Greener, at What Cost? Evaluating Energy Dispatch Policy Alternatives in China

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ABSTRACT

As China continues its energy market's reform, two alternatives exist for its future energy dispatch policy – either expanding the current pilot experiment of energy saving dispatch policy (which minimizes carbon emission), or adopting the economic dispatch policy (which minimizes cost) prevalent in the developed countries. I built an electricity dispatch model that dispatched generators and generator groups at consecutive time intervals based on a predefined order. By ordering generators either by the production cost or the China NDRC's Energy Saving Power Dispatch rules, I simulated the electricity dispatch in the Jiangsu province under each policy with hourly resolution for 2014. I then analyzed the cost and the emission of electricity supply under each policy. I also analyzed what impact each dispatch policy has on Jiangsu's power system flexibility. I found that the average cost of electricity under ESPD was 12% higher than under ED, while the average CO_2 emissions (kg/MWh) under ESPD was 5.6% lower than under ED. The emissions savings from ESPD, however, were not cost-effective compared to the value of CO_2 reported in China's carbon market or calculated by the Interagency Working Group on Social Cost of Carbon. I also found that with current renewable technologies, ESPD is the only viable way for renewable energy to competitively participate in Jiangsu's electricity market. However, ESPD poses threat to the system reliability, as fewer flexible natural gas generators were available to respond to rapid changes in load.

KEYWORDS

power dispatch model, Jiangsu, cost of carbon, energy saving power dispatch, economic dispatch

INTRODUCTION

China has become the largest emitter of carbon dioxide (CO_2) in the world, and the country's energy consumption contributes significantly to its emissions (Guan et al 2009). The efficiency of China's energy sector is low, according to a study on the CO_2 emissions in 28 Chinese provinces (Wang et al 2010), while the high-polluting coal-fired power plants generating most of the electricity (Chen 2009). Therefore, improving the efficiency and the carbon intensity of China's energy sector can effectively reduce the country's CO_2 contributions. China's commitment to join the global effort in tackling climate change is evident in their pledge to peak the nation's CO_2 emission by 2030 (NDRC 2015). To achieve this goal, China is rapidly expanding its renewable energy and aims to reach 550 gigawatts renewable capacity by 2017 (REN 2011). However, China's current energy market policies, especially its electricity dispatch policy based on predefined quota, hinders the development of an efficient energy sector by curtailing wind and solar energy (dumping wind and solar energy because there is a surplus in energy supply) and underutilizing more efficient thermal generators.

Electricity dispatch policy is a central piece of energy market policymaking because dispatch policy determines how electricity generation sources will be selected and compensated to meet electricity demand. Alerted by China's high level of energy consumption and its dependence on coal, the National Development and Reform Commission (NDRC), the State Electricity Regulation Commission (SERC) and the Ministry of Environmental Protection (MEP) announce the Energy Saving Power Dispatch (ESPD) pilot project in 2007 (State Council of China 2007). Under ESPD, system operators are required to prioritize renewable and low carbon energy resources while dispatching generators. The pilot project required 5 pilot provinces to start ESPD operation in 2008. Since China's ESPD is unprecedented in other countries, and the scale of this pilot experiment is large, studies on the results of ESPD policies provide valuable insights into how dispatch policies should evolve in China and around the world.

Studies prepared to date that compare the results of ESPD to conventional dispatch policy in China typically report cost savings that were too small to justify the full scale implementation of ESPD (Kahrl et al. 2013). However, previous studies did not measure the CO_2 emissions from energy production under ESPD, or quantitatively evaluate ESPD's impact on renewable energy resources and on the power system's reliability. Furthermore, ESPD is only in its pilot phase, and should not be assumed China's only viable option to reform their energy dispatch policy. Developed countries in North America and Europe use Economic Dispatch (ED) to regulate their electricity markets – an approach that aims to minimize costs of energy. This strategy might be alternatively considered to ESPD in China to achieve aims of emissions and cost reductions.

In this study, I modeled two scenarios of Jiangsu province's (one of the five ESPD pilot provinces) electricity market in 2014 with hourly resolution. I applied ESPD policy to one scenario and ED policy to the other, leaving hourly electricity demand, weather conditions, fuel prices and other variables unchanged. Based on the electricity market models, I computed the costs and the CO_2 emissions of electricity generation in Jiangsu in 2014 under ESPD and ED. I then calculated the implied cost of CO_2 emissions reduction for policy scenarios prioritizing lower emissions (but resulting in higher costs). I also compared each policy's impact on the incentives for developing renewable capacity and on the reliability of the power system.

The study site in this research, the Jiangsu province, is a highly industrialized region in China with a carbon-intensive economy. The province's GDP is ranked 2nd in China (Yue et al 2013). Therefore, the results and the methodology of this research may provide useful information and tools to analyze the electricity dispatch policy development in other carbon-intensive provinces in China.

METHODS

Electricity dispatch in China

Void of a transparent and efficient market mechanism, wholesale electricity pricing is based on an estimation of capital investment and cost of energy production (Chen 2007). In order to provide fair returns to investors, annual operating hours for generators were set by state departments and assigned evenly to each generator (Gao and Li 2011). Power dispatch based on predefined quotas means that expensive and high polluting generators were used as often as cheaper and cleaner generators (Zhang and Heller 2004). Alerted by China's high level of energy consumption and dependence on coal, the National Development and Reform Commission

(NDRC), the State Electricity Regulation Commission (SERC) and the Ministry of Environmental Protection (MEP) began the Energy Saving Power Dispatch (ESPD) in 2007 (State Council of China 2007). Under ESPD, system operators were required prioritize renewable and low carbon energy resources while dispatching generators. The pilot project mandated 5 pilot provinces to start ESPD operation in 2008.

As one of the ESPD pilot provinces, Jiangsu is an apt geography for the electricity dispatch study described in this research. In 2010, the population in Jiangsu province was 74 million people, with a 58% urban population; the annual household power consumption was 1348KWh compared to the nationwide average of 1138KWh (NBSC 2010). Jiangsu is also home to one of the seven gigawatt wind-power bases in China - supporting this region's strong potential in renewable energy capacity (Zhang and Yang 2012).

