RAP® 睿博能源智库

iGDP

碳市场设计讨论专题

改善电力调度机制
助力全国碳市场发挥功效

Topics in Carbon Market Design: Power Sector Dispatch Reform and China's National ETS

Max Dupuy and Ang Li

2016 年 12 月

December 2016

The Regulatory Assistance Project (RAP)® • 睿博能源智库
中国 • 欧盟 • 美国 • 印度
Beijing, China • Berlin, Germany • Brussels, Belgium • Montpelier, Vermont USA • New Delhi, India
北京市朝阳区建国门外大街19号国际大厦2504室 • *phone:* + 86-10-85262241
CITIC Building, Room 2504 • No 19 Jianguomenwai Dajie • Beijing 100004 • *phone:* +86-10-85262241
www.raponline.org

目录

Table of Contents

前言

在国务院发布的《“十三五”控制温室气体排放工作方案》中提出，中国将于 2017 年启动全国碳排放权交易市场，涵盖石化、化工、建材、钢铁、有色、造纸、电力和航空等 8 个行业中年耗能 1 万吨标准煤以上的企业。按照“方案”内容，几乎所有电力企业都要纳入全国碳交易市场。中国的电力行业消费了全国 50%以上的煤炭，贡献了 40%左右的 CO_2 排放，是最大的排放部门[1]，其排放的变化对全国达峰目标的完成与否至关重要。

与此同时，新一轮的电力行业改革也在进行中。《关于进一步深化电力体制改革的若干意见》（9 号文）于 2015 年 3 月下发，同时出台的还包括《关于有序放开发用电计划的实施意见》等 6 份配套文件。这些文件对具体的改革领域提出了明确的要求。其中，9 号文中明确提出了这轮改革的关键目标，包括“提高能源利用效率”以及“促进节能环保”，并且将节能减排作为了主要原则之一。

电力行业改革和碳市场建立这两个政策进程从设计到执行都有着紧密的联系。在缺乏相互协调的情况下，各自设定的政策目标可能会面临重重挑战，并限制两个政策实际作用效果。这两个进程之间的价格信号传导被视为最为关键的联系之一，而现行的电力调度机制可能是制约碳市场促进电力行业低碳化的障碍。

进一步放开发用电计划被视为此轮电改的核心任务之一。作为 9 号文的配套文件之一，《关于有序放开发用电计划的实施意见》提出了放开发用电计划的原则和方向。今年 7 月，发改委经济运行调节局下发的《关于有序放开发用电计划工作的通知（征求意见稿）》则预示此项工作进入操作层面。

本文将向对负责设计全国碳排放交易体系的相关方和决策者们简略介绍现行的电力调度机制及其与碳市场之间的关系 。

只有电力市场改革与碳市场建立有机结合，才能促进中国的电力行业低碳化。本文将着重介绍改善电力调度机制与碳市场。在之后的文章中，我们将探讨碳排放交易体系的设计与电力市场改革其他方面的结合。

[1] Zhao, X.L., Ma, Q., & Yang, R. (2013). Factors influencing CO2 emissions in China's power industry: Co-integration analysis[J]. *Energy Policy*= 57: 89-98.

什么是电力调度?

电力行业的属性与中国碳交易体系中包含的其他行业有很大差别。与那些能够提前生产出来并能在仓库中储存的大宗商品不同（比如铁和铝），电的生产和使用具有实时性[2]。 调度中心负责管理电网系统的运作， 要保证需求侧和供给侧的实时平衡。电力需求在一天之内是波动的，电网上的其他一些情况，比如输电线路拥堵也是如此。

电力调度是调度中心管控的过程，包括决定使用哪一台发电机来满足电力需求并保持电网运行的稳定。调度中心必须每分钟、每小时、每天都进行实时的电力调度决策才能保证电力供需的平衡。近年来，可再生能源（比如风能和太阳能）的装机容量不断增加，使调度中心在平衡电网方面遇到了新的挑战。与传统的燃煤和燃气发电站出力的方式不同，可再生能源的发电量基本依赖气象条件，存在间歇性和波动性，调度中心不能对可再生能源电源进行直接控制。这个挑战是能够克服的，可以通过有效的调度方法，连同其他的技术手段，并对电力价格和电力行业政策的其他方面做出改变等多元化措施来应对[3]。

