Evaluating Efficiency and Fairness of Renewable Portfolio Standard in China

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Abstract: This study evaluates the efficiency and fairness of China's Renewable Portfolio Standard (RPS) using a bi-level numerical model. The model comprises a regulatory level that sets the required share of renewables and a market level where electricity producers and consumers respond to these policies. In a perfectly competitive market, carbon pricing is identified as the most efficient policy to promote the development of renewable energy, while the RPS closely approximates an optimal policy tool. By mandating a certain percentage of renewable energy generation, the RPS significantly promotes renewable energy development and substantially reduces emissions. Additionally, RPS improves welfare levels in the central regions, addressing regional welfare disparities. RPS is deemed appropriate, especially considering that China's carbon pricing mechanisms are not yet fully supportive of renewable energy development.

1. Introduction

China is the largest renewable energy producer and consumer, benefiting from feed-in tariffs (FIT), which means the government procures the electricity generated from renewable resources at a fixed price, over the past few decades. In recent years, the renewable energy support scheme has transitioned from FITs to market-based renewable portfolio standards (RPS) [1][2]. RPS refers to a scheme in which the central government determines the required share of renewable energy for each province. Provincial governments meet these requirements by generating more renewable energy. According to RPS calculations, the required share is calculated by dividing the electricity generated from local renewable sources by overall local electricity production.

RPS has been widely used in most states in the US since the 2000s. There are studies evaluating efficiency (e.g., Upton and Snyder, 2017[3]; Barbosa et al., 2015; 2016[4][5]), capacity expansion (Joshi, 2021[6]), and electricity price changes (Wiser et al., 2017[7]) under RPS in the US context. Meanwhile, many studies have evaluated the efficiency of RPS in the context of today's China, where the renewable share is higher than in the US in the 2000s. Yi et al. (2019)[8] and Yu et al. (2023)[9]evaluate RPS by simplifying the required share for each province into a nationally unified share. Wang et al., (2018) [10], Fan et al., (2021) [11], Xu et al., (2021) [12], and Zhou et al., (2022) [13] investigate the distributional impact of RPS quota allocation, as the RPS target share for each province is decided by the central government in China, and they find that the initial allocation is critical.

Our objective is to evaluate the efficiency and fairness of the RPS in China. Based on our numerical model we assess the impact of the RPS on total welfare and their implications for consumer surplus and emissions reductions. We also examine how welfare is distributed across regions.

2. Methodology

We extend and apply a numerical model developed by Abrell et al.[14][15][16][17] to evaluate the efficiency and distributional impacts of RPS. The model evaluates the impact of various energy and climate policies in a competitive economy. To represent the electricity sector in proper spatial and temporal resolution, the model includes 6 regions and 672 representing hours.

The objective function of our model is to maximize social welfare from the perspective of regulator (the central government). In this paper, the regulator's choice variables are the target renewable share. The market, based on regulator's choices, determines the equilibrium quantity (production and consumption) and price; that is, electricity producers and consumers have their objective functions

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*Corresponding author: wangxinh21@mails.tsinghua.edu.cn that maximize their profits or utilities in a competitive market.

To capture the market's and regulator's objective functions, the model features a bi-level framework. The lower level employs a mixed complementarity problem (MCP). Various power generation technologies compete in the electricity market to maximize their profits through short-term (production) and long-term (investment) decisions. Consumers maximize their utilities by adjusting their demand according to electricity prices. At the upper level, a grid search approach is employed to select optimal policy (i.e., the choice variables that maximize total welfare).

2.1. Model Description

The problem of regulator is to maximize social welfare $\boldsymbol{W}$, including the environmental damage of emissions $\boldsymbol{\delta}$, by choosing RPS policy $\boldsymbol{K}$, subject to market equilibrium conditions for electricity supply and demand.

$$\max W(p(K), x(K); \delta) \quad (1)$$

$$s.t. \, p(K), x(K) \epsilon A \quad (2)$$

Where, $\boldsymbol{A}$ is the set of feasible allocations defined by equilibrium prices $\boldsymbol{p(K)}$ and quantities $\boldsymbol{x(K)}$ associated with market equilibrium. The market equilibrium can be viewed as the producers and the consumers response to RPS policy $\boldsymbol{K}$.

