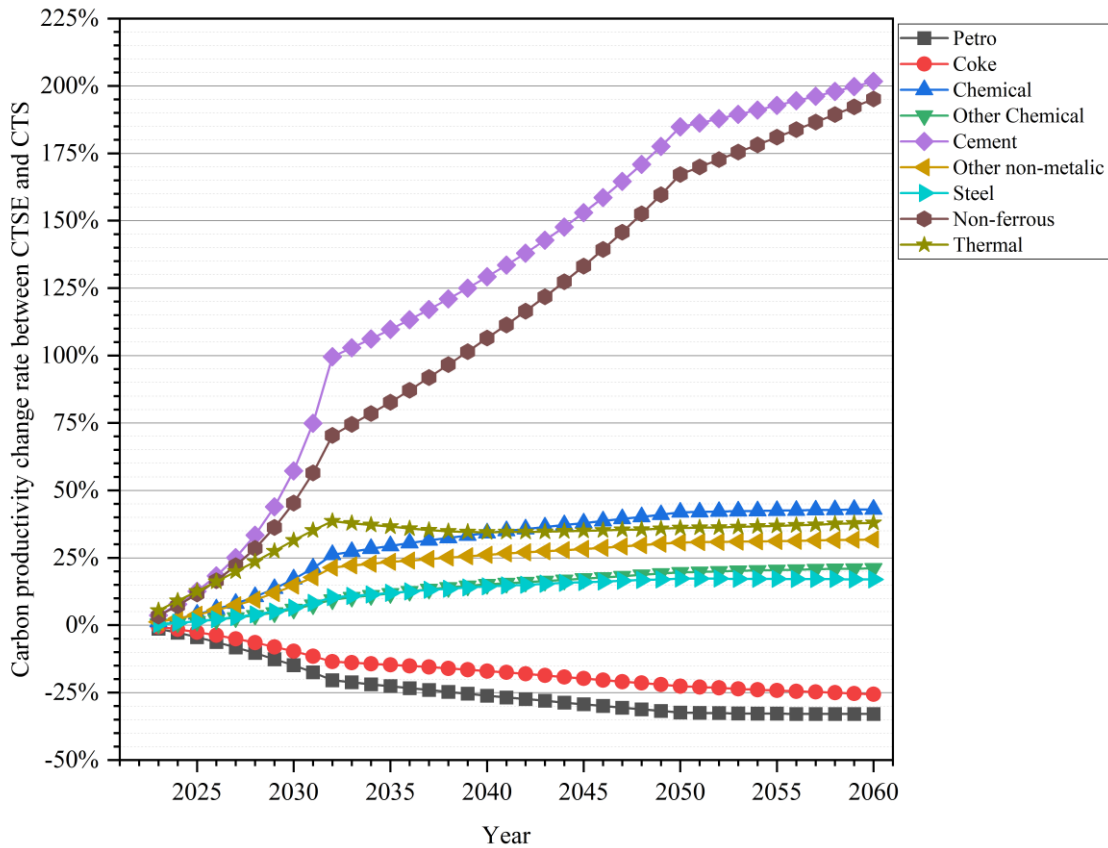


Figure. 4.3: The change rate of sectoral CP in CTSE compared with CTS

According to Fig.4.3, mandatory electrification in the industry can at different levels improve the economic and environmental performance of the uniform carbon tax for most studied energy-intensive industries, especially for the Cement industry and the Non-ferrous industry but except for the Coke industry and the Petroleum Refinery industry. The cement industry, which highly relies on electricity consumption, can environmentally and economically be benefited from electrification in the industry, as it can induce the improvement of energy efficiency, the increasing electricity supply from cleaning REs and its cost reduction (Griffiths et al., 2023). Comparatively, the energy efficiency improvement leading to the decrease in emission intensity, contributes most to the CP increase of the cement industry (Tautorat et al., 2023). Also, the Non-ferrous industry is another typical electricity-intensive industry, in which aluminum processing can be cleaner and more cost-effective with the increasing REs consumption induced by a higher level of electrification in the industry (S. Zhu et al., 2022). For other studied energy-intensive industries, electrifying the device can environmentally reduce carbon emission thereby leading to an increase in CP, and can economically reduce the cost of REs consumption with the markdown on electricity along with the increasing deployment of electrified devices. In specific, the promotion of electrification in most energy-intensive industries can substantially improve the LBD of REs by yielding huge demand for REs storage and consumption. With the increasing capacity deployment of REs and their storage, the lower cost of REs can further lead to an increase of CP in the long term.

However, the reduced CP in the energy-intensive industries of the Coke industry and the Petroleum refinery industry is on the ground that they are completely fossil fuel-based and work on supplying the processed fossil fuel for other industries, i.e., the Coke industry serving medicine, chemical and steel industries, and the Petroleum refinery industry serving for all of industries and end-users. Under the joint function of the uniform carbon tax, the REs-storage-based subsidy, and electrification, the falling fossil fuel consumption in the electricity market would directly hinder the development of these two industries, which cannot gain enough investment for further

technological innovation (L. Zhu et al., 2021). In this regard, the CP in these two industries can only decline without technological advancement supporting their structural transition.

In terms of the tech-intensive industry, the electrification in the industry tends to improve the economic and environmental performance of the uniform carbon tax, as a reflection of an increased CP shown in Fig. A4.6. The slight increase of CP in most high-tech industries is a joint result of less carbon emission led by electrification and markup on electricity induced by the increased REs penetration in the electricity market. However, the transport industry is an exception among the studied tech-intensive and tertiary industries, as its CP reduces with electrification in the industry. The main reason behind this is that it is tricky and costly to promote the electrification of railways, which would result in the reduction of its CP in the short term (Martins-Turner et al., 2020). However, the CP of the transport industry would slightly increase with the lower cost and larger scale of REs and their storage achieved in the long run (Tamba et al., 2022). Need to mention in particular that the variation trajectory of CP in the Battery industry has a swift transition in 2030, as the impact of electrification on the economic and environmental performance of the uniform carbon tax has immediately evolved from positive to none. The Battery industry specifically serves for the REs development, as over 80% of RE storage is battery storage (Xiao et al., 2022). According to (Feng & Lazkano, 2022), the LBD of battery storage for wind and solar power is negatively affected by electricity price, as its endogenous technological development would be hindered by the continual markup on electricity.

With the introduction of the uniform carbon tax under the REs-storage-based subsidy, the electrification in the industry can further force the penetration of enormous REs in the electricity market and result in more markup on electricity in CTSE compared to CTS, which would consequently decelerate the increase of CP in the Battery industry to zero since 2030. In terms of the tertiary industry, the economic and environmental performance of the uniform carbon tax has been improved dramatically with the electrification promoted in the industry. The ascending CP in the tertiary industry is mainly based on the decreasing carbon emission attributed to the phase-out

of fossil fuel under electrification (X. Li et al., 2023).