经济调度（Merit Order Dispatch）：国际大多数地区指导调度的原则

在北美、欧洲和世界大部分地区，调度中心基于经济调度方法做出调度决策。这种方法的基本思想是根据运营成本[4]把每个可用的发电机组进行排序。运营

[2] 未来可能会出现诸如大型储电池等形式的储电装置。然而，尽管储电成本在降低，但依然较高，目前相比于电力系统的整体规模有限。

[3] 关于如何应对可再生能源间歇性和波动性的讨论，可见 http://www.nrel.gov/docs/fy16osti/66728.pdf and http://www.raponline.org/document/download/id/7482

[4] 运营成本也可以叫“短期边际成本”或“可变成本”。

成本很大程度上反映了燃料成本和发电机把燃料转化成电力的效率。当碳价格存在时，排放成本也反映在每个发电机的运营成本中。

根据发电机的运营成本的“优先次序”，调度中心优先使用成本最低的发电机[5]。 为了处理供给和需求侧的变化[6]以及电网拥堵等情况，他们每天都会多次重复这样的排序流程。由于电网拥堵和其他一些电网可能出现的变化，调度中心并不一定每次都使用成本最低的发电机。但是对整个电网的运营来说，时刻最小化系统内的总运营成本是一条关键的原则。

经济调度与排放交易有什么关系？

理论上说，碳价与经济调度相互作用会鼓励可再生能源以及其他低排放发电机组。在欧盟碳交易地区以及美国执行碳交易的州，我们也看到了这种效果。由于碳成本是发电机组运营成本的一部分并且发电机组的碳排放各不相同，碳价格也使得低排放电源在“优先次序”中的地位进一步得到巩固，从而鼓励更低排放机组的使用。

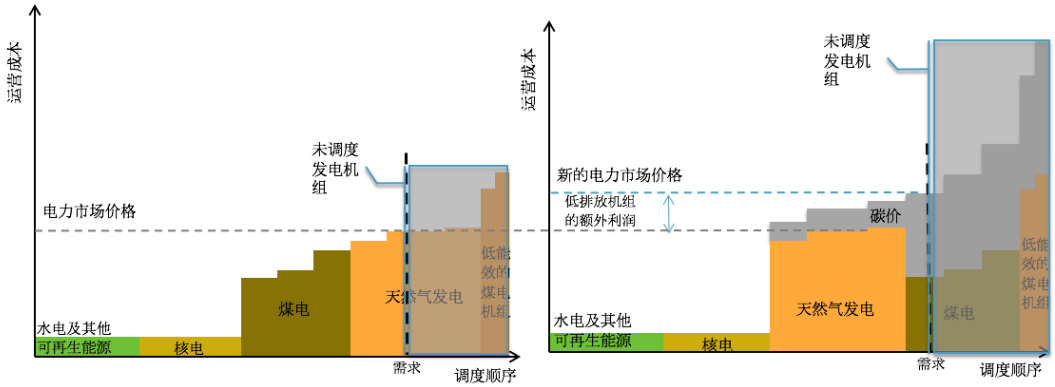
在电力现货市场中，碳价的出现相当于提高了以化石为燃料的发电机的运营成本。但核电以及可再生能源则没有这部分成本，而天然气的碳排放成本通常会低于煤电。碳价和经济调度的相互作用一般都会使排放相对较低的发电机组获得更高收益。这样就会鼓励投资者们将关注点更多的投放在低排放发电装机上 。如图 1 中左右两边的对比所示。

图 1 中左边的柱形图展示的是在电力系统中某一小时内不同类型发电机组的“优先次序”示意图。可再生能源没有燃料成本， 因此可再生能源发电通常会排序第一。以煤炭或者天然气作为燃料的发电机组能效也千差万别，因此运营成本也不一样，“优先次序”自然也不一样。图 1 中右边的柱形图展示了引入碳价后所带来的改变。