We compare the efficiency and distributional impact of three scenarios (Tab. 1). We also investigate the rationales how RPS affect welfare.

Table 1. Scenario design

	Description
CP	Carbon price scenario, the "first best" policy instrument for decarbonization
RPS	The traditional RPS
NP	No policy scenario

2.2. Data

The key data inputs of the model include the existing generation and transmission capacity, capacity factor and cost function for all technologies, the baseline demand and price, the demand elasticity (-0.05), SCC (240 RMB/ton)[18], and population.

For temporal and spatial resolution, we select 672 representing hours T from 8760 hours t in our model. To capture the time-dependent demand and generation across hours, days, and seasons, we choose 168 hours (7/24) in each representative week of each season. Our model considers six regions R, including northern grid (N), northeastern grid (NE), northwestern grid (NW), eastern grid (E), central grid (C), and southern grid (S). Each regional grid includes several (4 - 6) provincial grids r. All data are consistent with the data used by Zhang et al, 2024[19] which reflect China's electricity sector in 2020. Some data is listed in the following Tab. 2, Tab. 3 and Tab. 4.

Table 2 Existing capacity by region (GW).

	N	NE	NW	C	S	E
Coal	276	105	154	170	140	234
Others	12	14	36	153	153	52
Wind	87	34	68	37	27	39
Solar	68	15	62	33	26	49
Gas	22	1	3	8	22	43

Table 3 Transmission by region (GW).

	NE	NW	N	C	S	E
NE	0	0	17	0	0	0
NW	0	0	16.05	0.05	38.65	20
N	17	16.05	0	0	12.7	21
C	0	0.05	0	0	9.3	3.4
S	0	38.65	12.7	9.3	0	45.6
E	0	20	21	3.4	45.6	0

Table 4 Baseline price (based on a typical day of the equinox) by time. (RMB/MWh)

	NE	NW	N	C	S	E
1	216.4	230.02	186.04	180.74	246.03	191.35
2	216.14	230.03	186.02	180.78	245.78	191.09
3	216.18	230.03	186.09	180.73	171.93	190.9
4	216.1	230.03	186.17	180.65	171.96	190.83
5	217.76	230.03	186.15	180.65	172.09	190.81
6	217.6	230.03	186.17	315.92	172.66	190.82
7	217.87	261.04	186.26	381.33	191.86	214.11
8	330.55	379.74	279.3	438.58	233.26	242.55
9	381.01	379.74	461.14	439.14	462.18	546.6
10	480.15	406.17	501.74	509.47	432.19	573.02
11	490.8	539.15	499.3	509.25	432.41	573.17
12	373.85	539.14	575.35	344.71	314.58	373.59
13	275.61	379.74	438.58	345.02	297.94	344.35
14	301.1	410.75	438.96	344.97	297.81	427.26
15	364.37	410.75	493.4	344.97	227.14	451.99
16	440.49	410.76	454.12	413.64	226.58	452.58
17	452.1	512.67	452.65	415.44	297.64	452.57
18	481.82	512.66	430.29	569.77	318.84	544.98
19	494.1	539.11	513.67	569.95	382.08	545.67
20	494.01	508.08	513.84	509.17	452.74	618.52
21	470.48	508.07	600.9	470.92	461.89	618.31
22	441.41	508.06	547.52	345.23	451.71	547.52
23	381.49	375.16	377.32	209.18	416.13	322.23
24	329.54	230.06	278.8	180.71	333.78	273.14

However, our study has the following limitations. First, the expansion of transmission and storage is not considered. Second, we only have six regions in our model, whereas there are 34 provinces. The details within and between each province are not provided. Third, we do not simulate other scenarios that have special designs, e.g., adjusts the RPS calculation approach by including the renewables procured from another province (imported renewables) and excluding the renewables sold to another province (exported renewables).