Electricity dispatch models

I used two models of electricity dispatch to simulate the scheduling of electricity production required to meet Jiangsu's electricity load. The first model is the "Economic Dispatch" (ED), which has been widely used in U.S., Canada and European countries (Fernandes and Almeida 2003). Under ED, a system operator selects a combination of the cheapest generators that can satisfy energy demand and obey system requirements (Ongsakul and Chayakulkheeree 2003). The principle of ED facilitates an open and competitive energy market because it allows multiple companies to participate in the bidding process and the cost-based approach drives competition among vendors.

The second dispatch model is the "energy saving power dispatch" (ESPD). ESPD aims to minimize emissions of energy production and maximize energy savings. Starting in August 2007, the pilot operation of the ESPD was implemented in five Chinese provinces including Jiangsu. The order priority of ESPD dispatch is established in the following order:

1. Non-dispatchable renewables (including wind and solar) and hydropower;
2. Dispatchable renewables (including biomass) and hydropower;
3. Nuclear;
4. Cogeneration units, where electricity is the byproduct;
5. Demonstration projects and generators under national dispatch control;

6. Cogeneration units, where heat is the byproduct; coal gangue and washed coal;
7. Natural gas and gasified coal;
8. Coal;
9. And oil (NRDC et al. 2007).

Dispatch Model Implementation

The implementation of both ED and ESPD dispatch logics described above follows the thermal dispatch model that Kahrl and his colleagues built for the power dispatch in southern China (Kahrl et al. 2013). I assembled the information of all operating generators in Jiangsu, grouped them by fuel types and then thermal efficiencies, and ordered them either by the generation costs (ED) or by the priorities defined by the NRDC. I then incrementally allocated electricity generation following the order in the list of generator groups, until the full capacity of this generator group has been dispatched (in which case I allocated the remaining electricity generation to the next generator groups down the list) or the electricity demand at that hour was met. In the ED model, I included the minimal power output constraint to coal generators due to their limited ramping rate. When the minimal power output constraint was unsatisfied, I dispatched more coal generation and until the constraint was met, and curtailed other generators following the dispatch order until the electricity supply and demand were balanced again. The modeling process was illustrated in Figure 1.

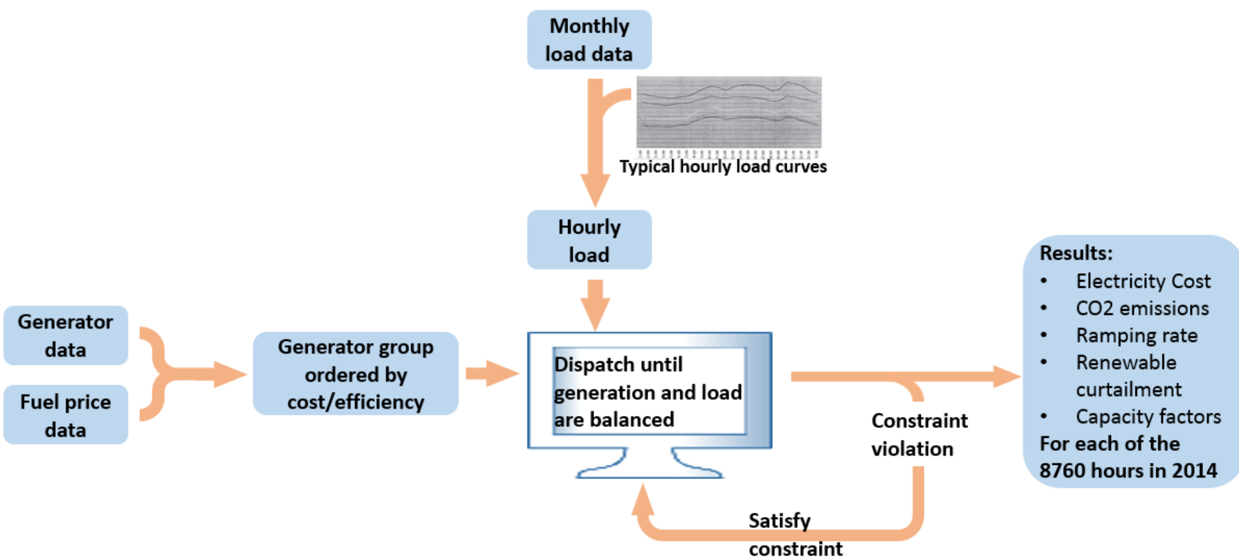


Figure 1. Energy dispatch modeling flowchart.

Data collection

Generators

I collected data on power plants in Jiangsu including their fuel type, generation capacity and heat rate from the Jiangsu Bureau of Statistics (JSSB 2014). I collected heat rates of thermal power plants from the Benchmarking and Competition in Energy Efficiency of National Thermal Plants results (China Electricity Council 2012). I assumed the marginal emission rate (CO_2 emission from the generation of one unit of energy, i.e. kg per MWh) of wind, solar, nuclear and hydropower to be zero because they do not consume fossil fuels to produce energy, although the life-cycle CO_2 emission of these energy sources do vary and exceed zero.

Load

I collected load data including the monthly electricity load and the monthly electricity generation in Jiangsu Province in 2014 and the typical daily load curves for peak and off-peak seasons. The peak season included the months of June, July, August, September and December; the off-peak season was defined to include all other months in a year (Yang 2007). To obtain hourly load data for each of the 8760 hours in 2014, I first extrapolated monthly load data between each month linearly to create daily load estimations for 365 days in 2014. I classified each of the 365 days as either a peak season day or an off-peak season day. Then I distributed daily load to each hour within the day based on the typical hourly load for the corresponding season. The final load data are presented in Figure 2 and

Figure 3. The total energy load in Jiangsu Province in 2014 was 501.254 TWh. 66.472 TWh was imported from other provinces and 434.782 TWh was produced in Jiangsu Province.