[5] 需要注意的是，资本成本并未反映到经济调度排序中 。

[6] 需求的波动源于终端用户的能源使用情况，这些变化是时时发生的。

图 1. 碳价形成前后电力系统中不同类型发电机组“优先次序”变化的简化示意图



发电调度在中国是怎样运行的？

在中国，电力部门以及电力调度的方式与世界上其他国家都有着明显的区别。近几十年以来，电力部门大力促进发电容量增长以满足重工业部门发展的电力需求。为了支持对发电厂投资，政府实行了“年度发电量计划”，目的是保障发电装机——特别是燃煤电厂——有稳定的收益。调度决策需要满足年度发电量计划，保障每一个燃煤发电机组都能达到年度计划分配的的运行小时数。总之，调度并不保证运营成本最小化。在任何给定时段，被调度的发电机组不一定是运营成本最低的可用机组 。

从前这种调度方式的不利影响并未突出显现：因为在一天之内，工业需求都相对稳定，很多工厂的生产昼夜不停，平衡电力系统的任务比较简单。这对于电力系统的灵活性并没有提出太高的要求。概括来说，中国在拉动发电投资以支持重工业发展方面取得了较大的成功，相比其他发展中国家获得了显著成就。

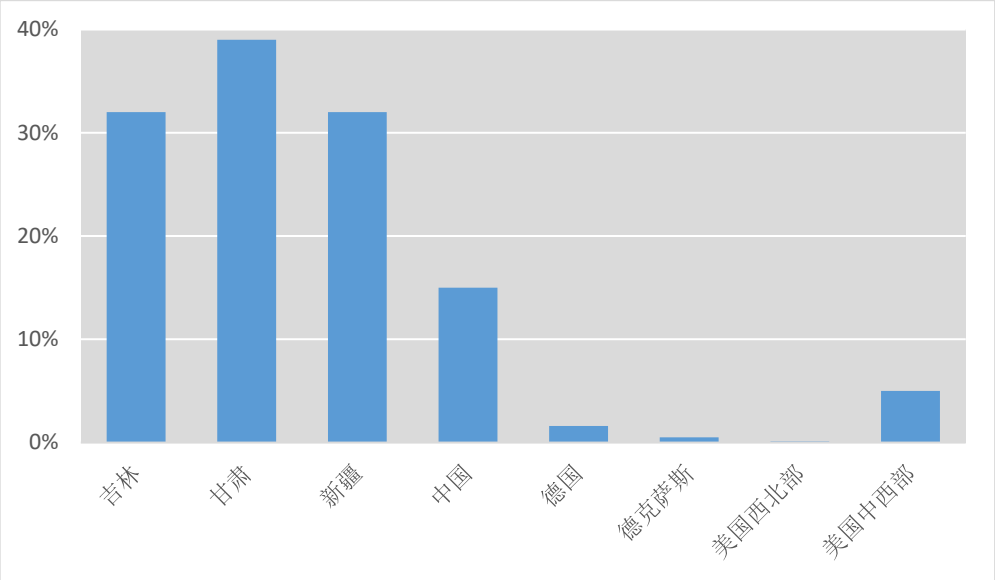
这种调度方式虽然以前取得了成功， 且与中国的国情相适应，然而现在，这种方式已经十分低效了。传统的电力调度方式不够灵活，无法支持供给侧（风能和太阳能等波动性的可再生能源）和需求侧（非工业用户）日益增加的多变性。这种调度方式导致了严重的弃风、弃光和弃水现象的发生（见图 2）。

另外，沿用传统调度方式意味着在更高效发电机组可用的情况下经常使用低效的燃煤发电机组，导致电力部门不必要的高成本和高排放。

中国的排放交易与电力调度

中国的电力调度方式是碳定价工作的一个壁垒。原则上，碳定价应当使得高排放发电站的运营成本上涨，从而影响到调度的优先次序，促使排放更低的资源被优先使用。这样也会发出信号，吸引更多资源投入到低排放电源中。但是，正如同我们所见，中国的电网企业一般不会根据运营成本来调度发电。这也就意味着与碳价相关联的价格信号并不会有效的传达到电力系统中，以达到电力系统低碳化的效果。

图 2. 中外不同地区、国家间弃风率的比较 [7]



[7] 吉林、甘肃、新疆及中国弃风率的数据为 2015 年度的，来自《2015 年风电产业发展情况》，http://www.nea.gov.cn/2016-02/02/c_135066586.htm；德国、德克萨斯、美国中西部及西北部弃风率的数据为 2014 年度的，引自 *Renewable Power Curtailment Skyrockets in Germany*，http://energytransition.de/2015/11/renewable-power-curtailment-in-germany