3. Results and Discussions

3.1. Efficiency evaluation

We evaluate total welfare in three scenarios (black dots in Fig. 1). The welfare in the CP scenario is the "first best" (indexing at 100%), reflecting the fact that carbon taxes could internalize environmental externalities. The revenue generated by carbon taxes is equal to the damage caused by emissions and is refunded to the electricity sector. According to Abrell et al. (2019)[14], carbon taxes reduce emissions through three channels: transferring from coal to gas, transferring from conventional (i.e., coal and gas) to renewables (i.e., wind and solar), and encouraging energy savings. NP (our baseline, indexed at 0) provides no additional support (none of the three channels) to decarbonize electricity sector, yielding the least welfare.

The welfare index of the RPS scenario is calculated by dividing the welfare wedge between the evaluated scenario and the baseline by the welfare wedge between the "first-best" scenario and the baseline. A higher indicator (closer to 100%) reveals a higher level of welfare. Since the RPS scenario does not distinguish between coal and gas, welfare wedges compared to the CP scenario (10.25%) result from the transfer of coal into gas. However, since the RPS scenario encourages the use of renewable energy sources, and save energy by properly increasing electricity prices, the wedges between RPS and NP are larger (89.75%).

Due to the small base, the differences in producer surplus among the three scenarios are relatively minor, while the differences in consumer surplus contribute significantly to the overall welfare differences. The consumer surplus is the highest in the NP scenario. The CP scenario has the smallest consumer surplus, which is 7.06% lower than that of the NP scenario. The consumer surplus in the RPS scenarios decreases, being 2.48% lower than that of the NP scenario.

From an emissions perspective, three scenarios have the same trends as total welfare. Without a mitigation approach, the NP scenario has the highest damage from emissions, while the CP scenario has the lowest. Compared to the CP scenario, emissions in RPS, increase by 2.13%.

Congestion revenues correlate positively with power transmission and electricity price gaps across regions. Compared to the NP scenario, congestion costs in CP and RPS increase by 64.4% and 58.2%. The NP scenario receives the least congestion revenues, reflecting that renewable support policies encourage transmission expansion. The RPS scenario receives the highest congestion revenues, as encouraging renewable energy consumption requires more transmission.

