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The Technical Impacts of the Carbon Tax in China

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Abstract

Despite the significant impacts of technology on the socioeconomic effects of climate policies, many previous researchers neglected the induced technical impacts and thus resulted in biased evaluations of climate policies. Hence, it is important that the induced technology should be endogenized in the policy evaluation framework. In this paper, I attempt to use a Computable General Equilibrium (CGE) model to quantify the technical impacts of the Chinese carbon tax. The technical impacts are denoted by the induced technological change (ITC), which is a function of the energy-use efficiency (EUE), energy-production efficiency (EPE), and nonenergy-production efficiency (ENE). The carbon tax will increase the energy cost share because the of the internalisation of the abatement costs. This paper empirically shows that the carbon tax will decrease the energy cost share and production efficiency but increase the energy use and nonenergy production efficiency. Overall, the carbon tax will promote the technological development, compared to the baseline scenario. In addition to the policy effects of the tax, the ITC will decrease the energy use and production efficiency but increase the nonenergy production efficiency. The ITC will increase the RGDP, decrease the household welfare, and increase the average social cost of carbon (ASCC). To summarise, despite that the carbon tax will decrease the welfare at the country and household level, the ITC of the carbon tax will increase the welfare at the country level but decrease the welfare at the household level. Under the ITC impacts, the emission abatement will become costlier.

Keywords: ITC; CGE; Technical Impacts; Carbon Tax; China

Introduction

To address the challenges aroused by the accelerating global warming, the United Nation Framework Convention on Climate Change (UNFCCC) emphasises that technological transfers should be an important element in the global action to mitigate the climate change. This is because technology is at the root of the climate change as well as an integral part of the mitigation process (Akhavan and Jabbari 2007). Despite the significant role of technology in relieving the global warming, many previous studies exogenously treated technology in designing climate policies (Popp 2004). The omission of the technological impacts may overestimate the costs of climate policies, because the technological progress can lower the cost of reducing carbon emissions (Fried 2018). Hence, it is important to endogenously model the technical impacts in the evaluation of climate policies (Baker and Shittu 2008).

The endogenization of technology has already become popular to cope with the climatic issues (Goulder and Schneider 1999, Goulder and Mathai 2000, van der Zwaan, Gerlagh et al. 2002). Previous researchers tend to use the induced technological change (ITC) to denote the technical impacts. As the ITC warrants earlier investments in the non-fossil carbon-free technology (van der Zwaan, Gerlagh et al. 2002), the inclusion of the ITC in modelling the climatic issues may reduce the costs of climate policies (Loschel 2002). The carbon pricing in climate policies may crowd out the intrinsic motivations and voluntary action to reduce emissions (van den Bergh 2013). For example, although the carbon pricing increased the clean invention patents, its effect on the overall R&D was negative (Lin, Wang et al. 2018). In addition to the negative impacts on technical progress, the ITC may have a negative feedback loop. For example, a promotion of the green technology induced by the ITC decreased the carbon price, and thus the fossil fuels would be used more, which would finally erase some stimulus by the ITC (Folster and Nystrom 2010).

Whether climate policies will promote or inhibit technical progress still remain to be seen. In the literature, very few studies considered the technical impacts of climate policies when evaluating the policy effects. Neglecting the ITC impacts tend to result in biased policy evaluations. Among the studies that quantified the ITC impacts of climate policies, Gans (2012) argued that only technologies directly abating the emissions would have an unambiguously positive impact on the technical innovation to enhance the policy effect of the emission reduction. However, the results in Gans (2012) were only based on a single-sector model, which didn't not conform to the multi-sector reality.

This paper contributes to the literature by designing a multi-sector Computable General Equilibrium (CGE) model to evaluate the ITC impacts on the policy effects of the climate policy. This is because a CGE model has many advantages, including the ability to study both national and sectoral mitigation policies (Jacoby, Reilly et al. 2006). Hence, modelling the technical impacts basing on the CGE model will lead to less biased evaluations of climate policies.

Method

Based on the general equilibrium theory of Walras, CGE models derives from the pioneering work of Johansen (1960). In this paper, the CGE model is dynamic recursive as the research period is 2015-2030. In the CGE model, there are two regions (China and the rest of the world) and four economic entities (the representative household, enterprise, foreigner, and government). The social accounting matrix (SAM), shown in Table A1 in Appendix A, of the CGE model is built basing on the 2015 China Input-Output (IO) Table. According to Table A2, there were 42 sectors in the 2015 China IO Table, but only 29 sectors are left through the aggregation and disaggregation process. Noticeably, the heat and electricity production sector is divided into the electricity sector and heat sector. Then the electricity sector is disaggregated into nine subsectors following Lindner, Legault [25]. The electricity disaggregation is necessary because the electricity subsectors exploiting renewables should not be limited by the carbon tax. Appendix C shows the equations denoting the disaggregation of the electricity sector.

1. Production Block

The production block of the CGE model shows the production of the goods within the economic system. The Leontief production function depicts the interrelations between the intermediate inputs and added values, while the constant elasticity of substitution (CES) functions denotes the production relations among the input factors. The elasticity parameters in the CES functions are from Guo, Zhang et al. (2014). How the elasticity parameters affect the model indexes will be assessed by the sensitivity analysis in this paper.

2. Income-Expenditure Block

In this block, the representative household consumes both the domestic and foreign goods, whilst its income source are from the labour, capital, and money transfers. The enterprise's income only comes from the capital factor, but it pays the taxes to the government and sends the money transfer to the household.

3. Government Block

The governmental income only comes from the income tax and carbon tax, but it sends money transfers to the household. As no officially published data of the governmental energy consumption are available, I assume that the government has no energy consumption and thus emissions.

4. Trade Block

In this block, the goods are imported from the foreigner to the household, meanwhile the goods are exported from the enterprise to the foreigner. According to the Armington (1969) assumption, the goods produced in different regions are imperfect substitutes.

5. Dynamic Block

The exogenously determined dynamic variables are the population, price, energy consumption growth rate, output growth rate, and capital accumulation. The projected population will follow the World Population Prospects by the United Nations. The export price will change proportionally to the price projection of the total OECD countries by OECD (2014), whereas the GDP deflator, domestic commodity price, and import price will change proportionally to the price projection of China by OECD (2014). The projected energy consumption growth rate is from the International Energy Outlook by EIA (2017). The output growth of the energy sectors will follow the projected growth of the energy consumption, whilst the output growth of the nonenergy sectors will follow the regional GDP long-term forecast by OECD (2018).

In the CGE policy evaluation framework, the ITC impact of the carbon tax is denoted by the efficiency changes resulting from the changes of the energy cost share (ECS). The rational of modelling the ITC impact is that the carbon tax increases the nonrenewable energy costs and thus changes the energy input, which finally affects the production functions of the CGE model.

In this paper, the quantification of the ITC impacts is based on Wang, Saunders et al. (2019) who studied the relation between the ECS and efficiencies. In the reality, the efficiency changes can be achieved by the R&D investment, which is influenced by the scale effect. For example, if the carbon tax increases the consumption costs of nonrenewable energy, the nonrenewable energy production will become less attractive, and thus resources will be shifted away from nonrenewable energy sectors. Consequently, the R&D investment in nonrenewable energy sectors will decrease, and thus the energy production efficiency will also decrease. Noticeable, the ITC in Wang, Saunders et al. (2019) were mainly the potential changes of the energy-saving technologies, but they excluded the induced development of the decarbonisation or clean energies. Hence, the ITC quantified in this paper may underestimate the technical impacts in the real world.

Wang, Saunders et al. (2019) endogenously determined the energy price, and the technical index was determined by the historical data using simple loglinear functions. In contrast, the energy price is exogenously determined in this paper according to OECD (2014), and the future technical index is endogenously determined by the CGE model.