改善中国的电力调度机制

近几年，中国出台了一些试点项目和政策文件，用于改善电力调度。例如，自 2007 年以来，法律规定了保障收购可再生能源。几个省级“节能调度“试点项目也已经运营了数年。自 2015 年 3 月以来，电力调度就成为了电力行业改革中的重要部分（“电改 9 号文”）。最近也出台了一些新的政策文件，旨在改善调度和减少可再生能源弃电现象。 相关文件包括：

- 2015 年 3 月，《关于改善电力运行调节促进清洁能源多发满发的指导意见》。
- 2015 年 8 月，《中华人民共和国大气污染防治法》中指出，“电力调度应当优先安排清洁能源发电上网”[8]（第 42 条）。
- 2015 年 9 月发布的中美元首气候变化联合声明，其中中国承诺“将推动绿色电力调度，优先调用可再生能源发电和高能效、低排放的化石能源发电资源”。
- 2016 年 3 月的《可再生能源发电全额保障性收购管理办法》（625 号文），再次强调了可再生能源发电的优先地位并提出了对弃电新的补偿办法。
- 2016 年 7 月的《关于有序放开发用电计划工作的通知（征求意见稿）》

这些政策文件表明相关部门对改善电力调度的日益重视。这可能会促进系统灵活性的改进，可再生能源限电情况的减少，系统成本和排放的降低。然而，实施的细节尚不清楚。这些政策也并未提出要向真正的经济调度转变。

改善调度机制的一个相关的问题是如何对发电商进行补偿。现行的上网电价机制使得燃煤电厂由于担心收入和利润的降低而对改善调度机制持反对态度。此外，现行的调度机制和定价政策还严重限制了对更灵活的燃煤和燃气电厂的

[8] “电力调度应当优先安排清洁能源发电上网,” 详见 http://news.xinhuanet.com/legal/2015-08/30/c_128180129.htm

投资，也限制了更灵活运营现有发电厂的商业模式。至今出台的这些政策文件也没有清晰的提出发电商补偿问题和灵活性奖励机制的具体改进办法[9]。

在刚刚公布的《电力发展“十三五”规划》中已经明确提出，中国将于“2018 年底前启动现货交易试点；2020 年全面启动现货交易市场”。理论上，如果设计并实施得当，这样的现货市场可以解决补偿问题，并为经济调度提供指导方向。

结论

理论上讲，碳排放交易体系帮助电力部门低碳化的重要渠道之一是在调度过程中发出信号。 其他国家使用的经济调度使其与碳定价机制进行相互的补充和激励。然而，中国的调度机制并没有遵从经济调度的方式，在这种背景下，碳交易无法有效助力电力系统低碳化的目标。

改善电力调度机制——作为电力体制改革的一部分，正在推进。然而，未来实施之路并不清晰。对负责设计全国碳排放交易体系的决策者和相关方来说，密切参与到完善电力调度机制的工作中十分重要。

[9] 更多关于发电商补偿的信息，请见 *Power Sector: Deepening Reform to Reduce Emissions, Improve Air Quality and Promote Economic Growth*, http://www.paulsoninstitute.org/economics-environment/climate-change-air-quality/research/power-sector (Chinese and English versions)

Introduction

The Chinese government plans to launch a national carbon emission trading scheme (ETS) in 2017, covering petrochemical, chemical, building materials, iron and steel, nonferrous metals, papermaking, electric power and aviation, among other sectors.[1]

China's electricity sector accounts for more than 50 percent of the country's annual coal consumption and contributes about 40 percent of its CO_2 emissions, so power sector policy will be critical to the success of the ETS.

At the same time, a major power sector reform effort is also underway in China, launched in March 2015.[2] The policy reform announcement includes "emission reduction" and "energy conservation and environmental protection" as "basic principles" for power sector reform. However, progress has been uneven and many implementation details have yet to be ironed out.

So far, there has been insufficient coordination between power sector reform and design of the ETS. The carbon market is unlikely to be very effective in transforming China's power sector unless ETS design is carefully integrated with power sector reform. This paper will address the links between ETS implementation and one aspect of power sector : dispatch reform. In particular, this paper will briefly introduce the topic of power sector dispatch reform for the benefit of policymakers and stakeholders in China who are focused on broader issues of national ETS design. We will explain how power sector dispatch reform is one element needed to facilitate the effective operation of the ETS in this crucial sector. In subsequent papers, we will discuss integrating ETS design with other aspects of power sector reform.