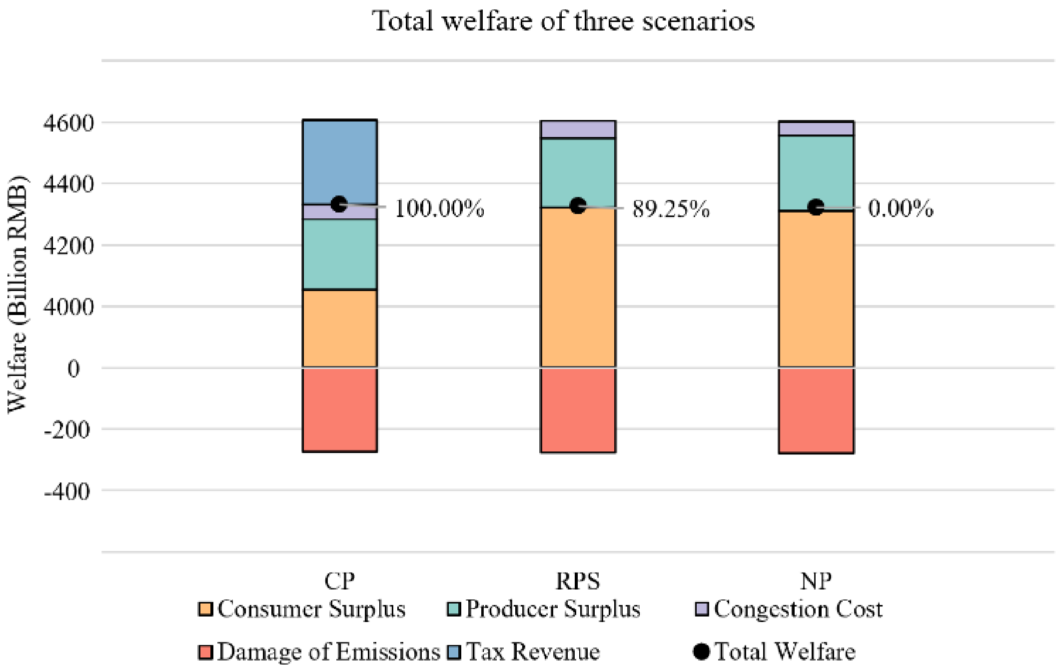

Figure 1. Overall social welfare. Three dots represent the overall welfare for three scenarios in descending order. We index welfare in CP as 100% and that in NP as 0. The RPSis indexed as the proportion of the gap between RPS and NP over the gap between CP and RPS' welfare. Accumulative bars represent sub-welfares for each scenario. The damage of emissions is negative, and others are positive.

3.2. Distributional impact evaluation

We simulate the optimal regulator's choice, i.e., carbon price and renewable energy share. The optimal carbon price equals to social cost of carbon. The optimal renewable energy share that is allocated to each region. As the regulator's object is to maximize social welfare for all regions, the optimized share could not be completely fair (the same for each region). The regions with abundant renewable energy resources are likely to have higher required share (in the real world, Qinghai's required share is 28.9% in 2024), and vice versa (Shanghai is 7.7% in 2024). Table 1 provide the simulated shares that maximize total welfare. As show in table 5.

Table 5. Optimal renewable energy share

	N	NE	NW	E	C	S
RPS	60%	55%	45%	20%	95%	40%

When considering distributional impact, we assume that the emissions affect individuals equally as the emissions are diffusive. Other sub-welfares are counted for each region. According to Fig. 2, the welfare per capita in NP scenario (the blue dashed line) is significantly smaller than that in other scenarios (the almost overlapped dashed lines), in line with the results of total welfare. The bars in dark blue represents the regional welfare per capita in NP scenario. The consumer surplus plays the most critical role in the total welfare (about 95.7% of the total welfare), thus, the regional welfares have almost the same order as GDP per capita (eastern, northern, southern, central, northwestern, and northeastern). The northwestern and northeastern regions make profits by exporting renewable energy (producer surplus accounts for 3.8% in the total welfare); thus improve the ranking. The northwestern region ranks the second as its plenty transmission capacity. While the northeastern region ranks the fifth because it only connects to the northern region.

The bars in other colors represent the difference of welfare per capita between each scenario and NP scenario. The direction of the bars shows the regional impacts across policy designs. The rising welfare in regions below average (i.e., central and northeastern regions) or the dropping welfare in regions above average (i.e., eastern, northwestern, and southern regions) implies improvement of equity. RPS improves equity by increasing welfare for the central region. CP strongly support northwestern while has limited effects on central region.