According to Wang, Saunders et al. (2019), the real GDP (RGDP) is as a constant-elasticity-of-substitution (CES) production function of the energy and nonenergy goods, shown in Eq. (1). The subscript t refers to the year; $RGDP_t$ is the real GDP; $NONEN_t$ is the nonenergy goods; EUE_t denotes the energy-use efficiency; TEC_t is the total energy consumption. In Eq. (1), the nonenergy-use efficiency is assumed to be one. σ is the elasticity of substitution between the energy and non-energy goods, and its centralised value is 0.4 given by Wang, Saunders et al. (2019).

$$RGDP_t = \left[(EUE_t \times TEC_t)^{\frac{\sigma-1}{\sigma}} + NONEN_t^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \tag{1}$$

$$ECS_t = \frac{\sum_i \sum_k (PE_{ikt} \times EC_{ikt})}{RGDP_t} \tag{2}$$

The energy cost share (ECS) is defined in Eq. (2), where the subscript i and k denote a sector and energy respectively. EC_{ikt} is the sectoral energy consumption; ECS_t is the total energy cost share; PE_{ikt} is the energy price. The energy price in 2015-2018 are from the online open source (shown in Table A3-A6 in Appendix A). As far as I am concerned, the predicted price in 2019-2030 is currently unavailable. Hence, the future energy price, except for the electricity price, is assumed to change proportionally to the 2018 energy price based on the price projection by OECD (2014). The future electricity price will change proportionally to the 2019 electricity price in OECD (2014).

$$EUE_t = ECS_t^{\frac{\sigma-1}{\sigma}} \times \frac{RGDP_t}{TEC_t} \tag{3}$$

The energy-use efficiency (EUE) is defined in Eq. (3), different from Wang, Saunders et al. (2019) who defined the EUE based on the historical data. Wang, Saunders et al. (2019) implicitly assumed that the consumption goods equal the production goods, which implies that the consumption of the imported goods is equal to the production of the export goods. In the reality, this assumption is seldom met in the open economy. By comparison, I assume that the ECS in the consumption goods is the same as that in the production goods. In Eq. (3), the exponent is always negative because the elasticity parameter σ is always less than one. Hence, the EUE is negatively correlated with the ECS, and thus the increase of the ECS will decrease the EUE. This correlation is contrary to Wang, Saunders et al. (2019) who defined the EUE as a loglinear function of the ECS with a positive slope.

Eq. (4) and (5) define the energy and nonenergy production goods respectively. The subscript e and ne refer to an energy sector and nonenergy sector respectively. QM_{it} and QE_{it} denote the sectoral import and export respectively. $TEPC_t$ and $NONEP_t$ denote the total energy and nonenergy production goods respectively. $SGDP_{et}$ and $SGDP_{ne,t}$ denote the output of the energy and nonenergy sector respectively.

$$\frac{TEPC_t}{TEC_t} = \frac{\sum_e SGDP_{et}}{\sum_e SGDP_{et} + \sum_e QM_{et} - \sum_e QE_{et}} \tag{4}$$

$$\frac{NONEP_t}{NONEN_t} = \frac{\sum_{ne} SGDP_{ne,t}}{\sum_{ne} SGDP_{ne,t} + \sum_{ne} QM_{ne,t} - \sum_{ne} QE_{ne,t}} \tag{5}$$

Eq. (6) and (7) denote the definition of the energy-production efficiency (EPE) and the nonenergy-production efficiency (ENE) respectively. I assume that the EPE and ENE in all the sectors are equal to the national level. Based on the definitions of the EUE, EPE and ENE, the technical index is defined in Eq. (8), according to Wang, Saunders et al. (2019). TI_t denotes the technical index.

$$EPE_t = \frac{TEPC_t}{RGDP_t \times ECS_t} = \frac{TEC_t}{RGDP_t \times ECS_t} \times \frac{\sum_e SGDP_{et}}{\sum_e SGDP_{et} + \sum_e QM_{et} - \sum_e QE_{et}} \tag{6}$$

$$ENE_t = \frac{NONEP_t}{RGDP_t \times (1 - ECS_t)} = \frac{NONEN_t}{RGDP_t \times (1 - ECS_t)} \times \frac{\sum_{ne} SGDP_{ne,t}}{\sum_{ne} SGDP_{ne,t} + \sum_{ne} QM_{ne,t} - \sum_{ne} QE_{ne,t}} \tag{7}$$

$$TI_t = \left[(EUE_t \times EPE_t)^{\sigma-1} + ENE_t{}^{\sigma-1}\right]^{\frac{1}{\sigma-1}} \tag{8}$$

The carbon tax is supposed to change the ECS and thus affects the EUE, EPE and ENE. The ECS in the tax scenarios is defined in Eq. (9), where the superscript * stands for the tax scenarios. Λ_t is the abatement costs, and its value is calculated using Eq. (10). $\theta_{1t} = 0.0741 \times 0.0904^{t-1}$ and $\theta_2 = 2.6$ are from the DICE model by Nordhaus (2018). μ_t is the proportion of the emission reduction, and its value is zero in the baseline scenario. Because of the abatement costs, the ECS in the tax scenarios is always larger than that in the baseline scenario.

$$ECS_t^* = \frac{\sum_i \sum_k (PE_{ikt} \times EC_{ikt}^*) + \Lambda_t}{RGDP_t^*} \tag{9}$$

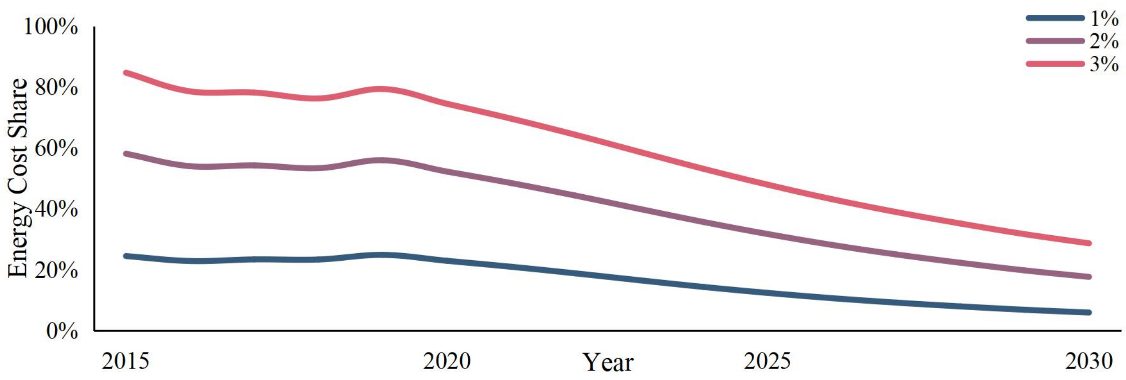
$$\Lambda_t = \theta_{1t} \times \mu_t{}^{\theta_2} \tag{10}$$

The internalisation of the abatement costs increases the costs of the energy consumption. Wang, Saunders et al. (2019) argued that increasing the energy costs might enhance the technical progress because the increasing costs could accelerate the development of renewable energy and induce the energy-saving efficiency improvements. Nonetheless, Wang, Saunders et al. (2019) neglected the negative impacts of increasing the costs on the technical progress. Because the energy goods become more expensive under the imposition of the tax, more resources may be shifted to the nonenergy or renewable energy sectors. However, the impacts of this resource shift cannot be modelled in Wang, Saunders et al. (2019). The resource shift is modelled in this paper: as more resources may be shifted away, the nonrenewable energy sectors may spend less funds on the R&D, and thus the EUE and EPE may decrease. Hence, a change in the energy cost share will finally change the technical index.

Finally, a sensitivity analysis is conducted where all the elasticity parameters are assumed to change between -50% and 50%. In the range of ±50%, the inputs in some sectors may turn from poor (good) substitutes to good (poor) substitutes (Lu and Stern 2016). In general, the low (high) elasticity parameters imply that the economy is flexible (stringent).

