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Indirect cost of renewable energy: Insights from dispatching

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ABSTRACT

The rapidly falling costs of renewable energy has made them the focus of efforts in making a low-carbon transition. However, when cheap large-scale energy storage is not available, the variability of renewables implies that fossil-based technologies have to ramp up-and-down frequently to provide flexibility for matching electricity demand and supply. Here we provide a study on the indirect cost of renewable energy due to thermal efficiency loss of coal plants with such ramping requirements. Using monthly panel data for China, we show that higher renewable share is associated with fewer operating hours of coal-fired units (*COHOUR*). We use an instrumental variable depending on natural river flows to identify the causal effect of reduced *COHOURs* in raising the heat rate of coal-fired units. Specifically, a 1 percentage point increase in the share of renewables leads to a 6.4 h reduction per month, and a reduction of one *COHOUR* results in a 0.09 gce/kWh increase of gross heat rate (+0.03%). We estimate that the thermal efficiency loss indicates 4.77 billion US dollars of indirect cost of renewables in 2019, or 9.44 billion if we include the social cost of carbon emissions. These results indicate that we should consider the indirect impacts of renewables on total coal use and the importance of increasing flexibility of the system.

1. Introduction

With the rapid decline in the cost of solar and wind energy, renewable energy has been increasingly viewed as a feasible alternative to fossil-based technologies[1] (La Monaca and Ryan, 2017; Liu and Mauzerall, 2020). Solar power can be generated only when the sun is shining and wind power only when the wind is blowing; one challenge raised by the large-scale intermittent renewables is the instantaneous balancing of electricity supply with demand when electricity cannot be stored easily (Antweiler, 2016; Martinot, 2016; Verdolini et al., 2018). Without cost-competitive storage, these renewables are non-dispatchable at naturally determined times. In such situations, fossil-based plants such as coal or gas units must be jointly installed to provide reliable and dispatchable back-up capacity.[2]

Such back-up capacity will have fewer operating hours than fossil fuel plants in a system without intermittent sources, which leads to indirect costs because of the loss in thermal efficiency. The operating hours of a plant refer to the annual equivalent hours running at the rated capacity. It is measured by the electricity output for a period (a month or a year) divided by the rated capacity. First, these plants have to ramp up and down more frequently to complement the intermittent sources, leading to extra fuel consumption for a given supply of electricity. Lew et al. (2012) show that wind and solar electricity causes fossil-fueled power plants to cycle on/off more frequently and ramp up/down more rapidly. Using the data for a typical unit, they show that heat rates may be higher during cycling and ramping, i.e., more coal per kWh. Second, given the existing excess capacity of fossil fuel plants in many regions, increasing renewables result in fewer operating hours for them. However, fossil-based technologies cannot achieve high efficiency while maintaining low loads or cycling (Sargent and Lundy, 2014). Dong et al.

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[1] For example, in the United States, wind energy has grown rapidly from being 0.1% of total electricity generation in 2000 to over 7% in 2019 (Energy Information Agency (EIA), n.d). There was also rapid growth in solar and other renewables. In 2016, according to the World Energy Outlook (IEA, 2017), a quarter of total worldwide electricity generation came from renewable sources in 2016, and electricity generation from renewables is projected to overtake that from coal in the 2020s to supply 40% of electricity by 2040 (IEA, 2017).

[2] Except for the fossil-based plants, nuclear power can also be used as dispatchable back-up and so that it can potentially provide flexibility. However, nuclear power plants, with a few exceptions, are generally considered the most non-dispatchable baseload. In a few countries such as France and Germany, nuclear power plants are designed and operated for flexibility, but it is not common worldwide, including China.

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(2018) show that for the lowest heat rate for 600 MW units occurs when they operate at around 500 MW while the lowest heat rate for 300 MW units occurs at rated power output. Therefore, the heat rate would be higher when fossil-based plants operate at lower load factors in order to compensate for variable renewables. That is, they must combust more fuel to generate the same amount of electricity, which means higher average costs.

This study leverages a panel data set of China's provincial electricity generation at monthly frequency to present these indirect costs of renewable energy. China is the largest electricity producer in the world and has the largest output of renewable energy but very little gas-fired electricity. It is also currently characterized by overcapacity in generation in many regions. We first show simple evidence of how renewables are negatively associated with the monthly operating hours of fossil-fueled plants (mostly coal). We then identify the causal effects from operating hours of coal plants to their heat rate. For causal inference, we use the operating hours of hydropower as an instrumental variable (IV) for the operating hours of coal plants. As will be discussed in detail, due to the dispatch order in China (Ho et al., 2017), the operating hours of hydropower are essentially exogenously determined by river flows. Furthermore, we go beyond estimating the impacts of renewables on heat rates of coal plants and make an additional effort to highlight the indirect cost of renewable energy through this mechanism. We show a sizeable indirect cost of renewable energy imposed on the entire electric power system that should not be ignored.

The remainder of this paper is organized as follows. In section 6, we describe the renewable electricity system in China and the associated flexibility needs for dispatching. Section 7 describes the empirical strategy where an instrumental variable is employed to establish the causal effect. To justify the validity of the instrumental variable, in Section 4, we discuss the dispatching policies in China, showing why it may be regarded as exogeneous and related to the variables of interest. Data are described in Section 5, and we present the results in Section 6. Section 7 concludes the study.