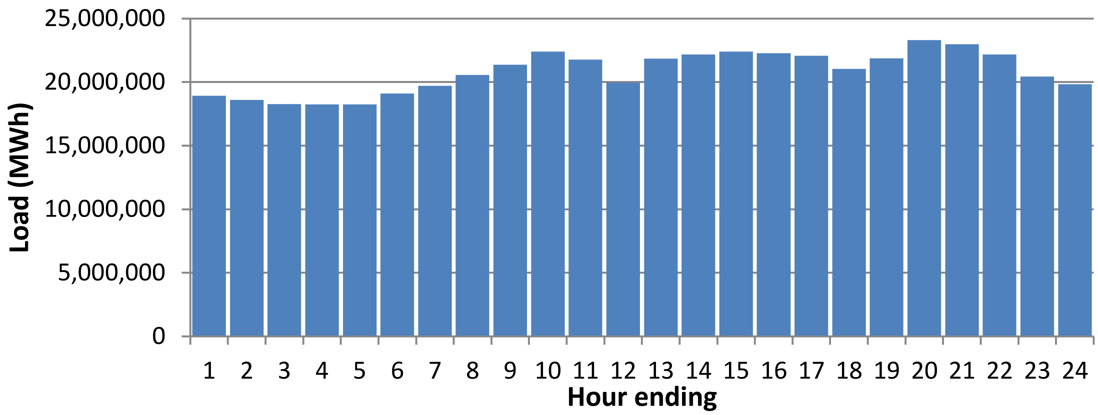


Figure 2. Jiangsu aggregate electricity load by hour. Each column represents the sum of all electricity loads in 2014 in the corresponding hour.

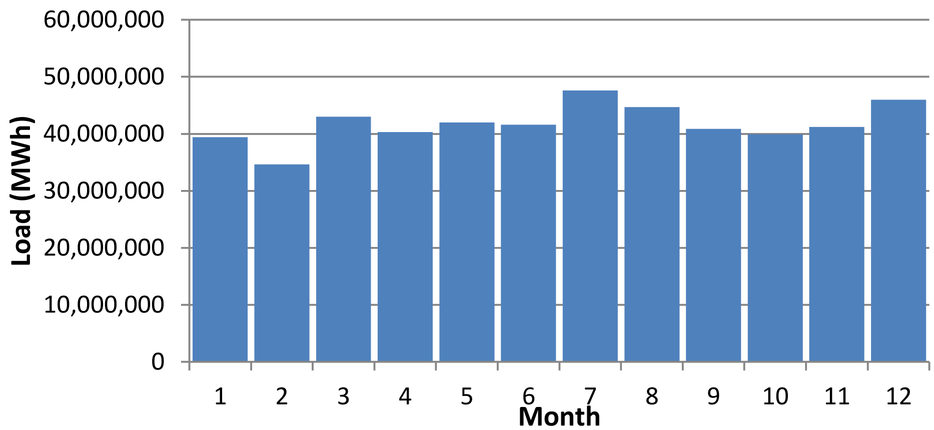


Figure 3. Jiangsu aggregate electricity load by month. Each column represents the sum of all electricity loads in 2014 in the corresponding month.

Comprehensive descriptions of the data collections in this research are given in Table 1.

Table 1. Summary of data sources and assumptions.

Data description	**Source**	**Major assumption(s)**
Monthly electricity load in Jiangsu in 2014	JSSB (Jiangsu Statistics Bureau)	
Monthly electricity generation in Jiangsu in 2014	Jiangsu Energy Regulatory Office of National Energy Administration of the PRC	The amount of electricity imported is the difference between Jiangsu's electricity generation and electricity load
Load of each hour within a typical	Yang 2007	The seasonal hourly load profile

day in Jiangsu; Definition of peak and off-peak seasons		applies to all days in the same season.
Generator information	SSB (Jiangsu Statistics Bureau) 2014 Yearbook	
Generator heat rate	Benchmarking and Competition in Energy Efficiency of National Thermal Plants in 2012	Generator heat rate does not change significantly between 2012 and 2014
Thermal generators minimum power output requirement	E.ON. "Improving flexibility of coal-fired power plants"	Minimum coal-fired power output requirement is aggregated on the system level and is 15% (as a percentage of the maximum coal-fired output in a day)
Wind power capacity factor in China	He and Kammen 2014	
Installed wind power in Jiangsu	National Energy Administration of China (NEA)	Used the total installed capacity at the end of 2014
Solar power capacity factor in China	He and Kammen 2016	
Installed solar power in Jiangsu	National Energy Administration of China (NEA)	Used the total installed capacity at the end of 2014
Price of coal in China	China Coal Transportation and Distribution Association (CCTD)	Used IRS 2014 Average Exchange Rates to Convert Chinese Yuan into U.S. Dollars
Price of natural gas in Jiangsu	Paltsev and Zhang 2015	Used IRS 2014 Average Exchange Rates to Convert Chinese Yuan into U.S. Dollars
Average price of nuclear fuel	Nuclear Energy Institute	
Levelized cost of solar and wind energy in China	Bloomberg New Energy Finance	Used average value of levelized cost for each technology in my calculation
Carbon intensity of fossil fuels	The U.S. Energy Information Administration (EIA)	

RESULTS

Cost of energy

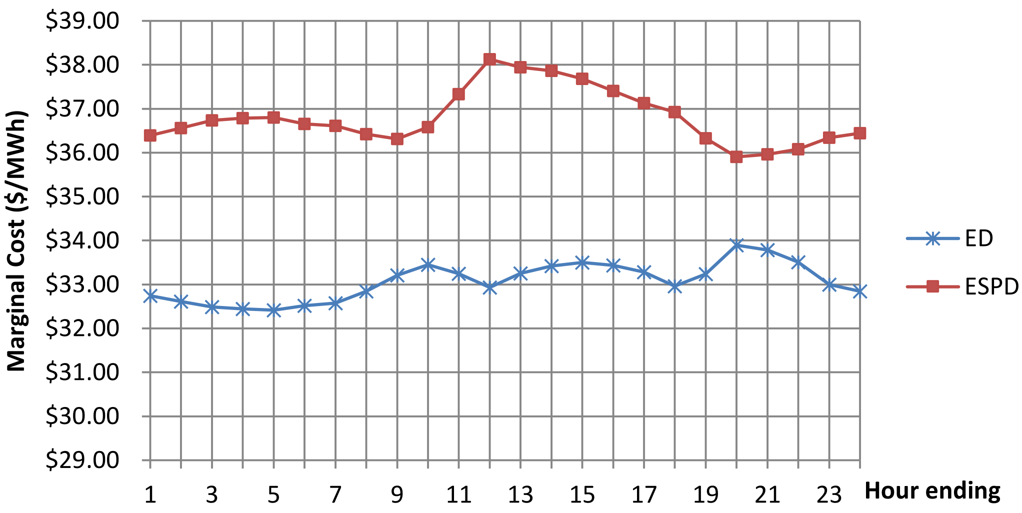
The total cost and the marginal cost of electricity were higher in ESPD by 12% (Table 2). For both ESPD and ED, the highest marginal cost occurred in winter and the lowest marginal cost occurred in summer (and both in August during evenings). The timing of the highest and the lowest marginal cost in both ESPD and ED followed the general pattern depicted in Figure 4.