In the results section, to analyse the ITC impact on the model equilibrium, I compare the results of the CGE model including the technical impacts with the one excluding the impacts. In the baseline scenario, there are no result differences between the two models; however, considering the socioeconomic impacts of the ITC will change the model equilibrium under the carbon tax.

Results



Note: 1%, 2%, and 3% refer to the 1%, 2%, and 3% tax scenarios respectively

Fig. 1 The ITC Impact on the Energy Cost Share (ECS)

Fig. B1 in Appendix B shows the tax effect on the ECS. The carbon tax will decrease the ECS. This is because the tax will decrease the amount of energy consumption despite that it will increase the energy price. Nevertheless, Fig. 1 shows that the ITC will increase the ECS, because of the internalisation of the abatement costs. This ITC impact will increase as the tax rate rises; however, it will fluctuate in 2015-2020 but decline steadily in 2020-2030. This finding complies with Diaz and Puch (2019) who argued that if the energy became scarcer under the imposition of the tax, the energy share would rise owing to the price increase.

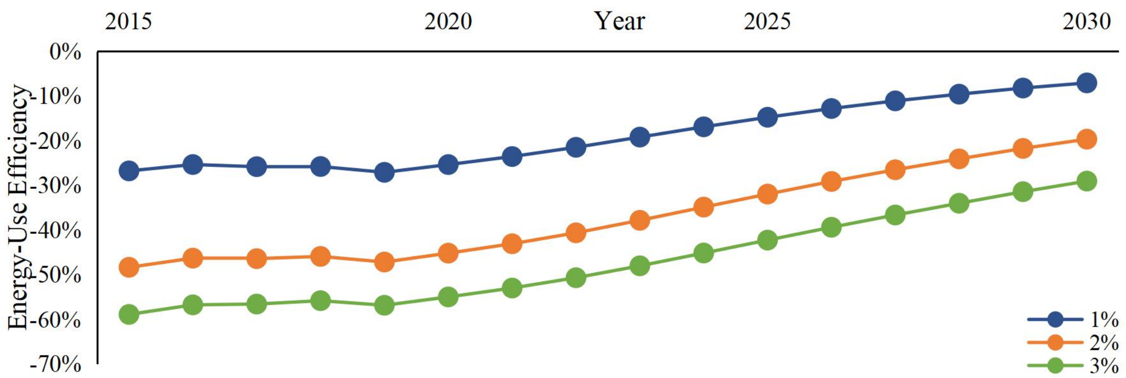


Fig. 2 The ITC Impact on the Energy-Use Efficiency (EUE)

According to Fig. B2 in Appendix B, the carbon tax will significantly increase the EUE compared to the baseline scenario. This is because the carbon tax decreases the amount of energy to be consumed, and thus a rational entity has an incentive to use the limited amount of energy more efficiently. Nevertheless, Fig. 2 shows that the ITC of the carbon tax will significantly decrease the EUE. The economic intuition underlying this result is that the carbon tax will shift the resources toward the nonenergy sectors, and thus the EUE will decrease because of the scale effect. According to Fig. 2, the ITC impact on the EUE will be strengthened as the tax rate increases; however, it will decrease gradually in 2020-2030.

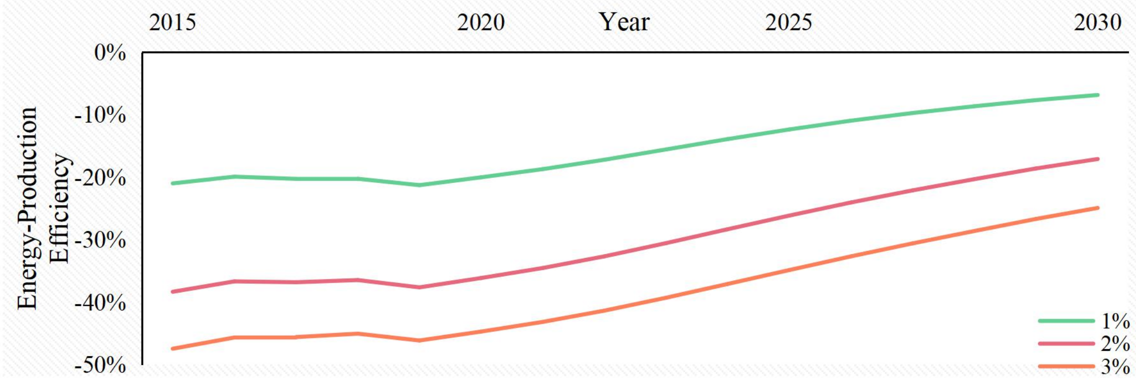


Fig. 3 The ITC Impact on the Energy-Production Efficiency (EPE)

Fig. B3 in Appendix B shows that the carbon tax will slightly decrease the EPE, compared to the baseline scenario. This is because the tax will increase the production costs of the energy sectors, and thus more resources will be shifted away, thereby reducing the R&D in energy production, according to Gerlagh (2008) who developed an endogenous growth model to measure the accumulated innovations globally in 1970–2000. In addition, Fig. 3 shows that the ITC of the carbon tax will significantly decrease the EPE. This is because the tax will increase the production costs of the nonrenewable energy sectors. Hence, more resources will be shifted away from these sectors, their output efficiency is likely to decrease considering the scale effect.

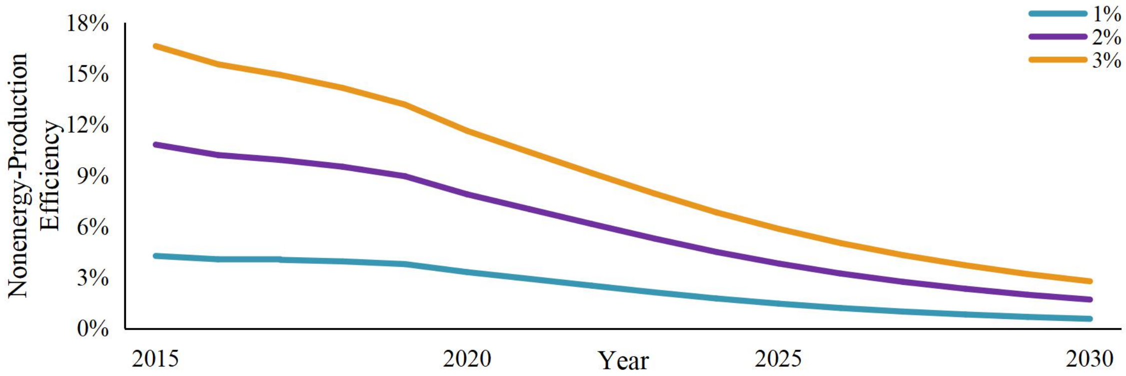


Fig. 4 The ITC Impact on the Nonenergy-Production Efficiency (ENE)

Fig. B4 shows in Appendix B shows the carbon tax will increase the ENE. This is because the carbon tax will reduce the competitivity of the nonrenewable energy sectors, which results in the transfer of the social capital towards the nonenergy sectors (Chen, Zhou et al. 2017). According to Fig. 4, the ITC of the tax will slightly increase the ENE. This ITC impact will rise as the tax rate increases, but it will decrease over time. The magnitude of the ITC impact on the ENE is smaller than that on the EUE and EPE.