Table 4.7: The change rate of sectoral carbon emission in CTSE compared with CTS

	2025	2030	2040	2050	2060
Petro	-0.3%	-2.6%	-7.7%	-11.0%	-12.7%
Coke	-1.0%	-4.4%	-9.8%	-11.5%	-11.7%
Chemical	-3.5%	-14.1%	-23.5%	-26.7%	-27.8%
Other chemical	-1.8%	-6.5%	-12.5%	-14.7%	-15.1%
Cement	-6.6%	-29.7%	-56.6%	-66.0%	-69.0%
Other non-metallic	-2.1%	-9.2%	-18.4%	-21.8%	-22.8%
Steel	-1.0%	-4.9%	-10.4%	-12.4%	-12.8%
Non-ferrous	-7.2%	-27.1%	-49.0%	-59.4%	-63.7%
Thermal	4.3%	12.6%	19.8%	17.9%	18.6%

As for the specific impact of electrification on the environmental performance of the uniform carbon tax, it can promote carbon emission reduction in most of the studied energy-intensive industries, especially for the Cement industry and the Non-ferrous industry but except for the Thermal Power industry. Taking the Cement industry as an example, the electrified calciner under electrification, is conducive to significantly mitigating the carbon emission (Jacob & Tokheim, 2023). As for the excepting Thermal power industry, on the one hand, electrification tends to inflict the increased industrial output of thermal power generation, as it is cheaper than REs generation in the electricity market. It is shown in Table 4.8 of more thermal power generation in CTSE than

in the CTS. On the other hand, the coal-power conversion coefficient in the CTSE is higher than that in the BaU before 2040 as shown in Fig.A4.1, meaning that the carbon emission would increase at this stage with the introduction of the uniform carbon tax under the Res-storage subsidy and electrification because lower energy efficiency of thermal power. In long term, the stable increase in carbon emission in thermal power indicates more active industrial activities in CTSE to meet demand for electricity than that in CTS.

To summarize the impact of electrification in the industry on the economic and environmental performance of the uniform carbon tax, it can be observed that the electrification promoted in the energy-intensive industry can at different levels improve the economic and environmental performance of the uniform carbon tax for most studied energy-intensive industries, except for the Coke industry and the Petroleum Refinery industry. Moreover, for most studied energy-intensive industries, the increased CP is along with the reduced carbon emission except for the Thermal power industry. And for the Coke industry and the Petroleum Refinery industry, their decreased CP is the joint result of reduced carbon emission and industrial outputs. Comparatively, electrification in the tech-intensive industry can improve the economic and environmental performance of the uniform carbon tax more significantly. The significant positive impact of electrification on increasing the CP of the tech-intensive industry can mostly attribute to its effectiveness in reducing carbon emissions.

Table 4.8: Thermal power generation in CTS and CTSE (Twh)

	2030	2040	2050	2060
CTS	5796.13	4443.22	4111.76	3719.92
CTSE	6179.77	5015.74	4541.88	4086.60

4.5.4 DCTSE and CTSE comparison

The aforementioned only evaluates the economic and environmental performance of the

uniform carbon tax but not the differentiated one. Thus, DCTSE is designed to assess the performance of the differentiated carbon tax under the introduction of REs-storage and electrification. As mentioned in section 4.3, the differentiated carbon tax is based on the principle of energy-intensive industries undertaking more responsibility than low energy-consuming industries. In the scenario setting, the carbon tax for non-energy-intensive industries is two-thirds of that for energy-intensive industries. Under this, the total revenue from the differentiated carbon tax tends to be lower than that from the uniform carbon tax as shown in Table 4.9. And the change rate of CP in DCTSE compared with that in CTSE in Fig.4.4, reflects different economic and environmental performances of the uniform carbon tax and the differentiated carbon tax with the promotion of the REs-storage-based subsidy and electrification.

Table 4.9: Total carbon tax revenue for subsidy (Trillion CNY/ton)

	2030	2040	2050	2060
CTSE	2.46	6.86	6.59	5.69
DCTSE	2.23	6.14	5.88	5.07

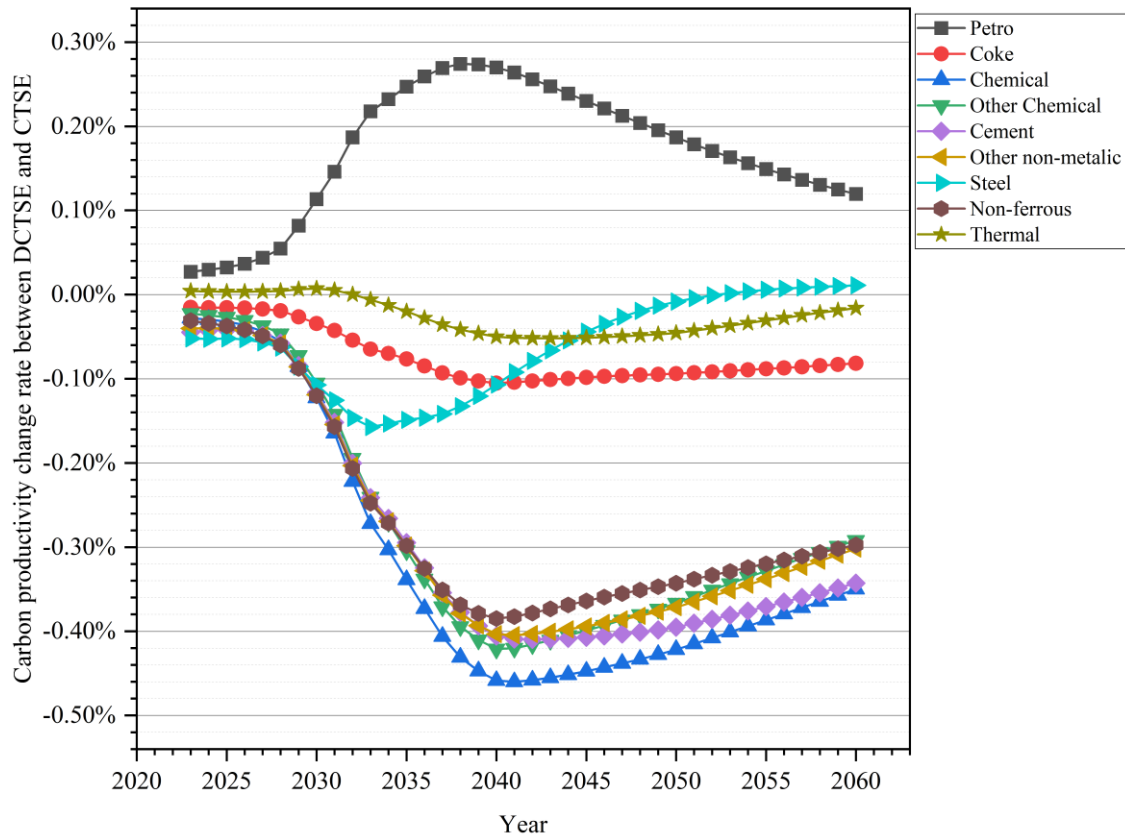


Figure. 4.4: The change rate of the sectoral CP in DCTSE compared with CTSE

As can be observed in Fig.4.4, the uniform carbon tax has better economic and environmental performance than the differentiated carbon tax for mostly studied energy-intensive industries, except for the Petro refinery industry. The worse performance of the differentiated carbon tax is on the ground that its less carbon tax revenue would lead to less subsidy for installing the capacity of REs storage, which would consequently mitigate the LBD effect of the REs. The cost reduction potential of REs cannot be sufficiently unleashed without increasing capacity deployment. Given the cost-competitiveness of REs under the differentiated carbon tax is not as high as that under the uniform carbon tax, thermal power would thus gain less stimulation for technological advancement in improving energy efficiency, as is disclosed in Fig.A4.1 that the CPCC in the DCTSE is slightly higher than that in CTSE. Although the energy efficiency of coal for thermal power under the differentiated carbon is lower than that under the uniform carbon tax, it remains has higher cost

competitiveness than REs and is thus consumed more.