Table 2. Summary of total cost and marginal cost of electricity in 2014.

	Total cost in 2014 (million $)	Average ($/MWh)	Highest ($/MWh)	Time when highest occurred	Lowest ($/MWh)	Time when lowest occurred
ED	$ 16,892	$ 33.70	$ 38.78	12/31/2015 hour 20	$ 30.53	08/21/2016 hour 1
ESPD	$ 18,865	$ 37.64	$ 42.75	01/31/2016 hour 12	$ 34.03	08/17/2016 hour 20

The inter-hour difference in marginal cost for ESPD and ED are shown in

Figure 4. The electricity cost was highest in hour 12[1] (at noon) in ESPD. The electricity cost was highest in hour 20 (in the evening) in ED, when the electricity cost in ESPD was the lowest. The lowest electricity cost in ED occurred in hour 5 (early morning). The changes in the electricity cost in ED were reverse to the changes in the electricity cost in ESPD from hour 18 to hour 15. The average difference between the costs under ED and ESPD was $3.94 per MWh.



[1] Hour n is the period corresponding to the nth hour in a 24-hour day, starting from 12:00am. Hour 12 is the 1-hour period between 11:00am and 12:00pm.

Figure 4. Marginal cost of electricity by hour under ED and ESPD in 2014

The inter-month difference in total electricity cost for ESPD and ED are shown in Figure 5, which shows similar patterns across the two dispatch models. The electricity cost was high in July and December, and was lowest in February in both ESPD and ED. The difference in the electricity cost between ESPD and ED was largest in September (265 million dollars) and was smallest in July (50 million dollars).

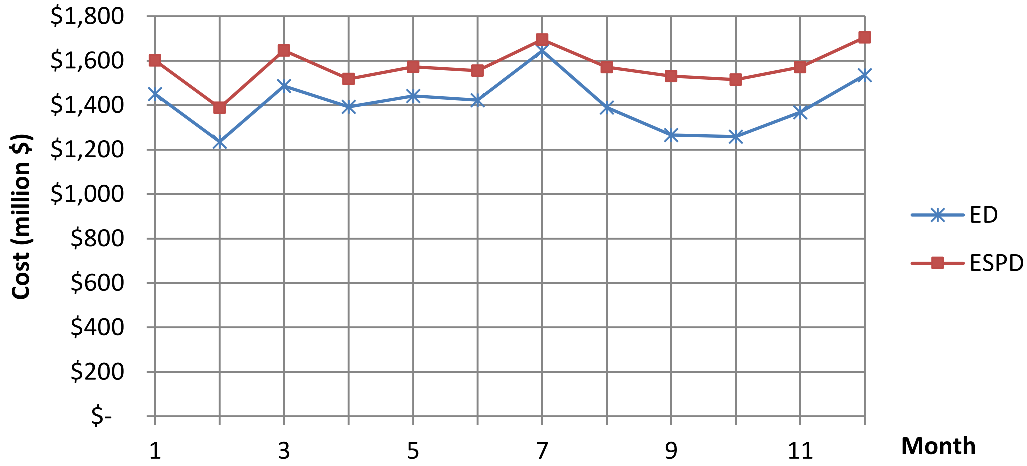


Figure 5. Monthly total cost of electricity under ED and ESPD in 2014

CO_2 emission from electricity generation

The annual total CO_2 emission and the marginal CO_2 emission rate were higher in ED by 6% (Table 3). For both ESPD and ED, the highest marginal emission rate occurred in summer during hour 20. The lowest marginal cost occurred in July in ED and occurred in January in ESPD, both around noon. The timing of the highest and the lowest emission rate in both ESPD and ED followed the general pattern in Figure 6.

It should be noted that the hour at which the lowest emission rate occurred is the same hour at which the highest marginal cost occurred in ESPD. This exemplified the contrary trends in the emission rate and the marginal cost under ESPD.

Table 3. Summary of total and marginal CO2 emission from electricity generation in 2014. For ED, the average emission rate was lower than the lowest marginal emission rate because marginal rate comes from the most polluting generator during that hour. The average emission rate is an average for all generators on the system.

	Total emission in 2014 (million tons CO_2)	**Average (kg/MWh)**	**Highest (kg/MWh)**	**Time when highest occurred**	**Lowest (kg/MWh)**	**Time when lowest occurred**
ED	376	751	1033.9	06/30/2016 hour 20	805.1	07/03/2016 hour 11
ESPD	355	709	766.3	07/08/2016 hour 20	661.0	01/31/2016 hour 12

The inter-hour difference in marginal cost for ESPD and ED are shown in

Figure 6. The marginal emission rate had two peaks in hour 20 in the evening and around hour 10 in the morning in both ESPD and ED. The lowest marginal emission rate occurred in hour 5 in ED and occurred in hour 12 in ESPD. The marginal emission rate had a smaller third peak in hour 15 in ED between the two peaks, but increased steadily from the trough to the second peak in ESPD.

Once again, I identified contrary trends in the emission rate and the marginal cost under ESPD. ESPD's hourly marginal emission curve in

Figure 6 is approximately the mirror reflection of its hourly marginal cost curve in

Figure 4.