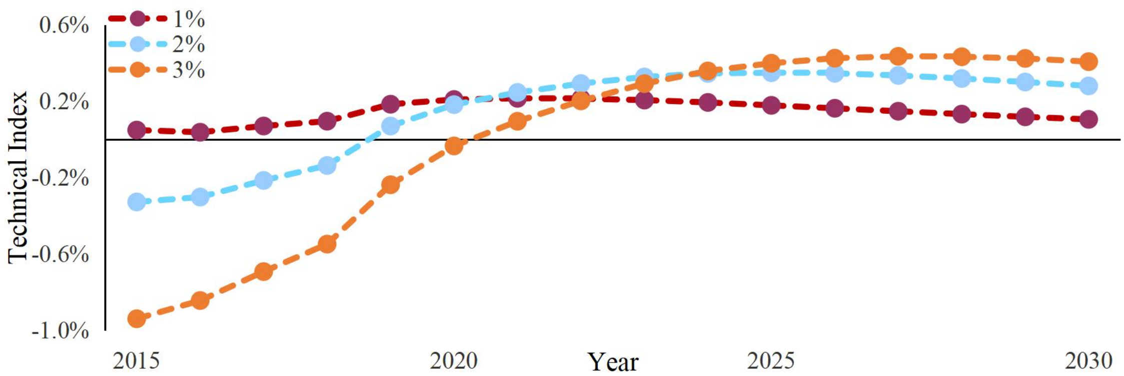


Fig. 5 The ITC Impact on the Technical Index

Fig. B5 in Appendix B shows that the carbon tax will increase the technical index, implying that the carbon tax will promote technical progress over the research period. In contrast, Fig. 5 shows that the ITC will slightly increase the technical index at the 1% tax over time. However, it had a negative impact recently at the 2% tax and 3% tax, but the ITC will increase the index since 2021.

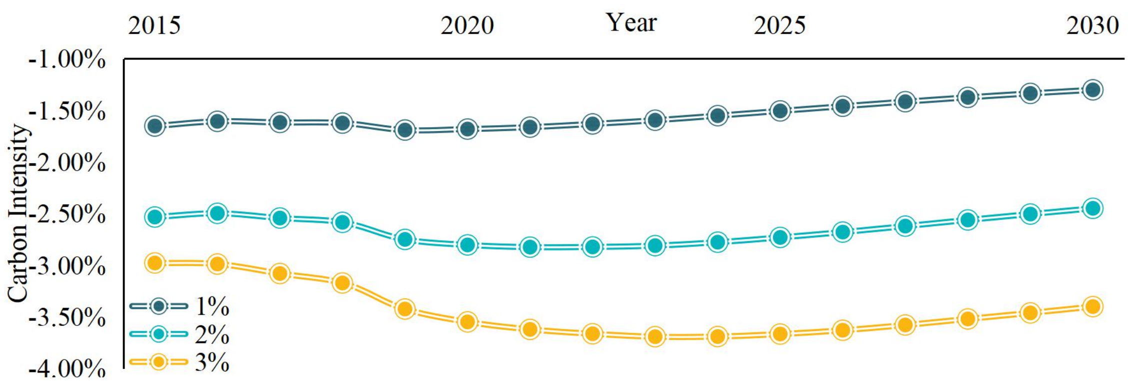


Fig. 6 The ITC Impact on the Carbon Intensity

Fig. 6 shows how the carbon intensity will change under the ITC impact. According to Fig. 6, the ITC will negatively affect the CI. When the tax rate increases, this ITC impact will be strengthened but will fluctuate over time. However, the ITC impact on the carbon intensity is not distinct. This finding agrees with Nordhaus (2002) who argued that the ITC had a modest impact on the reduction of the carbon intensity.

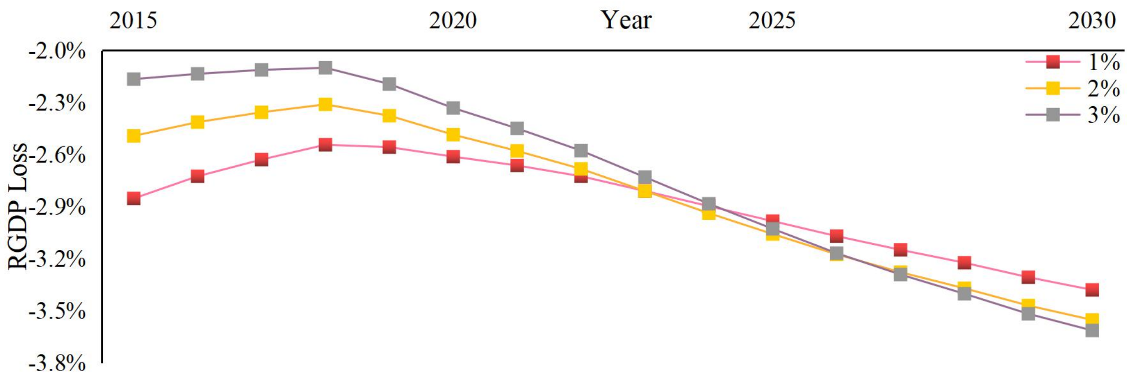


Fig. 7 The ITC Impact on the RGDP Loss

Fig. 7 shows how the ITC will affect the RGDP loss over time. Generally, the ITC will decrease the RGDP loss induced by the carbon tax; in other words, the ITC will bring about positive economic benefits. This is because technical progress increases productivity and thus boosts economic growth, according to the Solow–Swan Growth model (Solow 1956).

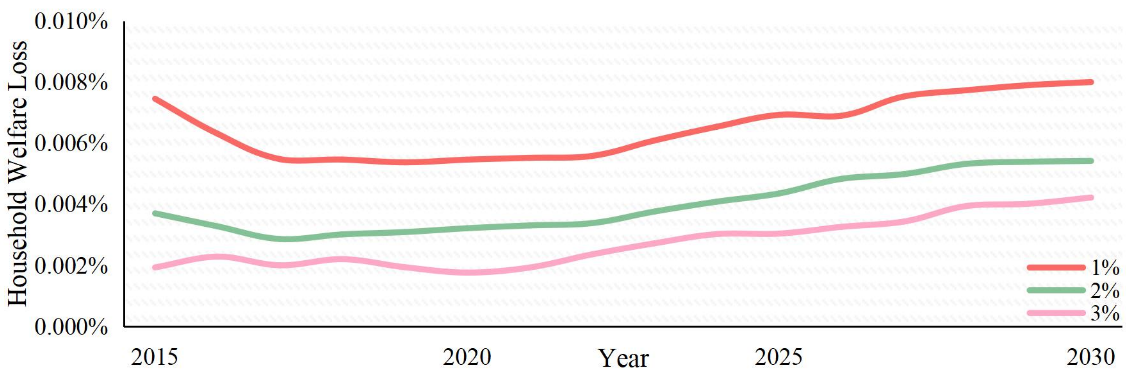


Fig. 8 The Relative Change of the Household Welfare Loss

In contrast, Fig. 8 shows the change of the household welfare loss under the ITC impact. Unlike the RGDP loss, the household welfare loss, induced by the carbon tax, will be increased by the ITC. This ITC impact will be weakened as the tax rate increases. Compared to the impact on the RGDP, the ITC impact on the household welfare is much smaller. This finding corresponds to the economic intuition that economic growth may not necessarily increase welfare, as economic growth may expand the wealth gap which decreases the overall welfare.