This finding about the environmental performance of the differentiated carbon tax is different from existing studies including (Liu et al., (2022)), in which more sectoral carbon emissions are yielded from energy-intensive industries under the differentiated carbon tax than the uniform carbon tax except for the steel and petroleum refinery industry. As is shown in Fig.4.5 that more sectoral carbon emission in CTSE than that in the DCTSE, which can be explained by the less cost-competitiveness of REs than thermal power under the differentiated carbon tax. For most of the studied energy-intensive industries, the increasing carbon emission contributes most to the CP reduction. However, this statement is not applicable to the Petroleum refinery industry and the Steel industry, in which the CP variations are dominated by the economic performance of the differentiated carbon tax rather than its environmental performance. For the Petroleum refinery industry, the increasing carbon emission does not reduce but increases its CP, on the ground that the higher-cost competitiveness of coal incentivizes the technological development of petroleum, as a reflection of its increased industrial output. For the Steel industry, its reduced carbon emission fails to improve its CP. The reason behind it is that electrifying machinery for REs consumption would reduce its carbon emissions but dramatically increase the cost, which cannot be offset by the REs-related subsidy from the differentiated carbon tax revenue (Toktarova et al., 2022).

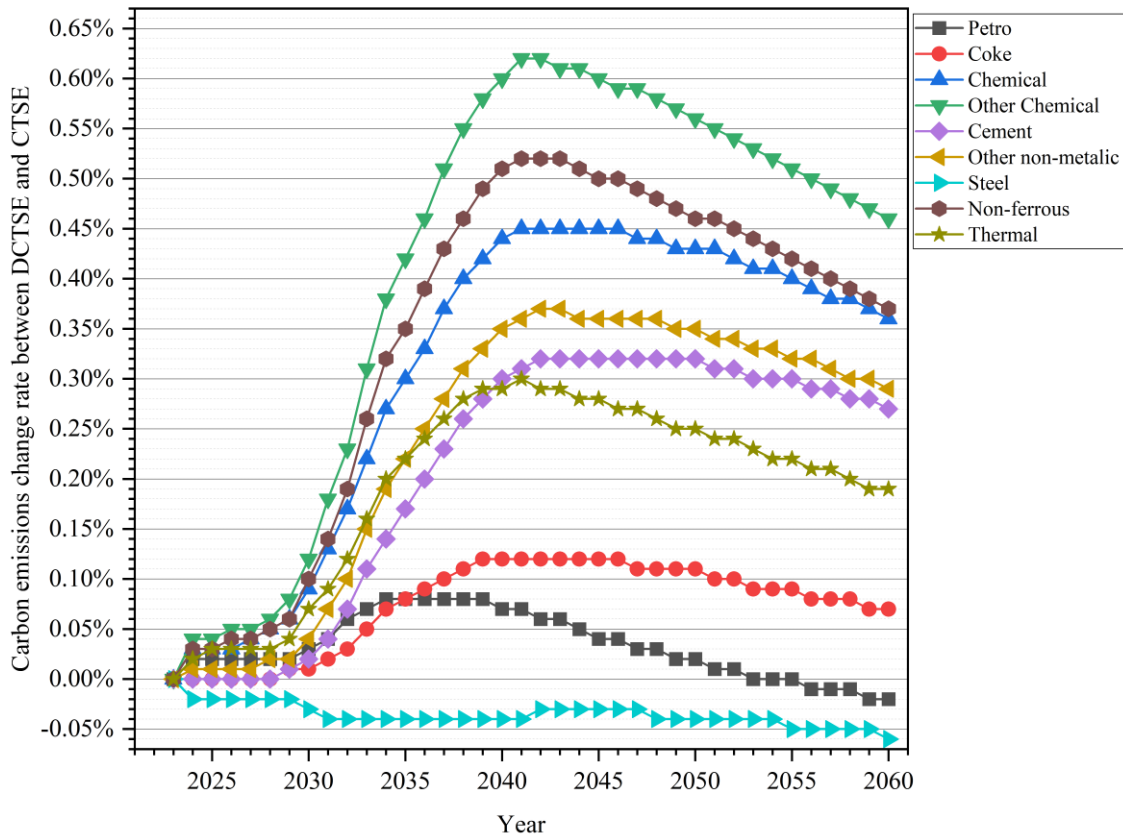


Figure. 4.5: The change rate of sectoral carbon emission in DCTSE compared to CTSE

Moreover, the economic and environmental performance of the differentiated carbon tax is worse than that of the uniform carbon tax for most of the studied tech-intensive industries, except for the Transport industry, as shown in Fig.A4.7. Given that thermal power has higher competitiveness than the REs under the differentiated carbon tax and it's resulting less REs-storage-based subsidy, it is more cost-effective for the tech-intensive industry to rely on thermal power in its electrification rather than REs. In this regard, CP falling in the tech-intensive industry is mainly attributed to the increasing carbon emissions from thermal power consumption. As for the exception of the Transport industry, the lower carbon tax in the DCTSE can further magnify the overwhelming advantage of internal combustion engine vehicles over electric vehicles at this stage and can impose a positive effect on both reducing carbon emission and increasing industrial outputs.

To summarize the economic and environmental performance of the differentiated carbon tax in comparison with the uniform carbon tax, it could be found that the performance of the uniform carbon tax is better than the differentiated one on the CP of the studied energy-intensive industries, tech-intensive industries, and tertiary industries. Even though the differentiated carbon tax in DCTSE is levied more strictly and heavier on the energy-intensive industry than on the tech-intensive and tertiary industries, it remains to generate similar results in reducing their CP. It is due to that the lower carbon tax demotivates the energy efficiency improvement of high-tech and tertiary industry, which is indirectly conducive to increasing the industrial output of some traditional energy-intensive industries, like the Thermal power industry, and result in increasing industrial output in all of these industries. As such, the reduced CP is mostly owing to more carbon emissions from the increasing consumption of less efficient thermal power. It is rooted cause that the LBD of REs weaken and is thereby less competitive than the thermal power under the less REs-related subsidy from the differentiated carbon tax revenue.

4.5.5 All scenarios comparison

Rather than assessing the overall economic and environmental performance of the carbon tax, Fig.4.6 shows the respective economic and environmental performance of the carbon tax in different forms and under different situations.