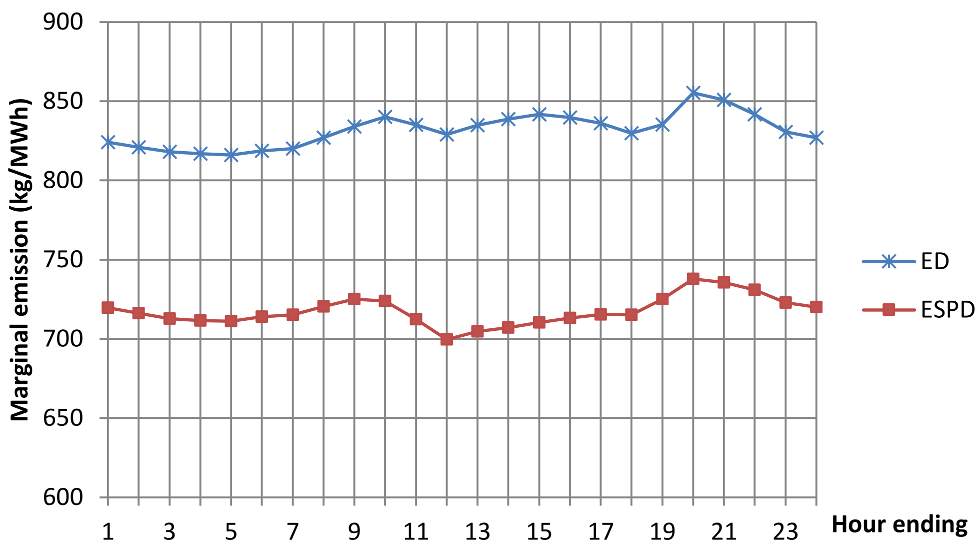


Figure 6. Marginal CO_2 emission from electricity generation by hour under ED and ESPD in 2014

The inter-month difference in the total CO_2 emission for ESPD and ED shows similar patterns in these two dispatch models (

Figure 7). The total emission was highest in July and lowest in February in both ESPD and ED. The monthly CO_2 emission in ED was consistently higher than in ESPD by about 6%. The trends in the monthly CO_2 emission follow the trends in the monthly cost in

Figure 5, suggesting that the aggregate emission and cost of electricity generation move in coordination in response to the inter-month changes in electricity load and renewable resources availability.

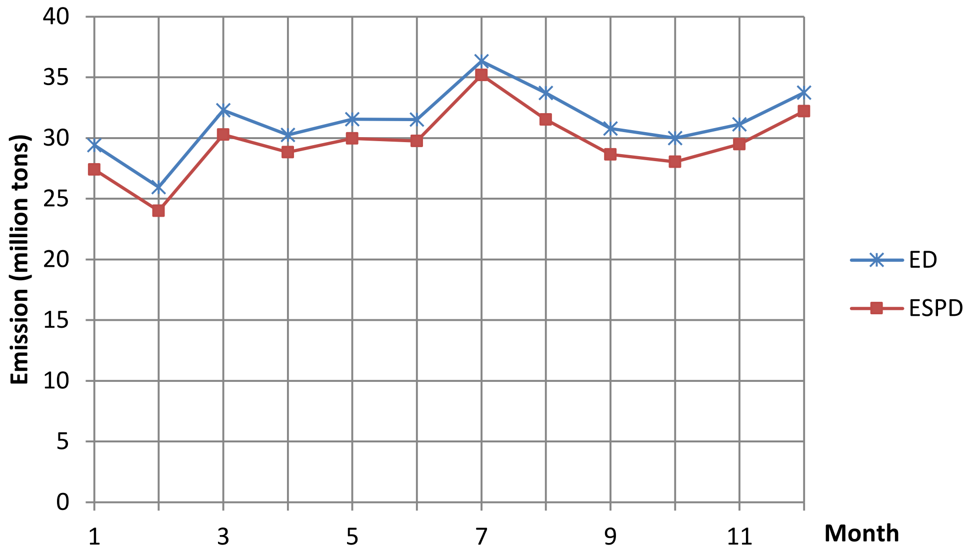


Figure 7. Monthly total CO_2 emission from electricity generation under ED and ESPD in 2014

Impact on renewable energy sources

Since the rule of ESPD prioritize renewable energy sources, solar and wind energy were not curtailed under ESPD. In the ED model, renewable resources were curtailed to allow coal generators to meet their minimum stable power output requirement.

1.31 million MWh of solar and wind energy were curtailed under ED in 2014, or 16% of the generation from solar and wind resources. At an average electricity cost of $33.70/MWh, the curtailment of 1.31 million MWh of renewables equals to $44.1 million additional fuel cost. It also means an additional 984 million kg of CO_2 emission. However, the consequence of curtailment was minor compared to the total electricity cost and CO_2 emission in Jiangsu at the current low level of renewable energy penetration. Figure 8 and Figure 9 show when the curtailment took place. The temporal distribution of curtailment was not clearly linked to the temporal variations in electricity load or the abundance of renewable energy.

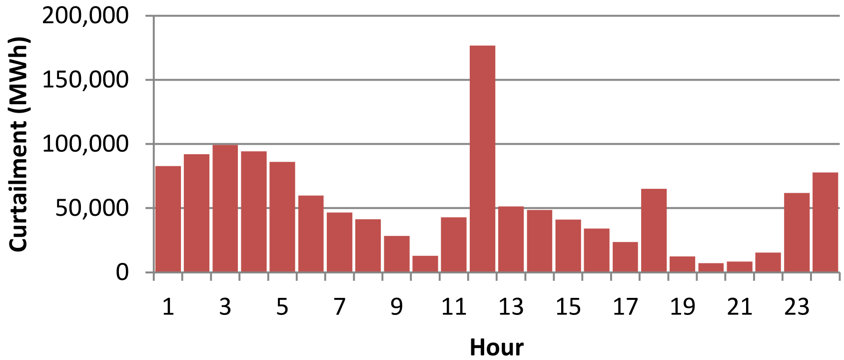


Figure 8. Wind and solar curtailment by hour under ED in 2014. Each column represents the sum of curtailments in the corresponding hour in 2014.