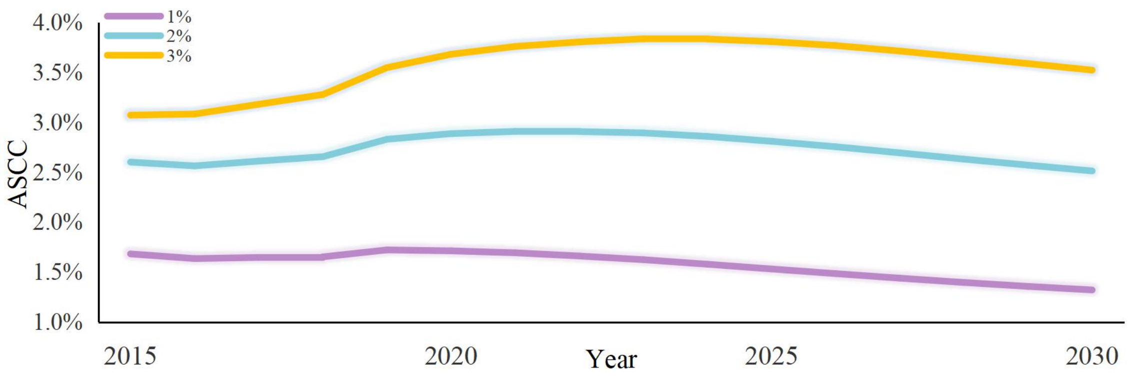


Fig. 9 The ITC Impact on the Average Social Cost of Carbon (ASCC)

According to Fig. 9, the ITC will increase the ASCC over the studied period in the tax scenarios. The magnitude of this ITC impact is positively related to the tax rate. This finding complies with Jensen and Traeger (2014) who empirically showed that the technological growth would increase the social cost of carbon when the economy growth was positive.

Table B1 and B2 in Appendix B show the results of the sensitivity analysis at the 1% tax in 2015 and 2030 respectively. According to these tables, the percentage changes of the variables are much lower than the corresponding changes of the income elasticity parameters. This finding implies that the model results are robust to the income elasticities.

Discussion

The carbon tax will slightly decrease the ECS, gradually increase the energy-use efficiency (EUE), minimally decrease the energy-production efficiency (EPE), significantly increase the nonenergy-production efficiency (ENE) and technical index, compared to the baseline scenario. Previously, Jin (2012) also used a CGE model to show that the carbon taxation could induce the technical innovation in China.

In the tax scenarios, the ITC of the carbon tax will decrease the EUE. This finding complies with Diaz and Puch (2019) who argued that if the energy became scarcer under the carbon tax, the energy share would increase in response to the rising energy price. In contrast, The ITC will decrease the EPE. This finding complies with Macaluso, Tuladhar et al. (2018) who showed the carbon tax would induce the substitutions toward less carbon-intensive energy sources and production technologies. Hence, with less resources allocated, the production efficiency of the energy sectors will decrease.

The ITC will increase the ENE. This finding complies with Ekins, Pollitt et al. (2012), who empirically found the environmental tax reform could increase the productivity by 3.4%, and Chavas, Aliber et al. (1997), who empirically found the R&D had a large and positive effect on the agricultural productivity in the US.

The ITC of the tax will promote the technological development at the lower tax rate. However, at the higher tax rate, the ITC impact inhibited the technical progress recently but will promote the progress in the future. The promotion impact of the ITC corresponds to the fact that a climate policy could induce additional R&D investment and knowledge application in the carbon-saving innovation (Jin 2012). In contrast, the inhibition impact of the ITC implies that owing to the political economy constraints, the carbon pricing may be ineffective in orientating technology in the emerging and developing countries (Finon 2019).

The ITC will decrease the deadweight loss induced by the carbon tax. Similar empirical evidence could be found in the previous research showing that the welfare costs of the environmental tax would decrease under the ITC impact (Liu and Yamagami 2018). This is because the ITC will increase the R&D expenditures to substantially lower the abatement costs (Kemfert 2005), and also it will induce the positive spill-over effects to support the carbon-free technologies (Kemfert 2005).

In contrast, the ITC will negatively affect the household welfare. This finding could be explained by the uncertainties existing in the household decision-making (Knobloch, Pollitt et al. 2019). The household may have the limited resources to cope with the rising price of the nonrenewable energies induced by the carbon tax. In addition, the ITC will significantly decrease the EPE, which may also increase the nonrenewable energy price.

The positive impact of the ITC on the ASCC implies that the emission abatement will become costlier if the ITC impacts are considered. This finding is contrary to the previous argument that the ITC was conducive to enhancing the level of the emission abatement as well as reducing the total social cost of the abatement (Wang, Mao et al. 2018). The result difference between Wang, Mao et al. (2018) and this paper lies in the targeted scope of the ITC: Wang, Mao et al. (2018) only focused on the impact of the low-carbon energy on the ASCC, but they did not analyse how such type of the ITC was related to the climate policies. In contrast, I have considered the general technological change induced by the carbon tax in this paper. In other words, this paper focuses on the ITC impacts on the policy effects of the carbon tax.

In summary, the empirical results in this paper generally fit in well with the previous research except that the result differences are mainly caused by the model assumptions and scope of the targeted sectors. However, I have only modelled the induced technological change (ITC) of the carbon tax, and thus this paper cannot reveal the pure socioeconomic impacts of the technical progress. In the reality, governmental policies targeted to promote the technical progress may be far more appealing than the carbon tax simulated in this paper.

Another limitation of this paper lies in the quantification method of the ITC. I have modelled the ITC based on Wang, Saunders et al. (2019). However, the ITC in their research mainly included the potential change of the energy-saving technologies but excluded the induced development of the decarbonisation or clean energies. The narrowed scope of the ITC is likely to underestimate the technical impacts. Future work may improve the quantification method of the ITC to cover all types of the potential technologies that may be changed.

Conclusions

This paper empirically shows that the carbon tax will decrease the energy cost share (ECS) and energy-production efficiency (EPE), but it will increase the energy-use efficiency (EUE), nonenergy-production efficiency (ENE) and technical index, compared to the baseline scenario. In the tax scenarios, the ITC will increase the ECS because of the internalization of the abatement costs. However, the ITC will decrease the EUE and EPE. The ITC will further increase the ENE and technical index in addition to the tax policy effects.

The ITC will have negative impacts on the carbon intensity. The negative impact of the ITC on the RGDP loss implies that the ITC will increase the welfare at the country level. In contrast, the positive impact of the ITC on the household welfare loss implies that the ITC will decrease the welfare at the household level. The ITC will increase the average social cost of carbon (ASCC), implying that the emission abatement will become costlier if the ITC impacts are considered.

Appendix A: Data Source

Table A1 The SAM of the CGE Model in 2015

	Commodity	Activity	Labour	Capital	Household	Enterprise	Government	RW	Investment	Stock	Sum
Commodity		140.1192			26.5980		9.7053	14.8448	29.1939	1.7080	222.1694
Activity	208.1447										208.1447
Labour		35.4110									35.4110
Capital		24.3869									24.3869
Household			35.4110	2.4909		2.9192	2.3524	-0.0488			43.1247
Enterprise				21.4388							21.4388
Government	1.5094	8.2275			0.8617	4.4622		-0.0052			15.0556
RW	12.5153			0.4573			0.0221				12.9947
Investment					15.6649	14.0573	2.9758	-1.7961			30.9019
Stock									1.7080		1.7080
Sum	222.1694	208.1447	35.4110	24.3869	43.1247	21.4388	15.0556	12.9947	30.9019	1.7080	636.6556

Table A2 The Sector Division of the Chinese Economy

1.Agriculture, Forestry, Animal Husbandry & Fishery	1.Agriculture (agric)
2.Mining and Washing of Coal	2. Mining and Washing of Coal (coalm)