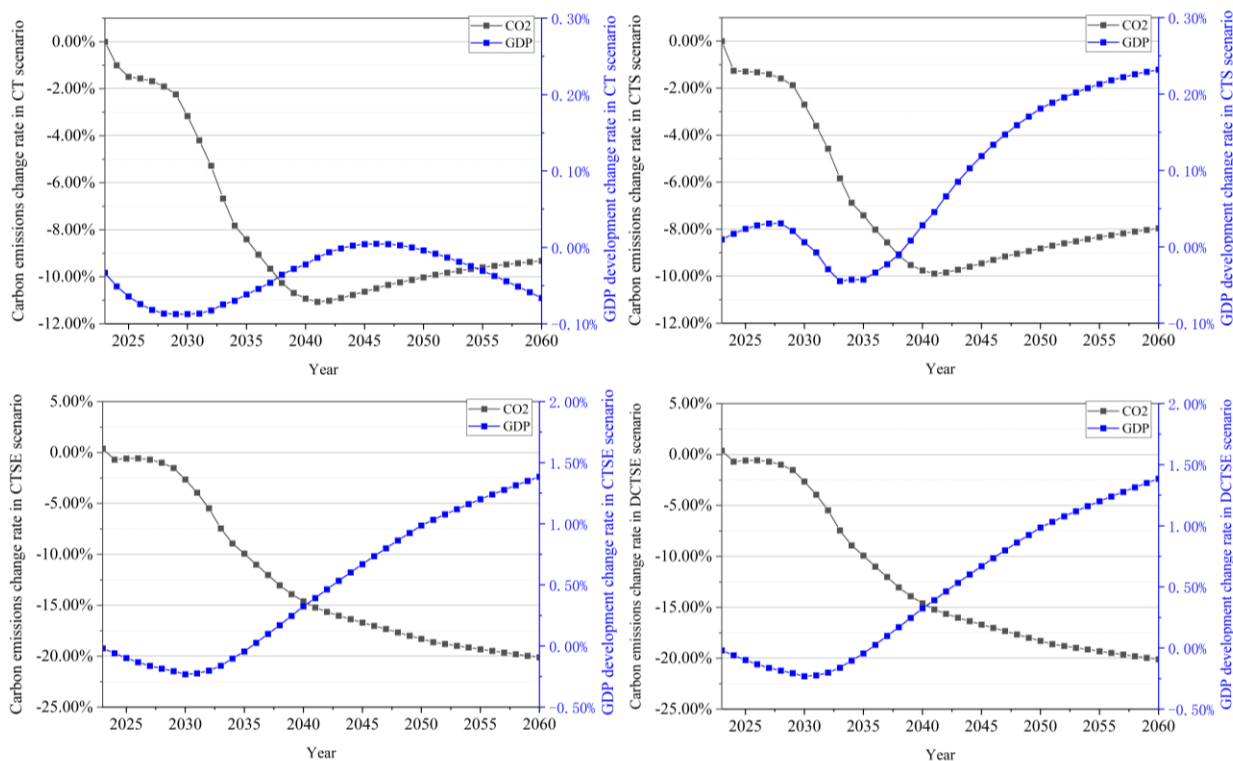


Figure 4.6: The change rates of GDP and carbon emissions in CT, CTS, CTSE and DCTSE scenarios compared with BaU

Table 4.10: Non-fossil fuel consumption ratio and REs generation under the differentiated carbon compared with that under the uniform carbon tax

	2030	2040	2050	2060
Non-fossil fuel consumption ratio	-0.002%	-0.002%	0.004%	0.008%
REs Generation	0.027%	0.095%	0.086%	0.074%
GDP	0.002%	0.015%	0.003%	-0.006%
Carbon emission	0.067%	0.291%	0.239%	0.177%

Note: Non-fossil fuel consumption ratio comparison is the difference between DCTSE and CTSE. RE generation is the sum of solar and power generation growth in DCTSE compared to CTSE.

In terms of the environmental performance of the carbon tax, the uniform carbon tax itself has a positive effect on reducing carbon emissions. Such a positive effect is subtle at an initial stage and becomes most significant in the medium stage then stabilizes and slightly weakens in the long run. On this basis, the economic performance of the uniform carbon tax tends to be worse under the implementation of the REs-storage-based subsidy but it would be significantly improved with electrification introduced in industry. Based on the scenario design that the REs-storage-based subsidy is sourced from the carbon tax revenue and the electrification mandatorily promoted in the industry, the reduced carbon emission under the differentiated carbon tax tends to be slightly lower than that under the uniform carbon tax. The worse environmental performance of the differentiated carbon tax is owing that a lower carbon tax for the tech-intensive and tertiary industries, (1) demotivates industries to improve energy efficiency, (2) creates an environment for them to increase industrial outputs, (3) results in less subsidy for installing the REs storage capacity and weaken the LBD effect of the REs.

In terms of the economic performance of the carbon tax, the uniform carbon tax itself has a varying impact on GDP growth in China over time, but such an impact is not significant. Its impact on GDP growth evolves from negative initially to none in the medium stage and then to negative again in the long term. Based on this, the introduction of the REs-storage-based subsidy can to a certain degree improve the economic performance of the uniform carbon tax. Moreover, its positive impact on GDP growth would be continually intensified in the medium and long term. Furthermore, with the promotion of electrification in the industry, the trajectory of the GDP change rate tends to fluctuate more pronouncedly. Specifically, the impact of the uniform carbon tax on GDP growth would be significantly negative at the starting point but such a condition would not last long, as it would be converted to positive with its positive effect becoming more significant exponentially over time. Comparing the economic performance of the uniform carbon tax with the differentiated carbon tax under the promotion of the REs-related subsidy and electrification, it is

observed that their impacts on the GDP growth of China have similar variation trajectories. Comparatively, the differentiated carbon tax has better economic performance on GDP growth at the initial and medium stages but the advantage of the uniform carbon tax become gradually distinct in the long term due to less increase in sectoral CP. Under the differentiated carbon tax, the total GDP growth is mainly due to more industrial output. Given electrification is mandatorily promoted in the industry, the increasing industrial output should be essentially supported by more electricity consumption. As the result in Table.4.10, the differentiated carbon tax is more effective than the uniform carbon tax in promoting the energy-consumption pattern from the fossil-fuel-dominant to electricity-based under the trend of electrification. It should be recognized as a strategy to levy less carbon tax from the tech-intensive and tertiary industries to prior promote their industrial output then indirectly increase the industrial output of some energy-intensive industry, and thereby speed up their transit into the electricity-reliance.

Therefore, despite that the differentiated carbon tax always has worse environmental performance in reducing carbon emissions and only has better economic performance in promoting GDP growth at the initial and medium phases, it should remain to serve as a strategy for China's energy structural transition, on the ground that it is more effective in increasing electricity consumption and correspondingly reducing fossil fuel reliance in the medium and long term.

4.6 Conclusion

This paper examines and comparing the economic and environmental performance of the carbon tax in different stringency and different situations, with the aim of figuring out their impacts on energy structural transition and economic growth in China via evaluation of sectoral CP and energy efficiency improvement. The differentiated carbon tax hastened by enlargement of Chinese national carbon emission market is designed to follow the principle of environmental prior, as the carbon tax levied on the tech-intensive and tertiary industries that is looser than that on the

energy-intensive industry. Moreover, this paper has its novelty in the scenario design, as it fully considers the demand side and the supply side and their interactive relationship under the policy intervention.