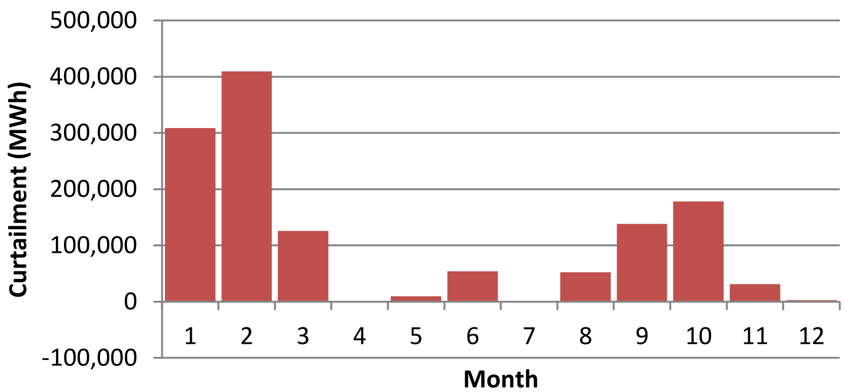


Figure 9. Monthly total wind and solar curtailment under ED in 2014.

Solar and wind energy producers also received higher economic incentives under ESPD than under ED in 2014. They were paid at a higher price per MWh on average, and received higher total payment under ESPD than under ED (Table 4).

Table 4. Payments to renewable energy sources under in 2014.

	Solar and wind generation in 2014 (MWh)	Total payment to solar and wind (million $)	Average payment to solar and wind ($/MWh)

ED	6,866,485	$	233	$	34.00
ESPD	8,176,230	$	786	$	96.19

Impact on the power system

Natural gas generators enjoyed a massive gain in capacity factor from 0.7% to 100% when the dispatch system switched from ED to ESPD (Table 5). Under ESPD, the decline in the capacity factors of coal generators was balanced by the increased capacity factors of gas and renewables.

Table 6, it is apparent that many of the 600MW coal generators replaced the 300MW coal generators as marginal units under ESPD. In ED, some 300MW coal generators needed to operate almost all the time to satisfy the electricity load. In ESPD, however, Jiangsu did not need that much coal generators to satisfy the load since gas generators were prioritized before coal generators.

Table 5. Capacity factors of different generator groups in 2014

	Solar	Wind	Coal 600MW	Coal 300MW	Coal <300MW	Gas
ED	15.8%	12.5%	98.1%	22.8%	1.0%	0.7%
ESPD	17.3%	16.2%	95.2%	13.2%	0.3%	100%

Table 6. Allocation of marginal generators

	Coal 600MW	Coal 300MW	Coal <300MW	Gas
ED	0%	99%	0%	1%
ESPD	46%	53%	0%	0%

Since coal generators have limitations on how fast they can change their power output, it is important to consider how coal generators were required to ramp under ESPD and ED. Overall, the ramping rate was slightly higher in ESPD than in ED (Table 7). I expected to find distinctive ramping rate duration curves for ED and ESPD since the dispatch orders in these two models were different. However, the ramping rate duration curves for ESPD and ED were similar (Figure 10). This could be explained by looking at the capacity factor of gas generators in Table 5: since the capacity factor of gas generators was around 0% in ED and around 100% in

ESPD, the power output of gas generators was almost constant in either ED or ESPD. Therefore the changes in the remaining loads were similar in ED and in ESPD even though the absolute loads could be different. Since incremental changes in the remaining loads were met with coal generators, the ramping rate duration curves for ESPD and ED look similar.

Although ESPD and ED resulted in the similar distributions of ramping rates, there was not enough natural gas generation capacity in ESPD to accommodate these ramping rates. For the top 10% of hours with the highest positive ramping rates, natural gas generation alone provided enough flexibility for more than half of the time in ED, but failed to provide enough flexibility for all 10 hours in ESPD (Table 7).

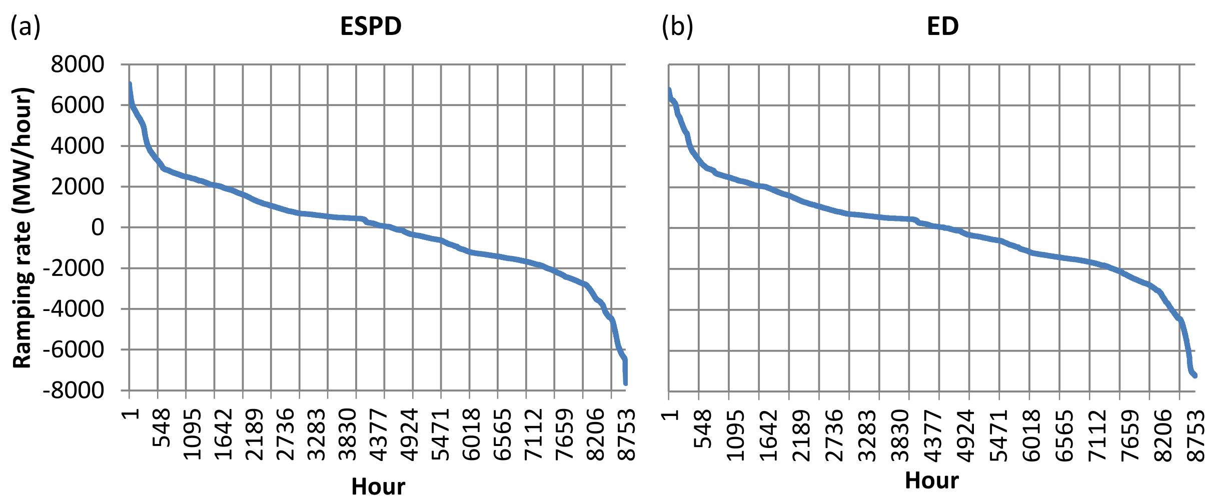


Figure 10. Ramping rate duration curves for ESPD (a) and ED (b) for coal generators. The ramping rate of 8760 hours in 2014 was ranked in the descending order. Positive ramping rate means an increase in power output and vice versa.

Table 7. Summary of ramping rate (positive ramping of coal generation).

	Maximum (MW/hour)	Time when maximum occurred	50 percentile	90 percentile	Flexibility coverage at 90 percentile
ED	6773	11/28/2016 hour 13	1172	2571	57%
ESPD	7051	7/10/2016 hour 20	1239	3413	0%

DISCUSSION

The cost of electricity in both the ESPD and ED models were aligned with the electricity load and the CO_2 emissions of electricity generation. The average cost of electricity under ESPD was 12% higher than the cost under ED, while the average CO_2 emissions from electricity generation in ESPD were 5.6% lower than those observed under ED. The cost of emissions savings under ESPD, however, were too high compared to the value of CO_2 emissions reported in China's carbon market or calculated by other studies (Interagency Working Group on Social Cost of Carbon, 2013). I also found that ED was not a viable policy for renewable energy to effectively participate in Jiangsu's electricity market with current technologies. However, ESPD posed threat to electricity grid's reliability, as fewer flexible natural gas generators were available to respond to changes in load.