3.Extraction of Petroleum and Natural Gas	3.Extraction of Petroleum (petrm) 4.Extraction of Natural Gas (gasn)
4.Ferrous Metal and Ore Mining 5.Non-metal Minerals and Other Mining	5. Metal, Ore, Non-metal and Other Mining (othm)
6.Foods and Tobaccos	6. Foods, Beverage & Tobacco (food)
7.Textile Products 8.Textile Wearing Apparel, Footwear and Caps, Leather, furs, down and related products	7.Textile Related Products (texti)
9.Processing and Manufacture of Timber and Furniture 10. Paper and Printing, Cultural, Sporting and Athletic and Recreation Products	8. Timber Related Products and Recreational Products (furni)
11. Petroleum Processing, Coking, and Nuclear Fuel Processing	9. Petroleum, Nuclear Fuel Processing (petrp) 10.Coking Processing (coking)
12. Chemical Product	11. Chemical Industry (chemical)
13. Manufacture of Non-metallic Mineral Products	12. Non-metallic Mineral Products (mineral)
14. Smelting and Pressing of Ferrous Metals	13. Metal Products (metal)
15. Metal products	
16. Manufacture of General-Purpose Machinery 17. Manufacture of Special Purpose Machinery 18. Manufacture of Railroad Transport Equipment 19. Manufacture of Electrical Machinery and Equipment 20. Manufacture of Communication Equipment, Computers and Other Electronic Equipment 21. Instruments, meters and other measuring equipment 22. Other Manufacturing Products 23. Scrap and Waste 24. Metal products, Machinery and Equipment Maintenance Service	14. Machinery and Equipment (machi)
25. Production and Distribution of Electric Power and Heat Power	15.Electricity Transmission and Distribution (TD) 16.Supercritical Coal Generation (Supercrit) 17.Ultra-Supercritical Coal Generation (USC) 18.Sub-c Coal Generation (Subc) 19.Natural Gas Generation (NG) 20.Nuclear Power Generation (Nuclear) 21.Hydro Power Generation (Hydro) 22.Wind Power Generation (Wind) 23.Solar Power Generation (Solar) 24. Heat Production and Distribution (fipow)
26. Production and Distribution of Gas	25. Gas Production and Distribution (gasm)
27. Production and Distribution of Water	26. Water Production and Distribution (water)

28. Construction	27. Construction (const)
29. Wholesale and Retail Trade	29. Other Service (service)
30. Transport, Storage and Post	28. Transport, Storage and Post (trans)
31. Hotels and Restaurants 32. Information Transfer, Computer Services and Software 33. Finance 34. Real Estate 35. Tenancy and Business Services 36. Scientific Research and Technical Service 37. Management of Water Conservancy, Environment and Public Establishment 38. Resident Services, Maintenance Service and Other Services 39. Education 40. Sanitation and Social Work 41. Culture, Sports and Entertainment 42. Public Management Social Security & Social Organisations	29. Other Service (service)

As China Statistical Yearbooks have not published the coal price data, I have referred to the data given by China Coal Industry (CCI 2016, 2017, 2018, 2019). According to Table A3 in Appendix A, the coal price decreased sharply from 2015 to 2016 but remained stable in 2016-2018. In contrast, the coke price grew steadily in 2015-2018.

Table A3 The Coal Price and Coke Price in 2015-2018 (Unit: CNY/tonne)

Year	2015	2016	2017	2018
Coal	370	639	611.7	620.7
Coke	569	787	1356	1528

As far as I am concerned, there are no official data of the petroleum price. I have used the data given by PetroChina Company Limited (PCCL 2017, 2019) and China Petroleum and Chemical Corporation (CPCC 2017, 2019). According to Table A4 in Appendix A, the gasoline has the highest price, whilst the crude oil has the lowest price.

Table A4 The Petroleum Prices in 2015-2018 (Unit: CNY/tonne)

Year	2015	2016	2017	2018
Crude Oil	2124	1865	2392	3207
Kerosene	3366	2832	3539	4553
Gasoline	6388	6091	6698	7492
Diesel Oil	4733	4316	4821	5734
Fuel Oil	2439	1892	2380	3335

The retail price of the natural gas in China is unavailable from the official source. I have used the price data from China Gas Holdings Limited (CGHL 2017, 2018, 2019), shown in Table A5 in Appendix A. In this paper, the 2015-2018 price corresponds to the 2015/16, 2016/17, 2017/18, and 2018/19 fiscal year price of the natural gas in CGHL. All the sectors, except for the transport, storage and post sector and service sector, face the price for the industrial use, whilst these sectors face the price for the commercial use. According to Table A5, the natural gas price for the household use was the lowest, whilst the price for the commercial use was the highest.

Table A5 The Natural Gas Price in 2015-2018 (Unit: CNY/m^3)

Year	2015	2016	2017	2018
Household Use	2.29	2.36	2.40	2.52

Industrial Use	2.59	2.38	2.50	2.65
Commercial Use	2.68	2.55	2.60	2.79

All the sectors are assumed to face the 2015-2017 electricity price according to National Energy Administration (NEA 2016, 2017, 2018). The electricity price is the same regardless of the generation sources. The Chinese government (CG 2018) announced that it would reduce the electricity price for the general industry and commerce by 10% in 2018, and the target was met in the 2019 government report (CG 2019). The 2019 report also announced a further 10% reduction (CG 2019). Hence, the electricity price is assumed to decrease by 10% in 2018 and 2019. According to Table A6 in Appendix A, the electricity price decreased steadily in 2015-2019.

Table A6 The Electricity Price in 2015-2019 (Unit: CNY/1000 kw.h)

Year	2015	2016	2017	2018	2019
Electricity	825.14	817.44	765.24	688.72	619.84

Appendix B: Tables and Figures

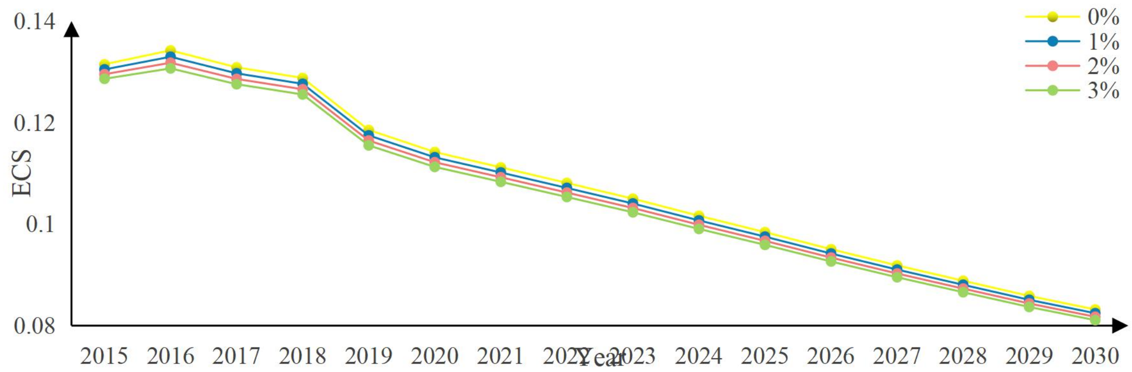
Table B1 The Results of the Sensitivity Analysis in 2015 at the 1% Tax

Parametric Changes	-50%	-20%	-10%	10%	20%	50%
ECS	-13.43%	-5.64%	-2.84%	2.84%	5.66%	13.88%
EUE	22.55%	8.57%	4.16%	-3.89%	-7.51%	-16.83%
EPE	16.73%	6.40%	3.12%	-2.94%	-5.70%	-12.93%
ENE	-3.62%	-1.53%	-0.77%	0.78%	1.56%	3.91%
Technical Index	-0.77%	-0.28%	-0.14%	0.13%	0.25%	0.55%
Carbon Intensity	0.90%	0.33%	0.16%	-0.15%	-0.29%	-0.67%
RGDP Loss	-35.60%	-12.13%	-5.78%	5.30%	10.17%	22.73%
HWL	-35.73%	-12.16%	-5.79%	5.30%	10.17%	22.67%
ASCC	1.28%	0.60%	0.31%	-0.32%	-0.65%	-1.67%