What is generator dispatch?

The power sector has some characteristics that are very different from other sectors that will be covered under China's emissions trading scheme. Unlike, say, steel or aluminum, which can be produced ahead of time and stored in warehouses until delivered to customers, electricity generation must be matched with use of electricity on a moment-by-moment basis.[3]

---

[1] State Council 13th Five Year Plan, Controlling Greenhouse Gas Emissions Working Agenda《"十三五"控制温室气体排放工作方案》

[2] Document 9, State Council and Central Committee of the Communist Party, Opinions on Deepening Electricity Reforms (关于进一步深化电力体制改革的若干 意见; March 2015)

[3] In the future, there may be large-scale storage of electricity, in the shape of large batteries or other forms. However, although storage costs are decreasing, it is still expensive and will likely be limited, compared with the overall size of the power system, for some time.

Electricity grids are managed by system operators, who are responsible for maintaining near-instantaneous balance of overall supply and demand on the grid. Demand fluctuates throughout the day, as do other conditions on the grid, such as congestion of various transmission lines.

Generator dispatch is the process, managed by the system operators, of deciding which generators to use to meet demand and maintaining stability of the grid.[4] The system operators must make these dispatch decisions on a day-by-day, hour-by-hour, and minute-by-minute basis so that electricity demand and supply are always in balance. In recent years, system operators have begun to face a new challenge of balancing the grid with the presence of growing amounts of renewable sources of generation—wind and solar—that cannot be directly controlled in the manner of a traditional coal- or gas-fired power plant. This challenge is surmountable, but requires multi-faceted solutions, including efficient approaches to dispatch, along with other technical approaches and changes to electricity pricing and other areas of power sector policy. Dispatch reform in China is the subject of the current paper.

Economic dispatch: The guiding principle of dispatch in most of the world

In North America, Europe, and most other places in the world, system operators make dispatch decisions based on the "economic dispatch" approach. The basic idea of economic dispatch is to rank each available generator by operating cost (also called "short-run marginal costs" or "variable costs"). Operating cost mostly reflects fuel cost and the efficiency with which the generator converts the fuel into electricity. *Where there is a carbon price, the cost of emissions is also (at least partially) reflected in the operating cost of each generator.*

According to this ranking of available generators, also known as the "merit order," the system operator *makes use of the least costly generators first.*[5] The system operator repeats this exercise multiple times each day in order to deal with fluctuating demand, supply, and grid conditions. The system operator may not always be able to use the least-cost generator, due to grid congestion or other changes in grid conditions, but minimization of total operating costs (across generators) is a key principle for operation of the grid.

Figure 1 demonstrates a merit order for a given hour on a hypothetical power system. Renewable energy has zero fuel cost and zero social cost of emissions, so when it is available, it is usually ranked first in the merit order. Coal- and gas-fired generators have varying levels

[4] In Chinese, the word "diaodu," literally "dispatch," is commonly used to refer to a wide variety of system operations, including day ahead and real-time operations. We follow that usage here.

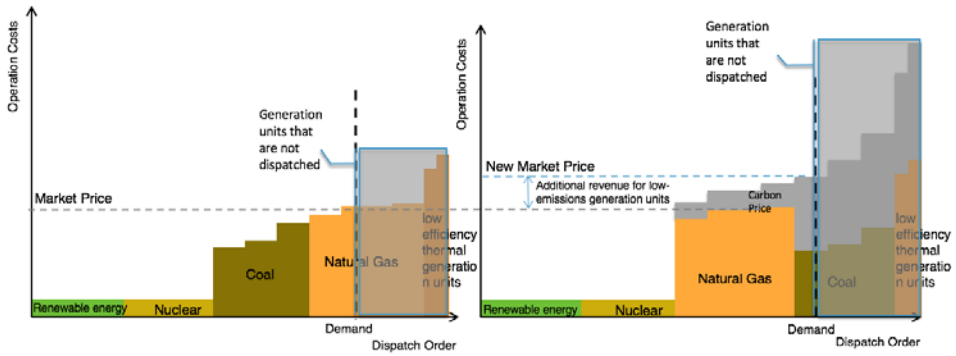
[5] Note that capital costs are *not* reflected in the dispatch ranking. The basic logic is that dispatchers are responsible for minimizing the costs of producing electricity from the set of resources that already exist.

of efficiency, and thus different operating costs, so have different positions in the merit order.