Comparing costs

My results suggest that although the cost of electricity was generally higher under ESPD than under ED, both models provided prices that fluctuated in response to changes in load (at least on monthly basis). In addition, both dispatch models resulted in lower electricity cost than the actual electricity price in Jiangsu in 2014.

Since ESPD prioritizes gas generators over coal generators regardless of the cost of fuels, higher natural gas prices in 2014 ($12.17 per MMBtu) relative with coal prices ($3.83 per MMBtu) contributed to the higher cost under ESPD. However, the actual difference in the electricity cost between ED and ESPD was smaller than the price difference between natural gas and coal. This is because natural gas generators were generally more efficient than coal generators, and the capacity of natural gas generation (3.8 GW) was small compared with coal-fired generation capacity (23 GW). My observation suggests that the cost of electricity under ESPD was more sensitive to the price volatility of natural gas, as was the cost disparity between ESPD and ED. The outlook of electricity cost under ESPD remains uncertain due to the uncertainties in the future gas prices in China. On the one hand, the global natural gas price has been declining since 2008 due to the weaker demand in Asia and the abundant supply of shale gas from the U.S., despite of the small rebound in gas price in 2014[2]. On the other hand, Chinese NDRC has been raising the domestic natural gas wholesale price regularly, with the latest 10% increase in June 2015[3].

The cost of electricity was generally higher when monthly load and monthly total CO_2 emissions were high, thus providing appropriate price signals that discourage consumption during high load and high emission periods. The monthly total cost curves of ED and ESPD have similar shapes (

Figure 5). Their shapes follow the changes in monthly electricity load (

Figure 3). The pattern suggests that both models respond to increased load with increased electricity prices in the long run. This correlation between load and electricity wholesale price will likely lead to consistency between wholesale and retail price, and thus, improve market efficiency (Borenstein 2005). The consistency between electricity price and load will also enable real-time pricing of demand response programs, which give customers higher incentives to reduce their energy consumption during peak load hours (Hogan 2010). On an hourly basis, ED price followed more closely to the load than ESPD price (compare

Figure 5 and Figure 2).

Both ED and ESPD resulted in cheaper electricity (in $ per MWh) than the actual electricity price in Jiangsu in 2014 (Table 8). Given that the ESPD pilot program was announced in 2007 and began operation in 2008, the discrepancy between the actual electricity price and the ESPD modeled price supports NEA report findings that the ESPD pilot program was only partially implemented in Jiangsu (NEA 2015). The lowest retail rate from Table 8 ($42/MWh) should be close to the wholesale cost of electricity because the lowest rate applies to customers with the highest voltage requirement; higher end-user voltage reduces transmission losses and capital investment in substations (v. Meier 2006). Even when compared to the lowest rate in 2014, the cost of electricity under ED and ESPD were generally cheaper.

Table 8. Jiangsu province electricity energy rate structure from January 2014 to January 2015[4]. Excluding fixed monthly charges such as meter charge and capacity charge.

[2] U.S. Energy Information Administration (EIA) Natural Gas Weekly Update. Accessed on March 13 2016.
[3] National Development and Reform Commission. Filing ID: [2015] 2688.
[4] Source: (Jiangsu Electric Power Company City of Jiangyin Branch 2016)

Rate category	2014 rate ($/MWh)	2014 average rate ($/MWh)
Residential	$ 81 - $ 128	$ 96
Commercial and small industrial	$ 133 - $ 138	$ 135
Big industrial	$ 42 - $ 151	$ 105

One study that compared ESPD to the existing dispatch policy in China reported that the savings from ESPD was 1% of total electricity cost (Kahrl et al. 2013). My results demonstrated that switching from the existing dispatch policy to ED would result in a much larger cost savings (12% of annual total electricity cost) than switching to ESPD.

Is ESPD a cost-effective policy to reduce CO_2 emissions?

ESPD reduced CO_2 emissions from electricity generation, but the increased cost of electricity under ESPD relative to ED could not be: the CO_2 savings under ESPD implied a CO_2 price that is higher than both the market price of CO_2 in China and the global social cost of CO_2.

CO_2 emissions from electricity generation would decrease by 5.6% in 2014 if Jiangsu province adopted ESPD instead of ED. The reduction of CO_2 emissions under ESPD was mainly contributed by the prioritization of natural gas units, which emit less CO_2 to generate one MWh of electricity than coal units. The CO_2 emission rates under ESPD and ED were lower than the actual emission rates in China under the incumbent dispatch policy. The annual total CO_2 emissions from the electricity sector were 299 million tons (equivalent to 960 kg/MWh[5]) in 2008 (Liu Z. 2015). This value is higher than the average emissions under ED (751 kg/MWh) and ESPD (709 kg/MWh). The existing dispatch policy in China allocates similar load amounts to each thermal generator regardless of efficiency, so the observed reductions in emissions under ESPD and ED were expected.

The 5.6% carbon emission saving from ESPD seemed disproportional to the 12% cost premium compared with ED. However, in order to examine the cost-effectiveness of ESPD's emission reduction, I calculated the implied cost of carbon and compared it with carbon prices

[5] Electricity load in Jiangsu in 2008 was 311.8 TWh. Source: Jiangsu Energy Regulatory Office of National Energy Administration of China.

reported in other studies. The implied cost of CO_2 resulting from utilizing ESPD over ED would be:

$$Implied\ Cost\ of\ CO_2(\$\ per\ ton) = \frac{\text{additional cost of ESPD in 2014}}{CO_2\ \text{saving of ESPD in 2014}}$$

$$= \frac{\$\ 18{,}865\ \text{million}\ -\ \$\ 16{,}892\ \text{million}}{376\ \text{million tons}\ CO_2 - 355\ \text{million tons}\ CO_2}$$

$$= \$94\ \text{per ton}\ CO_2$$

The Social Cost of Carbon for Regulatory Impact Analysis under the Obama Administration's Executive Order 12866 calculated the global social cost of carbon and the average value for emissions from 2014 at $42 per ton of CO_2[6] (Interagency Working Group on Social Cost of Carbon, 2013). The implied cost of CO_2 in my study, $94 per ton of CO_2, falls between the 90th percentile and the 95th percentile in the Interagency Working Group's estimated range of the global social cost of carbon. It is also 15 times higher than the average carbon trading price at Shanghai Carbon Market in 2014[7], the nearest carbon trading market to Jiangsu province. Therefore, the emission savings from ESPD cannot justify the cost premium in ESPD compared with ED. A more effective way to mitigate carbon emissions from China's electricity sector is adopting ED instead of ESPD and simultaneously implementing policies that directly price CO_2 emissions, such as carbon taxes bundled with rebate or tax cuts in other sectors (Cao 2014).