Note: HWL denotes the household welfare loss

Table B2 The Results of the Sensitivity Analysis in 2030 at the 1% Tax

Parametric Changes	-50%	-20%	-10%	10%	20%	50%
ECS	-3.88%	-1.74%	-0.89%	0.93%	1.88%	4.82%
EUE	4.95%	2.22%	1.13%	-1.16%	-2.33%	-5.83%
EPE	5.02%	2.15%	1.09%	-1.10%	-2.21%	-5.47%
ENE	-0.95%	-0.40%	-0.20%	0.20%	0.40%	1.02%
Technical Index	-0.62%	-0.25%	-0.12%	0.12%	0.24%	0.59%
Carbon Intensity	0.77%	0.30%	0.15%	-0.15%	-0.30%	-0.72%
RGDP Loss	-36.55%	-13.02%	-6.28%	5.87%	11.38%	26.02%
HWL	-36.78%	-13.12%	-6.34%	5.93%	11.49%	26.29%
ASCC	0.32%	0.11%	0.05%	-0.05%	-0.09%	-0.20%



Note: 0% is the baseline scenario; 1%, 2%, and 3% refer to the 1%, 2%, and 3% tax scenarios respectively

Fig. B1 The ECS in the Baseline and Tax Scenarios

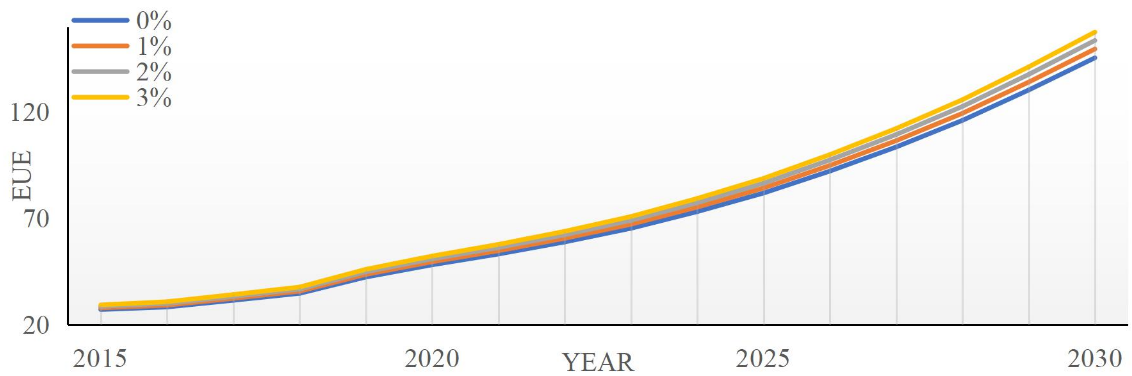


Fig. B2 The EUE in the Baseline and Tax Scenarios

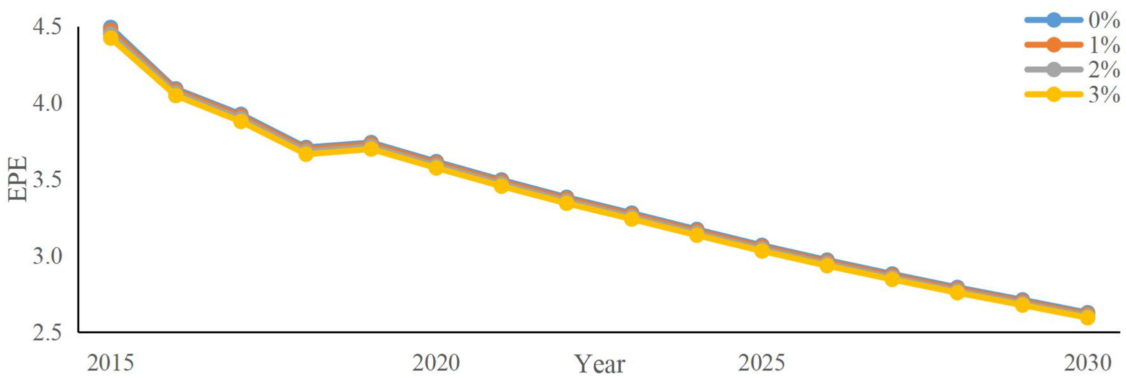


Fig. B3 The EPE in the Baseline and Tax Scenarios

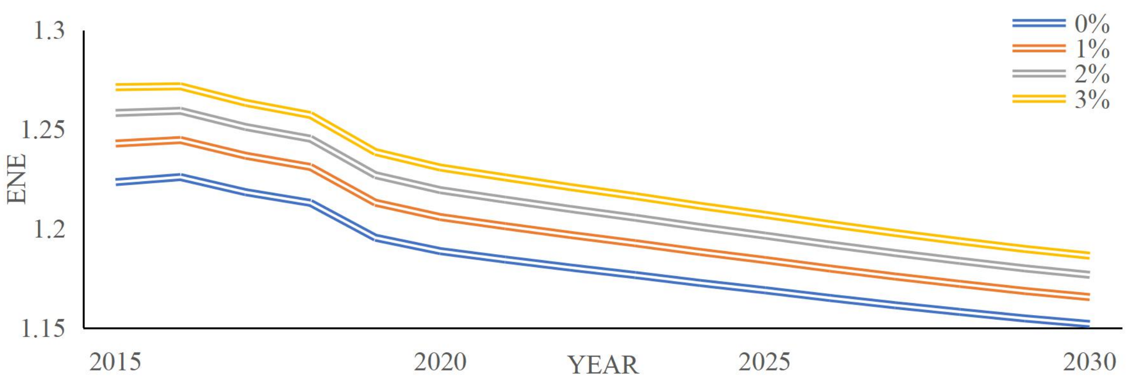


Fig. B4 The ENE in the Baseline and Tax Scenarios

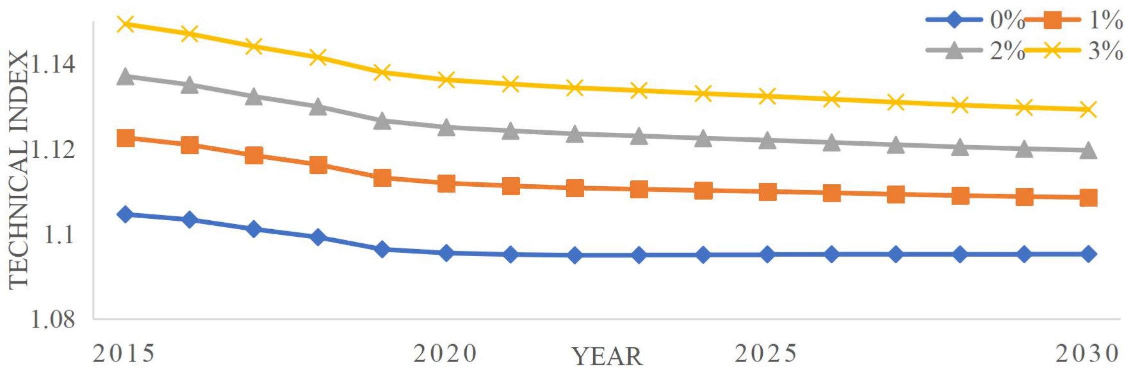


Fig. B5 The Technical Index in the Baseline and Tax Scenarios

Appendix C The Disaggregation of the Electricity Sector

$$\mathrm{Efipow_{it}} = \mathrm{deltafipow_{it}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times {\frac{\mathrm{Ppow_t}}{\mathrm{Pfipow_t}}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \mathrm{Epow_{it}};$$

$$\mathrm{Eelec_{it}} = \mathrm{deltaelec_{it}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \left(\frac{\mathrm{Ppow_t}}{\mathrm{Pelec_t}}\right)^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \mathrm{Epow_{it}};$$

$$\mathrm{ETD_{it}} = \mathrm{deltaTD_{it}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times {\frac{\mathrm{Pelec_t}}{\mathrm{PQ_{"TD",\ t}}\times(1+\mathrm{tc_{"TD",\ t}})}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \mathrm{Eelec_{it}};$$

$$\mathrm{Eelecgen_{it}} = \mathrm{deltaelecgen_{it}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \left(\frac{\mathrm{Pelec_t}}{\mathrm{PEelecgen_t}}\right)^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \mathrm{Eelec_{it}};$$