What does economic dispatch have to do with emissions trading?

Carbon pricing and economic dispatch interact to support renewable generators and other relatively low-emissions generators. Because carbon costs are part of any generator's operating costs, and because carbon emissions vary across generators, a carbon price reinforces the position of relatively-low emission resources in the merit order. Carbon pricing can sometimes cause rearrangement of the merit order in favor of relatively low-emissions generators. In addition, in the EU and US the interaction of carbon pricing and economic dispatch typically allows relatively low-emission generators to earn higher revenue in any given year.[6] In turn, this provides incentive to investors to invest in more low-emissions generation capacity and to invest less in high-emission capacity. In the context of a typical competitive electricity spot market, all generators are paid the market price and the effect of implementation of a carbon price will be to increase profits for zero-emission power plants (as in Figure 1).

Figure 1. Carbon pricing in the context of merit order dispatch and a competitive spot market: A simplified example



How generator dispatch works in China

In China, the power sector—including the approach to dispatch—evolved in a way significantly different from the rest of the world. In recent decades, policymakers put great emphasis on ensuring the rapid expansion of generation capacity to meet demand for

[6] Where does this higher revenue come from? Many parts of the US and Europe have electricity wholesale markets, in which all dispatched generators are paid the marginal cost of the last generator dispatched. In this way, a carbon price leads to higher revenues for generators that have better rankings in the merit order. For renewable generators, with near-zero marginal costs and zero emissions, higher prices mean higher revenues.

electricity from heavy industry. To support investment in power plants, an annual planning process was implemented with the goal of providing a stable source of revenues to generators—which, in practice, focused on coal-fired generation. Dispatch decisions were required to support this plan and were based on the objective of making sure each coal-fired generator gets an annually planned allocation (年度发电量计划) of operating hours. In short, minimizing operating costs were typically *not* a focus of system operators. The generators dispatched at any given moment were often *not* the lowest-operating-cost generators available.

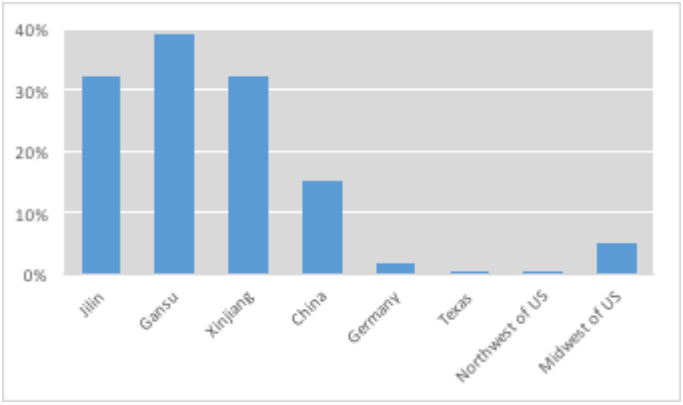
In past decades, the downsides were limited: Because industrial demand tends to be fairly constant throughout the day, with many factories running production at a more-or-less constantly throughout the day and night, the system operators' task of balancing the system from hour to hour was relatively straightforward and there was little need for flexibility. In short, China's approach can be considered to have been quite successful in meeting the goal of mobilizing huge investments in generation capacity to support the development of heavy industry. This was a significant accomplishment that other developing countries have struggled to match.

However, while the approach to dispatch that evolved in China may have suited China's conditions in earlier years, it now represents significant inefficiency. China's typical approach to dispatch is not sufficiently flexible to support the rising variability of demand (due to increasing importance of non-industrial customers) and supply (due to growing wind and solar generation). The approach to dispatch contributes to significant curtailment of wind, solar, and hydro generators. (See Figure 2.) In addition, China's typical approach to dispatch means that less efficient coal-fired power plants are often used when more efficient plants are available. As a result of these problems, power sector costs and emissions are unnecessarily high.