Comparing incentives for developing renewables

ESPD provided greater incentives for solar and wind energy industries by reducing curtailment rates and offering higher price per MWh. The higher price paid to renewables in ESPD contributed more to the high revenue of wind and solar in ESPD than the reduction in curtailment. According to my results, the costs of solar and wind energy need to decrease by about 65% in order to become competitive with fossil fuels energy sources in the current market under ED without government subsidies.

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[6] The calculation intended to include (but is not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change. I converted cost from 2007 $ into 2014 $ using Bureau of Labor Statistics of the U.S.'s inflation data.

[7] Source: ChinaCarbon.net. Shanghai Carbon Market Trading Data. Accessed on March 14, 2016.

There was no curtailment of wind and solar energy in ESPD because ESPD inherently prioritizes renewable energy. In ED, however, 16% of wind and solar energy output was curtailed in 2014. The curtailment had a greater impact on wind than on solar in terms of reductions in capacity factors (actual energy output as a percentage of nameplate capacity): the capacity factor for wind reduced from 16.2% to 12.5%, while the capacity factor for solar reduced from 17.3% to 15.8%. The difference between wind and solar was largely caused by desynchronization between wind resource abundance and electricity load in Jiangsu – wind resources were less abundant during the day and in the summer when electricity load was generally higher.

Other studies have also suggested that curtailment of wind energy is a notable issue in China. The U.S. - China Economic and Security Review Commission found that 11% of China's wind power was curtailed in 2013, compared with 1% - 4% in the United States (Koch-Weser and Meick 2015). The higher curtailment rate in 2014 observed in my calculations was probably due to the rapid expansion of renewable energy in Jiangsu in 2013 and 2014 when the growth in electricity demand was moderate.

Solar and wind energy received a total payment in ESPD that was more than three times as high as they received in ED. While solar and wind resources received market electricity price in ED, they were paid levelized costs of energy of wind or solar under ESPD which are usually higher than the market electricity price. My result implied that under ED, the levelized costs of wind and solar energy need to go down to $34 per MWh (or 65% reduction) to just breakeven without subsidies. Solar power in Jiangsu received a local subsidy of $31 - $47 per MWh in 2014 (Jiangsu Provincial Government 2012), but a subsidy of this amount could not help solar farms to breakeven in that year. Once the levelized costs of wind and solar energy drop below $34 per MWh, wind and solar will be paid at a higher price under ED than under ESPD.

Comparing electricity grid's flexibility

Because renewable energy penetration was low in my model (only 1.3% - 1.5% of total generation was from solar and wind resources derived from 2014 data), the prioritization of intermittent renewable energy in ESPD did not disturb the system's ramping rate substantially.

The ramping rate duration curve for ESPD is not significantly different from the curve for ED (Figure 10).

Although the ramping rates were similar in both models, ESPD policy undermined the electricity system's ability to accommodate these ramping rates (Table 7. Summary of ramping rate (positive ramping of coal generation)). Natural gas generation is an important flexible electricity source that can follow changes in load. However, since natural gas resource was prioritized in ESPD, the remaining capacity of natural gas generation was depleted. My result is a quantitative confirmation of the qualitative observation that ESPD might reduce the energy system's flexibility compared to the conventional dispatch method (Kahrl et al. 2013).

Limitations and Future Directions

The difference between the results of ED and ESPD observed in this study are primarily caused by the prioritization of natural gas generators in ESPD. Therefore, the cost disparity in this model is sensitive to changes in the relative prices of coal and natural gas. If solar and wind power continue to expand in Jiangsu Province, the cost and emissions gap between ED and ESPD will be increasingly influenced by the utilization of wind and solar generation units. Future studies should expand and solidify this comparison by studying the growth of solar and wind power in Jiangsu province and test the sensitivities of ED and ESPD to higher penetration of renewable energy and different coal and gas price outlooks.

CONCLUSIONS

My research provided a quantitative comparison between two alternatives, Economic Dispatch and Energy Saving Power Dispatch, to reform China's electricity dispatch policy. Results suggest it is better to reform than not to: both reform options align the electricity wholesale price with the system load and CO_2 emissions condition, which can improve energy market efficiency and facilitate demand response programs. Effective implementations of ESPD and ED also both provide cleaner and less expensive electricity than the existing dispatch in China does currently.

My research also demonstrated that ED has several advantages over ESPD and can be a better reform option. Electricity cost is lower under ED and the CO_2 emissions savings under ESPD are not cost-effective. ED also provides stronger system flexibility, although it curtails more and offers fewer incentives to develop renewable energy. A combination of policies can make the best use of ED while achieving emissions reduction. For example, ED can be implemented together with a carbon taxation and rebate program that reduces CO_2 emission with a specific and transparent price on carbon. The cost-savings from ED can then be used to fund renewable energy subsidies to maintain a reasonable level of incentives for supporting an expanding renewables industry.

This case study of Jiangsu province provides useful data and a framework for policy makers to evaluate and compare ESPD and ED. My results support the current reform of dispatch policy in China – a better market policy can lead to tangible improvement in the quality and the carbon intensity of the nation's energy supply. In order to maximally derive benefits from China's dispatch policy reform, policy makers need to at least consider the ED option and evaluate potential policies based on cost, emissions, impact on renewable energies and impact on the energy system's flexibility.

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