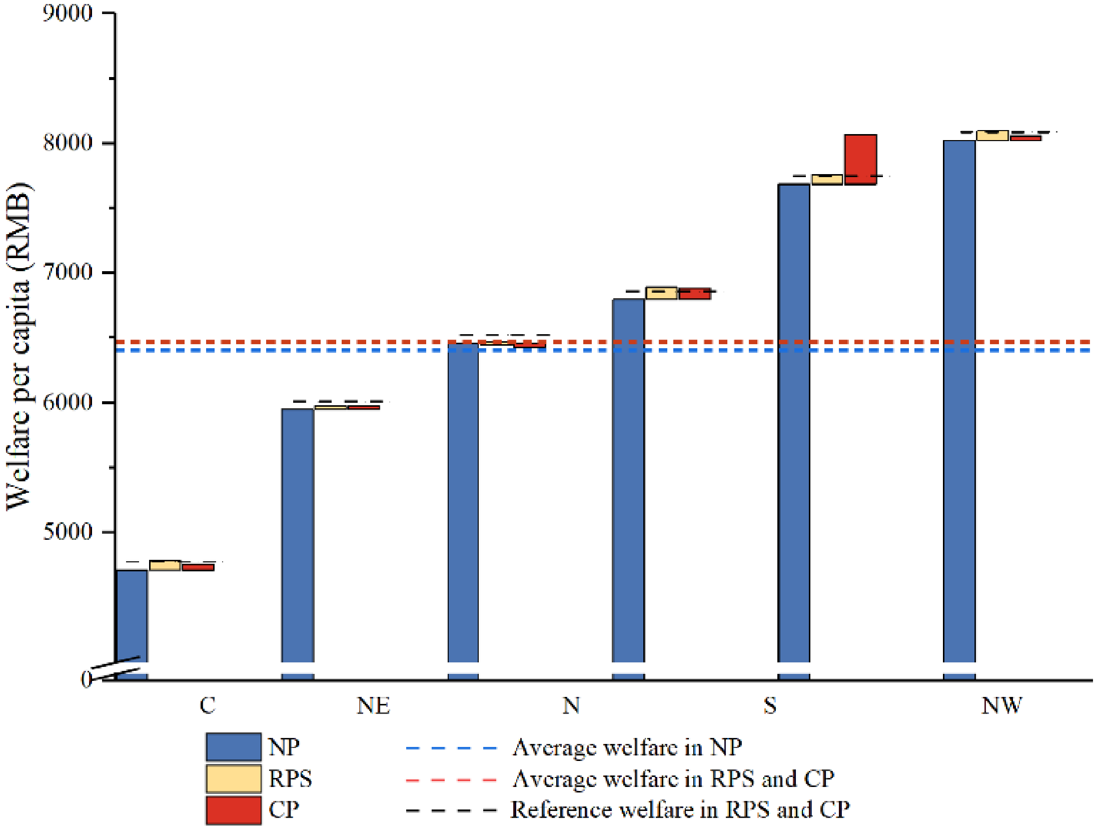

Figure 2. Regional welfare per capita. The dashed lines are national welfare per capita. The dark blue lines represent the national welfare per capita in NP scenario and the almost coincident dashed lines in other colors represent the national welfare per capita in RPS and CP scenarios. The bars in dark blue are the regional welfare per capita in the central (C), northeastern (NE), northern (N), southern (S), northwestern (NW) and eastern (E) regions in NP scenarios. The order is arranged from lowest to highest according to the regional welfare per capita. The bars in other colors are the differences in regional welfare per capita between NP scenario and other scenarios.

3.3. Policy recommendations

Based on these findings, the following policy recommendations are proposed: Optimizing the RPS design remains a viable strategy. Optimizing the RPS design remains a viable strategy. Policymakers should flexibly adjust RPS quotas based on regional renewable energy resource endowments and transmission capacities to enhance policy efficiency and fairness. First, introducing cross-regional renewable energy trading mechanisms, allowing regions to purchase renewable energy quotas to meet their requirements, can improve overall resource allocation efficiency. Second, investments in cross-regional transmission capacity should be increased, particularly for the renewable energy-rich northwestern region, to optimize resource allocation and improve the nationwide emission reduction effect. Third, a robust monitoring and evaluation mechanism should be established post-policy implementation to track execution and effects across regions. Continuous data analysis and model simulations will allow for dynamic adjustments to policy designs and quota allocations, ensuring the achievement of policy objectives.

4. Conclusions

In conclusion, we use a bi-level model to evaluate RPS in a completely competitive market. The model includes a regulatory level that sets the required share of renewables and a market level where electricity producers and consumers respond to these policies. The analysis focused on three scenarios: the baseline scenario (NP), the RPS scenario (RPS), and the carbon pricing scenario (CP). The results indicate that the carbon pricing scenario yields the highest total welfare, making it the most efficient policy for achieving emission reduction targets. The RPS scenario, while not as efficient as carbon pricing, significantly promotes renewable energy development, substantially reduces emissions, and improves welfare levels in central regions, thereby addressing regional welfare disparities. Regionally, the RPS significantly enhances welfare in the central and northeastern regions, while carbon pricing primarily benefits the northwestern region. The study also finds that with existing cross-regional transmission capacity, the northwestern region, endowed with abundant renewable energy resources, experiences substantial welfare gains under both RPS and carbon pricing policies.

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