Emissions trading and dispatch in China

China's approach to generator dispatch represents a barrier to the working of carbon pricing. In principle, carbon pricing should increase the operating cost of high-emission power plants. In other countries, this then influences the dispatch merit order, resulting in lower-emissions resources being used first. This also sends signals for more investment in low-emissions resources. But, as we have seen, in China system operators have typically not dispatched based on operating costs. This means that the economic signals associated with carbon pricing are not effectively transmitted through the power system.

Figure 2. Wind Energy Curtailment in China, with International Comparison[7]



Dispatch reform in China

A number of pilots and policies in recent years have attempted to reform dispatch in recent years. For example, China has had a law requiring mandatory purchase of renewable energy since 2007. Several provincial pilots for "energy efficient" dispatch have been under operation for years. Since March 2015, dispatch reform is a major part of the current power sector reform effort（9 号文）. Recently there have been several new policy documents intended to reform dispatch and reduce renewable energy curtailment. Relevant documents include:

- Document 518, *Improving Operation and Utilization of Clean Energy* (《关于改善电力运行调节促进清洁能源多发满发的指导意见》)
- The revised Air Law, which requires that "clean energy be given priority in electricity dispatch" (Article 42).[8] （《中华人民共和国大气污染防治法》）
- The US-China Joint Presidential Statement on Climate Change, issued in September 2015, in which China commits to "promote green power dispatch, giving priority, in distribution and dispatching, to renewable power generation and fossil fuel power generation of higher efficiency and lower emission levels."
- Document 625 of March 2016, *Measures for Guaranteed Full Purchase of Renewable Energy Allocation*, again emphasizes generation priority rights for renewable generators and outlines new compensation for curtailment.

[7] For data for Jilin, Gansu, Xinjiang and China, see:《2015 年风电产业发展情况》, http://www.nea.gov.cn/2016-02/02/c_135066586.htm; for data for Germany and US, see: Morris, C. (2015, November 23). Renewable Power Curtailment Skyrockets in Germany. *Energy Transition.* Retrieved from https://energytransition.org/2015/11/renewable-power-curtailment-in-germany/

[8] "电力调度应当优先安排清洁能源发电上网," http://news.xinhuanet.com/legal/2015-08/30/c_128180129.htm

- July 2016, Notification on Orderly Liberation Generation Output Planning (request for public consultation draft)（《关于有序放开发用电计划工作的通知（征求意见稿）》）

These policy statements indicate increasing attention to dispatch reform. These may lead to improvements in system flexibility, reduction in curtailment, reduced costs, and lower emissions. However, implementation details are still unclear. The policies also stop short of calling for a transition to true economic dispatch.

One significant sticking point for dispatch reform is likely to continue to be generator compensation. The current structure of on-grid pricing makes generators reluctant to support dispatch reform for fear of losing revenue and profits. The current structure also severely limits the business case for investing in more flexible coal- and gas-fired power plants—and limits the business case for operating existing power plants more flexibly. The policy statements to date have yet to delineate a clear path for resolving compensation issues and for providing incentives for much-needed flexibility.[9] The 13th Five Year Plan for Electricity, released in November 2016, calls for an electricity "spot market." If designed and implemented well, such a spot market could solve compensation problems and serve as a guide for economic dispatch.

Conclusions

One of the channels through which an ETS can help decarbonize the power sector is through reinforcing the position of low-emission generators—including renewable energy generators and relatively efficient coal-fired generators—in the dispatch order. The "economic dispatch" approach used in other countries complements carbon pricing by prioritizing relatively efficient generators on a day-by-day and hour-by-hour basis. However, system operators in China typically do not use economic dispatch, and their approach to generator dispatch is still inefficient and unnecessarily rigid. Implementation of carbon trading—without complementary dispatch reform—will be unable to fully achieve key goals of decarbonizing the power sector.

Dispatch reform is now getting under way, as a part of broader power sector reform. However, the road to implementation is not yet clear. Close involvement with the details of dispatch reform will be important for the decision-makers responsible for designing a national carbon trading scheme that covers the power sector.

[9] For more on this generator compensation issue, see Paulson Institute. *Power Sector: Deepening Reform to Reduce Emissions, Improve Air Quality and Promote Economic Growth.* Retrieved from www.paulsoninstitute.org/economics-environment/climate-change-air-quality/research/power-sector (Chinese and English versions)