$$\mathrm{Efosgen_{it}} = \mathrm{deltafosgen_{it}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \left(\frac{\mathrm{PEelecgen_t}}{\mathrm{PEfosgen_t}}\right)^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \mathrm{Eelecgen_{it}};$$

$$\mathrm{Erenewgen_{it}} = \mathrm{deltarenewgen_{it}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \left(\frac{\mathrm{PEelecgen_t}}{\mathrm{PErenewgen_t}}\right)^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \mathrm{Eelecgen_{it}};$$

$$\mathrm{Ecoalgen_{it}} = \mathrm{deltacoalgen_{it}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \left(\frac{\mathrm{PEfosgen_t}}{\mathrm{PEcoalgen_t}}\right)^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \mathrm{Efosgen_{it}};$$

$$\mathrm{ENG_{it}} = \mathrm{deltaNG_{it}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times {\frac{\mathrm{PEfosgen_t}}{\mathrm{PQ_{"NG",\ t}}\times(1+\mathrm{tc_{"NG",\ t}})}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \mathrm{Efosgen_{it}};$$

$$\mathrm{ESuper_{it}} = \mathrm{deltaSuper_{it}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times {\frac{\mathrm{PEcoalgen_t}}{\mathrm{PQ_{"Supercrit",\ t}}\times(1+\mathrm{tc_{"Supercrit",\ t}})}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \mathrm{Ecoalgen_{it}};$$

$$\mathrm{EUSC\_subc_{it}} = \mathrm{deltaUSC\_subc_{it}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times {\frac{\mathrm{PEcoalgen_t}}{\mathrm{PEUSC\_subc_{it}}}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \mathrm{Ecoalgen_{it}};$$

$$\mathrm{EUSC_{it}} = \mathrm{deltaUSC_{it}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times {\frac{\mathrm{PEUSC\_subc_{it}}}{\mathrm{PQ_{"USC",\ t}}\times(1+\mathrm{tc_{"USC",\ t}})}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \mathrm{EUSC\_subc_{it}};$$

$$\mathrm{Esubc_{it}} = \mathrm{deltasubc_{it}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times {\frac{\mathrm{PEUSC\_subc_{it}}}{\mathrm{PQ_{"subc",\ t}}\times(1+\mathrm{tc_{"subc",\ t}})}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \mathrm{EUSC\_subc_{it}};$$

$$\mathrm{EFuel14_{it}} = \mathrm{deltaFuel14_{it}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times {\frac{\mathrm{PErenewgen_t}}{\mathrm{PQ_{"Nuclear",\ t}}\times(1+\mathrm{tc_{"Nuclear",\ t}})}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \mathrm{Erenewgen_t};$$

$$\mathrm{EFuel15\_16\_17_{it}} = \mathrm{deltaFuel15\_16\_17_{it}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times {\frac{\mathrm{PErenewgen_t}}{\mathrm{PEFuel15\_16\_17_{it}}}}^{\frac{1}{1-\mathrm{parpow_{it}}}} \times \mathrm{Erenewgen_t};$$

$$EFuel15_{it} = deltaFuel15_{it}^{\frac{1}{1-parpow_{it}}} \times \frac{PEFuel15\_16\_17_{it}}{PQ_{"Hydro",\ t} \times (1+tc_{"Hydro",\ t})}^{\frac{1}{1-parpow_{it}}} \times EFuel15\_16\_17_{it};$$

$$EFuel16\_17_{it} = deltaFuel16\_17_{it}^{\frac{1}{1-parpow_{it}}} \times \frac{PEFuel15\_16\_17_{it}}{PEFuel16\_17_{it}}^{\frac{1}{1-parpow_{it}}} \times EFuel15\_16\_17_{it};$$

$$EFuel16_{it} = deltaFuel16_{it}^{\frac{1}{1-parpow_{it}}} \times \frac{PEFuel16\_17_{it}}{PQ_{"wind",\ t} \times (1+tc_{"wind",\ t})}^{\frac{1}{1-parpow_{it}}} \times EFuel16\_17_{it};$$

$$EFuel17_{it} = deltaFuel17_{it}^{\frac{1}{1-parpow_{it}}} \times \frac{PEFuel16\_17_{it}}{PQ_{"solarpv",\ t} \times (1+tc_{"solarpv",\ t})}^{\frac{1}{1-parpow_{it}}} \times EFuel16\_17_{it}.$$

The subscript i refers to a sector; t is the time.
$deltacoalgen_{it}$ is the share of the coal electricity composite input.
$deltaelec_{it}$ is the share of the electricity composite input.
$deltaelecgen_{it}$ is the share of the electricity-generation composite input;
$deltafipow_{it}$ is the share of the heat input.
$deltafosgen_{it}$ is the share of the fossil electricity input.
$deltaTD_{it}$ is the share of the electricity transmission input.
$deltaSuper_{it}$ is the share of the supercrit-coal electricity input.
$deltaUSC_{it}$ is the share of the USC-coal electricity input.
$deltaUSC\_subc_{it}$ is the share of the USC-subc-coal electricity composite input.
$deltasubc_{it}$ is the share of the subc-coal electricity input.
$deltaNG_{it}$ is the share of the gas electricity input.
$deltaFuel14_{it}$ is the share of the nuclear electricity input.
$deltaFuel15_{it}$ is the share of the hydroelectricity input.
$deltaFuel15\_16\_17_{it}$ is the share of the hydro-wind-solar electricity composite input.
$deltaFuel16_{it}$ is the share of the wind electricity input.
$deltaFuel16\_17_{it}$ is the share of the wind-solar electricity composite input.
$deltaFuel17_{it}$ is the share of the solar electricity input.
$deltarenewgen_{it}$ is the share of the renewable electricity generation input.
$Ecoalgen_{it}$ is the coal electricity composite input.
$Eelec_{it}$ is the electricity composite input.
$Eelecgen_{it}$ is the electricity-generation composite input;
$Efipow_{it}$ is the heat input.
$Efosgen_{it}$ is the fossil electricity input.
ETD_{it} is the electricity transmission input.
$ESuper_{it}$ is the supercrit-coal electricity input.
$EUSC_{it}$ is the USC-coal electricity input.
$EUSC\_subc_{it}$ is the USC-subc-coal electricity composite input.
$Esubc_{it}$ is the subc-coal electricity input.
ENG_{it} is the gas electricity input.
$EFuel14_{it}$ is the nuclear electricity input.
$EFuel15_{it}$ is the hydroelectricity input.
$EFuel15\_16\_17_{it}$ is the hydro-wind-solar electricity composite input.

$EFuel16_{it}$ is the wind electricity input.

$EFuel16\_17_{it}$ is the wind-solar electricity composite input.

$EFuel17_{it}$ is the solar electricity input.

$Epow_{it}$ is the electricity-heat composite input.

$Erenewgen_{it}$ is the renewable electricity generation input.

$parpow_{it}$ is the elasticity parameter.

$PEcoalgen_{it}$ is the price of the coal electricity composite input.

$Pelec_{it}$ is the price of the electricity composite input.

$Pfipow_{it}$ is the price of the heat input.

$PEelecgen_{it}$ is the price of the electricity-generation composite input;

$PEfosgen_{it}$ is the price of the fossil electricity input.

$PEUSC\_subc_{it}$ is the price of the USC-subc-coal electricity composite input.

$PEFuel15\_16\_17_{it}$ is the price of the hydro-wind-solar electricity composite input.

$PEFuel16\_17_{it}$ is the price of the wind-solar electricity composite input.

$PErenewgen_{it}$ is the price of the renewable electricity generation input.

$Ppow_{it}$ is the price of the electricity-heat composite input.

PQ is the energy price.

tc is the tax rate.

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