The first is that the economic and environmental performance of the carbon tax for the energy-intensive industry would be significantly impacted by the policy environment and the exogenous development trend, including the REs-related subsidy and electrification. Confirming the finding from the existing literature, the carbon tax in either uniform or differentiated form, tends to exert a negative impact on the CP of the energy-intensive industry, on the ground that it would be adverse to GDP growth even though it can reduce carbon emissions. The overall economic and environmental performance of the carbon tax can be improved with the introduction of the REs-storage-based subsidy. By stimulating the LBD effect of the REs and REs storage, the subsidy can increase the penetration of REs in the electricity market. As a result, it can lead to GDP growth being higher but reduced carbon emissions being lower than in the no subsidy situation. On the basis of the REs-related subsidy introduced, the promotion of electrification in the industry tends to worsen the initial economic and environmental performance of the carbon tax initially but significantly improve its overall performance in the medium and long term.

The second is that the economic and environmental performance of the uniform carbon tax is different between the energy-intensive industry and the tech-intensive industry. Without the exogenous development trend, the effect of the uniform carbon tax is always negative on the mostly studied energy-intensive industries but transit from initially negative to positive in the medium and long term on the mostly studied tech-intensive industries. Under the introduction of REs-storage-based subsidy, the economic and environmental performance of the uniform carbon tax tends to be generally better for the energy-intensive industry than the tech-intensive industry. On this basis, with the promotion of electrification in the industry, the impact of the uniform carbon tax on the CP of the studied energy-intensive industries becomes dichotomized, as its impact is negative on the CP of the Coke industry and the Petro industry, but positive on the CP of other

studied energy-intensive industry. But such an impact is non-dichotomized on the studied technology-intensive industries, as it tends to be positive on most of them.

The third is that it is the comparative advantage of the differentiated carbon tax to speed up the energy structural transition in the medium and long term, compared with the uniform carbon tax. Under the introduction of REs-related subsidy and electrification in industry, it would be found that the introduction of the uniform carbon tax is conducive to promoting the energy structural transition initially but its performance is worse than the differentiated carbon tax in the medium and long term. In terms of the overall economic and environmental performance of the energy-intensive industry, the uniform carbon tax is always better than the differentiated carbon tax since stricter carbon tax guarantees more green innovation and energy efficiency, which leads to higher sectoral CP and less sectoral carbon emission. In this process, the uniform carbon tax always has a more significant positive on carbon emission reduction, but its economic performance is worse in the initial and medium stages and gradually becomes better in the long term. As for the differentiated carbon tax, it inflicts more carbon emissions but with less GDP growth which are led by less improved energy efficiency due to loose restriction in long term. In short, the introduction of the differentiated carbon tax has some comparative advantages to the uniform carbon tax, as it is conducive to accelerating the energy structural transition in the medium and long term.

The conclusions at a large level disclose the intricate relationship among carbon tax, sectoral CP, REs-related subsidy, electrification, and LBD of REs. The impact of the carbon tax on the sectoral CP reflects its economic and environmental performance. This overall performance is generated on the basis of its effect on energy efficiency improvement. The increasing carbon tax can stimulate the energy-intensive industry to improve energy efficiency and thus reduce carbon emissions but at an enormous cost of its economic gain initially, and such a cost could be eliminated with time. Financially sourced from the carbon tax revenue, the higher subsidy for the REs storage can more effectively motivate the LBD effect of REs. The promotion of electrification

in the industry can increase electricity consumption and further exert the LBD effect on the REs development, with capacity increasing and thereby cost reduction. With the improving LBD of REs, the sectoral CP tends to be increased accordingly on the ground that the industry can gain sufficient clean energy at a lower cost. Furthermore, environmental policy stringency affects overall economic and environmental performances that looser carbon tax on high-tech and tertiary industries shows lower CP and energy efficiency improvement, thereby more sectoral carbon emission compared to uniform carbon tax .

In addition, this paper might provide insights for policymakers to implement national carbon emission trading scheme in energy-intensive industries that environment-based differentiated carbon pricing partly ensures both economic and environmental indicators for local government if all energy-intensive industries are entitled to achieve carbon emission under control of central government.

Appendix

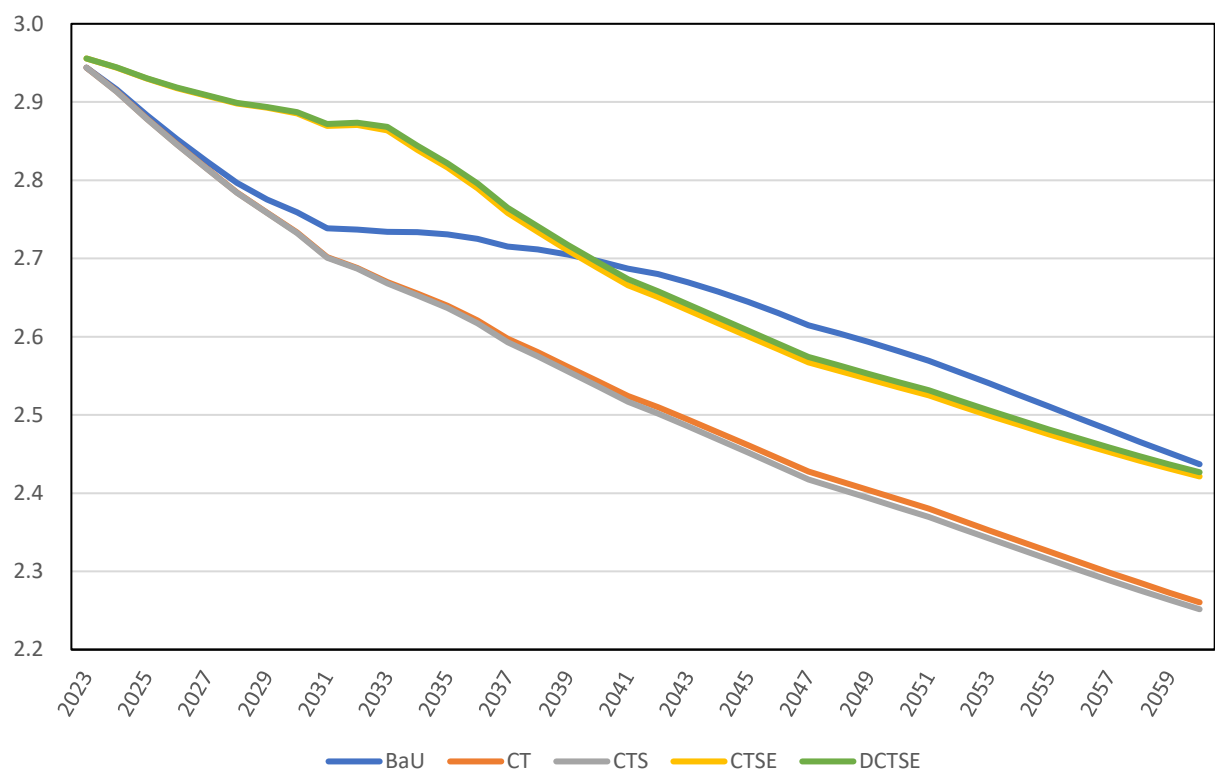


Figure. A4.1: Coal-power conversion coefficient (CPCC) of thermal power in the designed scenarios

Unit: 100g/Kwh

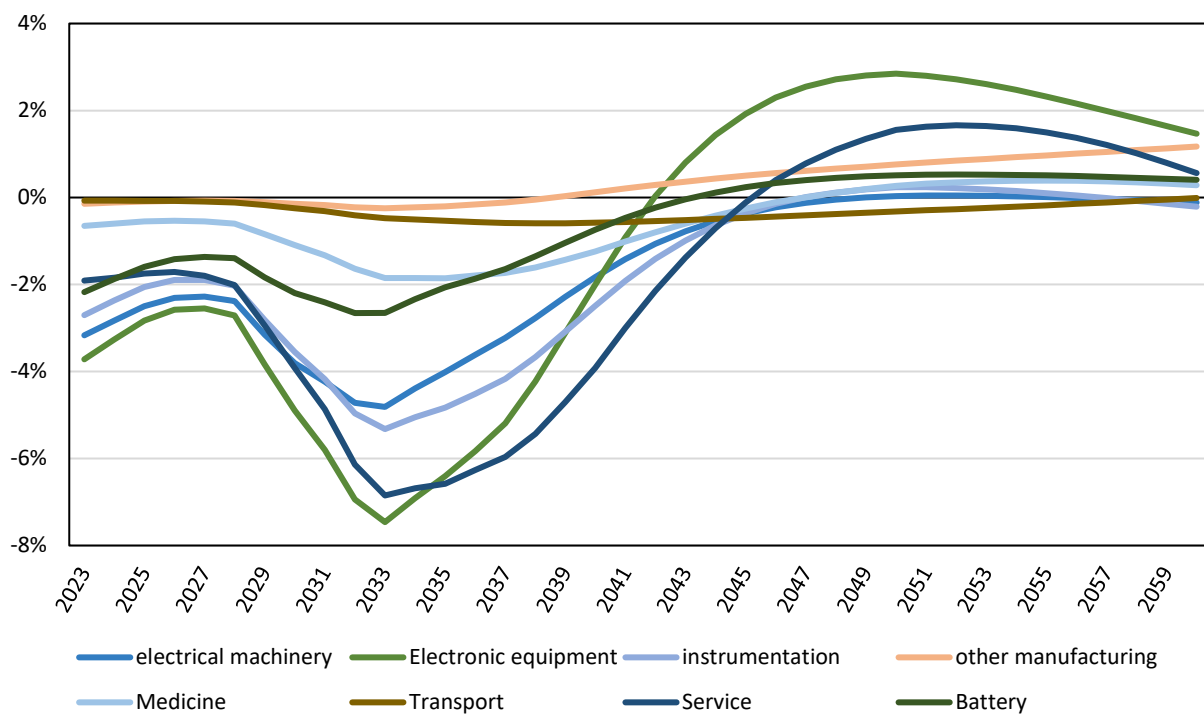


Figure. A4.2: The change rate of sectoral CP in CT compared with BaU about the tech-intensive industry and tertiary industry

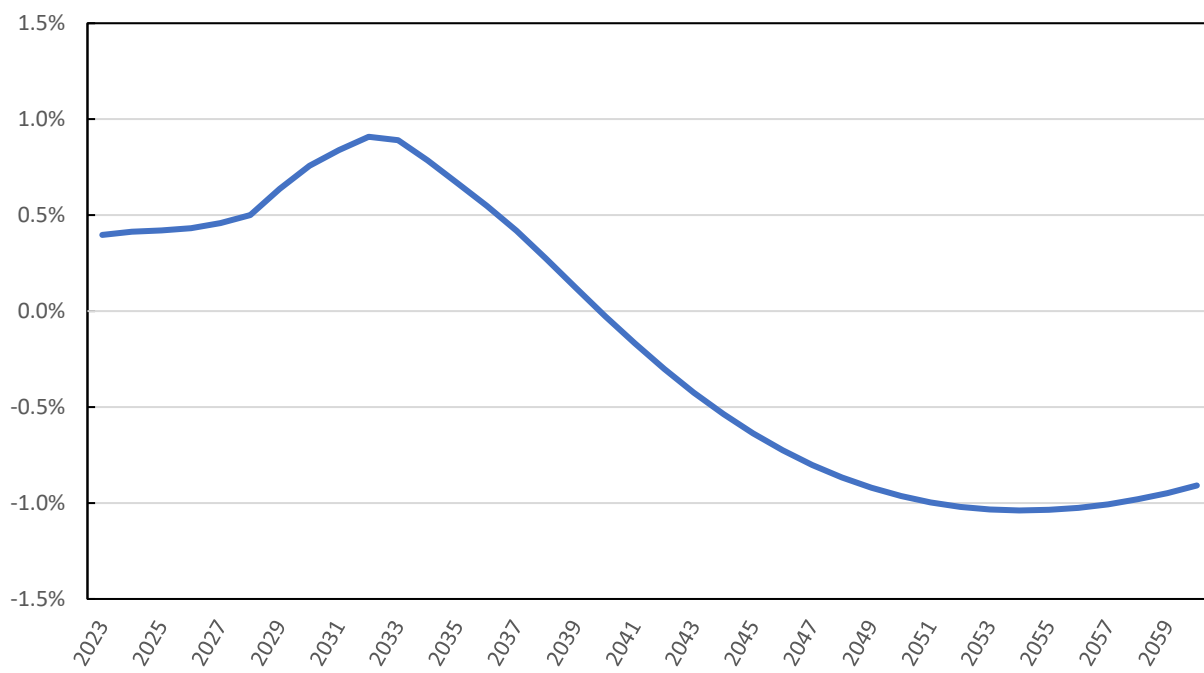


Figure. A4.3: The change rate of electricity price in CTS compared to CT about tech-intensive and tertiary industry

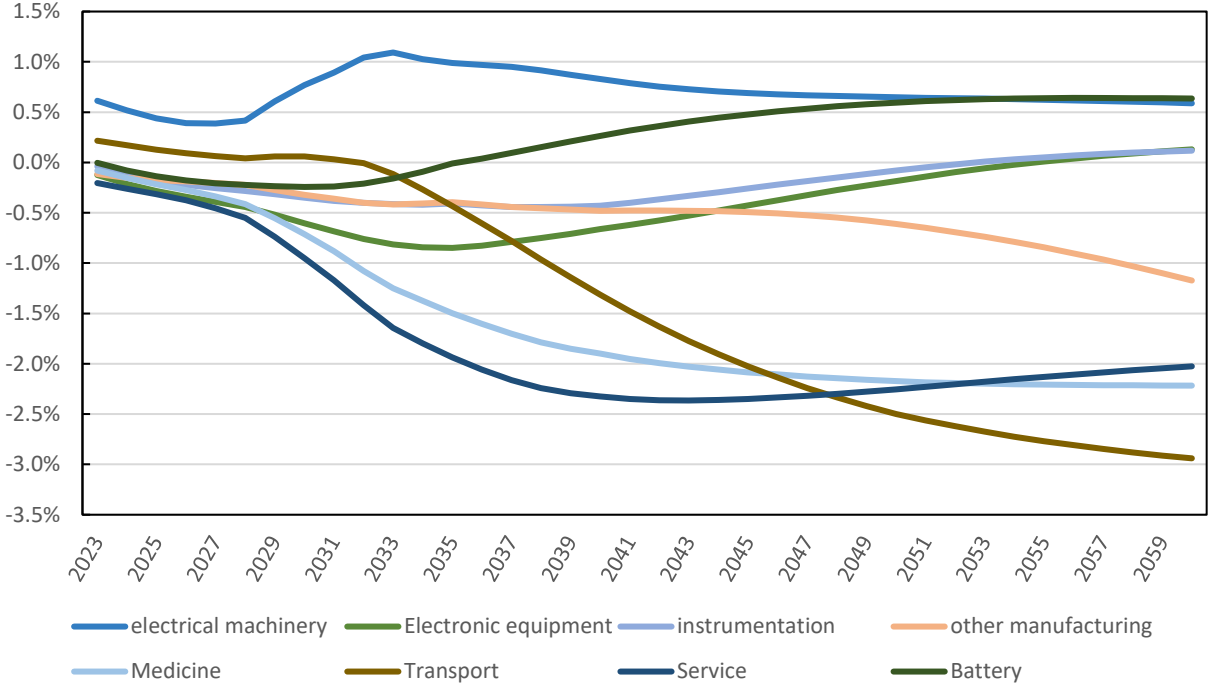


Figure. A4.4: The change rate of sectoral CP in CTS compared with CT about tech-intensive industry and the tertiary industry

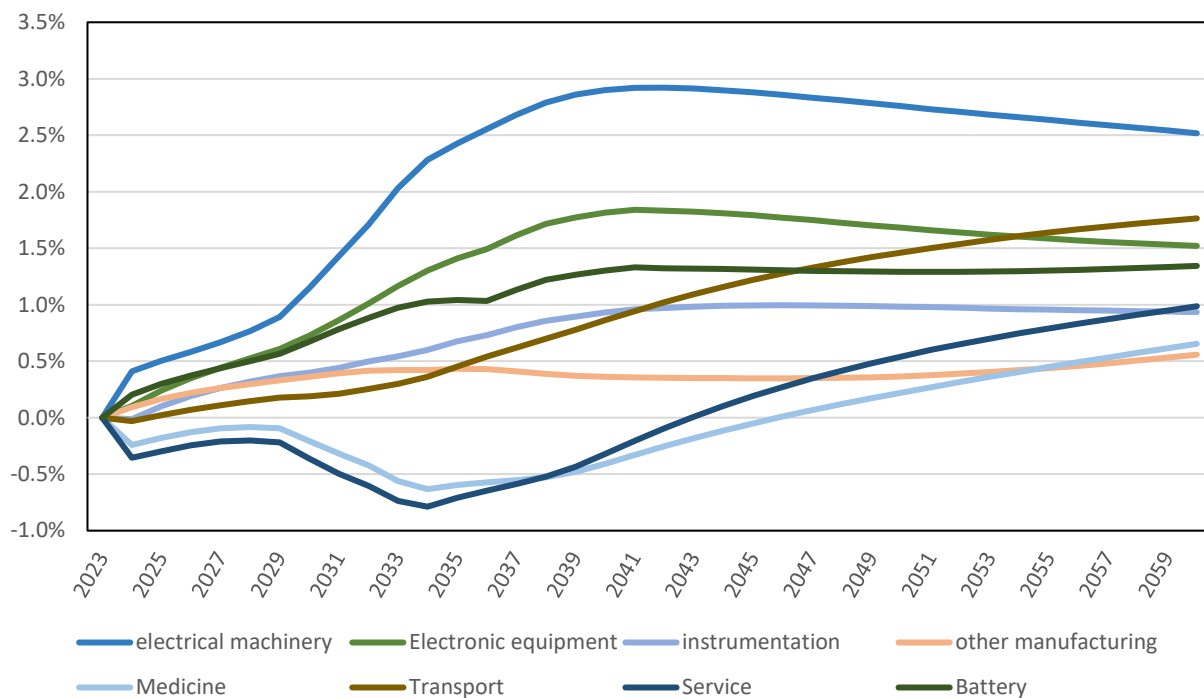


Figure. A4.5: The change rate of sectoral carbon emissions in CTS compared with CT about the tech-intensive industry and the tertiary industry

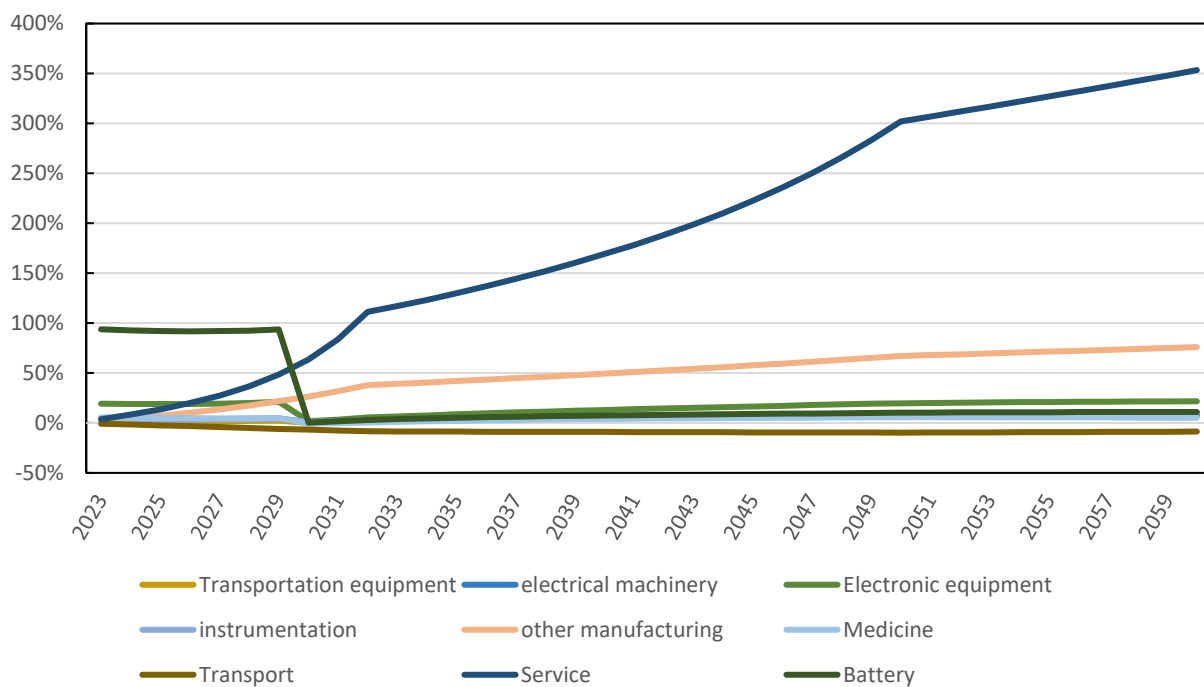


Figure. A4.6: The change rate of sectoral CP in CTSE compared with CTS about the tech-intensive

industry and the tertiary industry

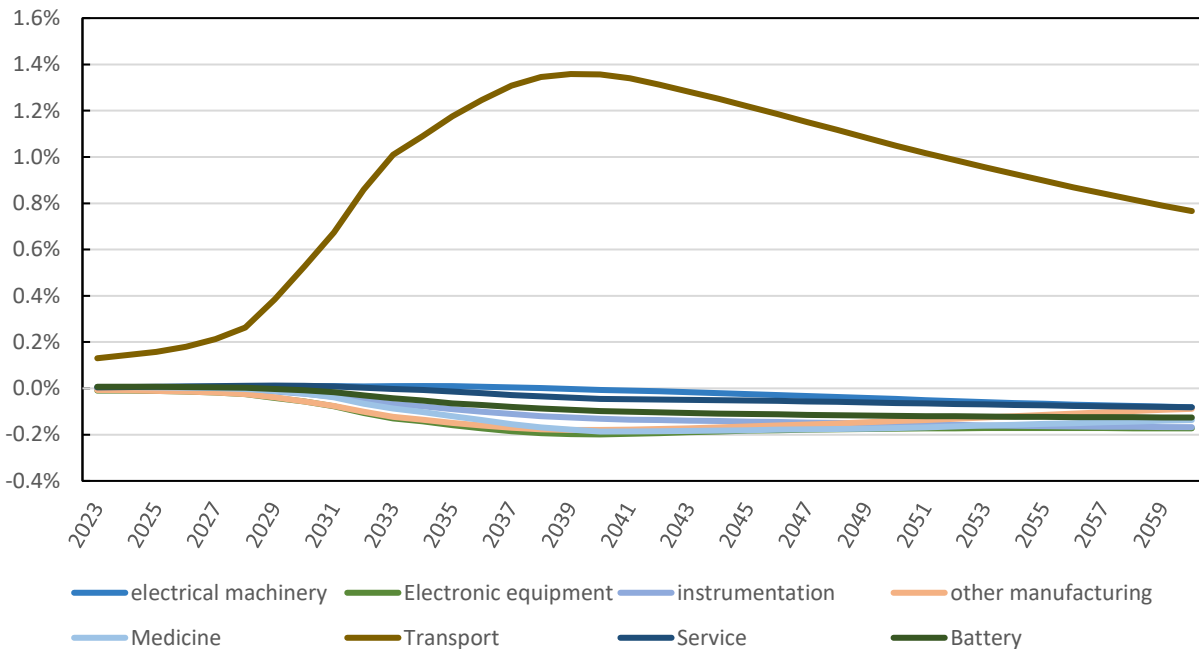


Figure. A4.7: The change rate of sectoral CP in DCTSE compared with CTSE about the tech-intensive industry and the tertiary industry

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Chapter 5 Conclusion

My results reveal that the endogenous improved RE with environmental policies facilitates energy structural transition, which offsets the negative impact of carbon tax. The energy impossible trinity (EIT) is gradually solved in our models that RE is always more expensive than traditional fossil fuel until LBD effect significantly functions in long term in **Chapter 2**. The **Chapter 3** and **Chapter 4**, we further discuss the sustainability of RE that storage becomes necessary as more RE takes more market share in electricity market. The contribution of this study is: 1) through empirical examination, LBD of RE can offset the GDP loss caused by carbon pricing in the case of China. 2) storage is an unignorable factor in RE development which greatly relies on demand-side regulation to accelerates the LBD for green energy transition at low cost. 3) Studying further about sectoral impacts, energy efficiency improved by stricter carbon tax in the context of China can be more efficient for environmental protection but slight GDP loss, comparing to industrial-differentiated carbon tax.

Chapter 2 applies bottom-up LBD module with a top-down CGE model to investigation of offsets effect induced by improved RE on carbon tax. The LBD effect on RE weakly offsets negative impact brought by carbon tax on industries. However, higher carbon tax covers more GDP loss with less carbon emission even it is a single carbon tax implementation. The single carbon tax slightly increases non-fossil fuel energy consumption ratio though carbon tax exceeds Europe level (at 2017 price). While RE is subsidized by carbon tax revenue, the overall economic and environmental performance is far greater than those scenarios with single carbon tax. The non-fossil fuel consumption ratio increases 31.5% in subsidized scenarios compared to single carbon tax scenario. The GDP even increases nearly 1% in scenarios with high carbon tax revenue financing RE subsidies compared to single high carbon scenario which causes GDP loss. The reversed results between two scenarios implies that subsidized RE with severe exit of thermal

power significantly prompts energy structural transition since LBD effect on RE is also enhanced by environmental policies mix.

Chapter 3 studies based on **Chapter 2**, taking RE storage and electrification into consideration. Similar to results of former chapter, the single carbon can only exerts negative impact on economic growth in long term but less than 0.1%. Different from former chapter, the introduction of storage leads to intricate impact of subsidy for RE on environmental protection. The subsidy for RE induces 0.2% GDP gain but also 0.12 billion tons of carbon emission more than single carbon tax scenario. The improved RE leads to markdown on electricity price which leads to increase in industrial output, thereby both growth of GDP and carbon emission. For electrification, we compare single electrification and mixed electrification (carbon tax and subsidy) scenarios. The single electrification leads to significant carbon abatement which is far more than scenarios with demand-side policies, accounting 0.3 billion tons of carbon abatement. While mixed electrification scenario leads to greater carbon abatement than single one, accounting 0.65 billion tons of carbon mitigation. Two scenarios lead to significant GDP growth attributed to accelerated LBD effect, 1.39% for mixed and 1.12% for single one, respectively. However, increase in carbon emission is observed in two scenarios with electrification because thermal power still has overwhelming advantages in short term. Policy-mix always performs better than single one and demand-side regulation is better than supply-side policy in long term.

Chapter 4 further investigates overall impact of two carbon taxes, differentiated and uniform, at industrial level by evaluating sectoral carbon productivity (energy efficiency). The energy efficiency improved by carbon tax at different stringency-level shows results similar to the past studies that stricter (uniform) carbon tax leads to better environmental and economic performance because it improves greater energy efficiency as its sectoral carbon productivity is higher. However, the absolute value of RE power generation is lower than that of looser (differentiated) carbon tax because differentiated carbon encourages more industrial output which leads to more carbon emission. The GDP growth in differentiated carbon tax scenario is slightly lower than that of

uniform carbon because of less energy efficiency improvement. Different from long-term effect, the differentiated carbon tax shows better economic and environmental performance because of less markup on energy. However, such advantage is covered by acceleration of LBD on RE in long term. The differentiated carbon tax is that carbon tax on low-energy consuming industries is two third of that on energy-intensive industries, which is failed to demonstrate significant gap because energy-intensive industries are more susceptible to environmental policies.