2. Renewable energy in China and the associated flexibility needs

There is growing support for renewable energy because of the global interest in addressing climate change (Li and Huang, 2020; Zhang et al., 2020). China is the largest renewable energy market worldwide, with double the power generation of the second-ranked United States. By the end of 2019, China had 794 GW of renewable capacity, mainly from solar photovoltaics (PV), onshore wind, and hydropower, out of the total capacity of the year 2008 in the entire country. According to the National Energy Administration of China, in 2020, the cumulative installed capacity of hydropower is 365 GW, wind power 223 GW, and solar power 223 GW. As a comparison, the capacity of biomass is 26 GW which is much smaller than hydro, wind, and solar power.[3] Other renewables such as geothermal are tiny in China. Thus, renewables in this paper refer to hydropower, wind and solar power.

China's wind and solar energy is continuing a strong growth which started in the late 2000s, rising faster than even the rapid growth of coal and nuclear power. Despite this growth, renewable sources including hydro still only provide 28% of total electricity generation in 2019, and most of the remainder are provided by coal-fired and nuclear power plants. The World Energy Outlook by International Energy Agency (IEA) (2017) projects that the share of renewable capacity will rise to about 60% of the total by 2040, the majority of which comes from the growth in wind and solar PV.

The sharp growth of wind and solar PV raised the variability of electricity supply and thus increased the "flexibility needs" of electric power systems for dispatching (International Energy Agency (IEA), 2020). According to Babatunde et al. (2020), "flexibility describes the degree to which a power system can adjust the electricity demand or generation in reaction to both anticipated and unanticipated variability." The flexibility requirements cover time scales ranging from hours to days (for wind and solar), and over seasons (for hydropower). IEA (2020) projects the power system's flexibility needs over 2020–2030 as shown in Fig. 1 for the major regions of the world. They project that China will have the largest flexibility needs, increasing by

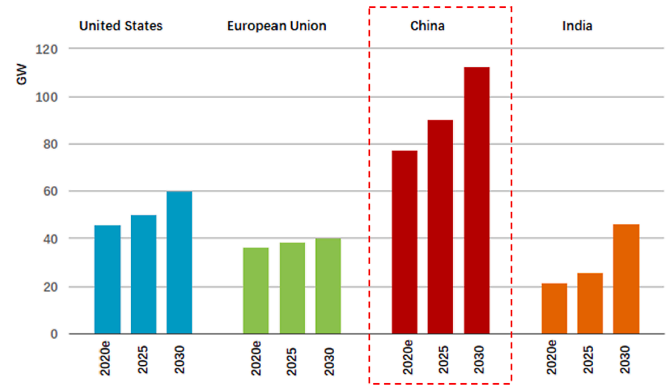

Fig. 1. Projected flexibility needs in power systems.
Source: International Energy Agency (IEA), 2020, Fig. 6.17), adjusted. 2020e denotes estimated values for 2020. Flexibility needs are projected by taking "the average of the highest 100 hour-to-hour ramping requirements after removing wind and solar production from electricity demand."

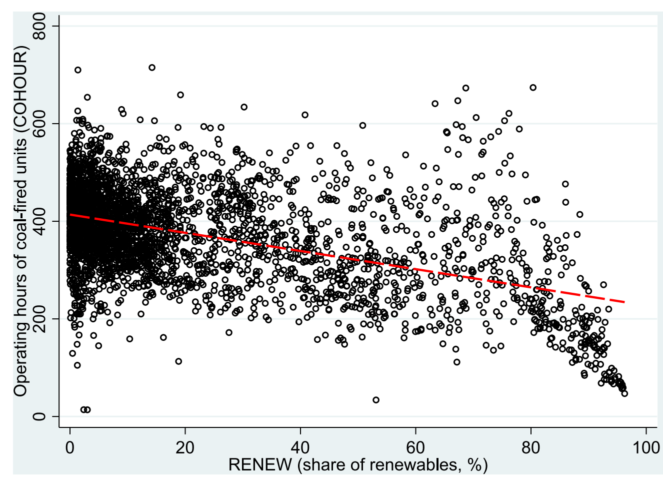

Fig. 2. Renewable generation share and monthly operating hours of coal-fired units.
Note: The data source is discussed in section 5.

[3] The National Energy Agency announcement is reported in the government news site: http://www.gov.cn/xinwen/2020-10/30/content_5556247.htm (accessed at April-1, 2021)

almost 50% over this period.[4] With the larger share of wind and solar PV, the hour-to-hour ramping requirement is an important component of China's flexibility needs.

Flexibility needs can be met by various measures, including power plants, electricity networks, storage technologies, and demand response measures. For China where gas plants provided only 3% of electricity in 2019, coal-fired power plants are the main source of flexibility and remain so for decades to come (International Energy Agency (IEA), 2020). The data we use below is a monthly panel of provincial generation data. In Fig. 2 we plot the monthly operating hours over 2009–19 for our sample of coal plants against the share of renewable output by province; this shows that coal plants acting as dispatchable sources to meet flexibility needs tend to have fewer operating hours.

3. Empirical methods

We focus on coal-fired power as representative of fossil-fuel technologies since they generate more than 95% of such electricity. We first consider the following equation determining the monthly operating hours of coal-fired units (*COHOUR*):

$$COHOUR_{iym} = \alpha \times RENEW_{iym} + \boldsymbol{\gamma}\mathbf{X}_{iym} + e_{iym} \tag{1}$$

where the key explanatory variable $RENEW_{iym}$ is the share of renewable energy generation in the overall generation of province *i,* during month *m* of year *y*. We control for monthly electricity demand in **X** as it may affect both *RENEW* and *COHOUR*. We expect that $\alpha < 0$ so that more renewables lead to lower operating hours of coal-fired units. *e* represents the unexplained factor.

We consider a variety of fixed effects for the unexplained factor, *e*:

$$e_{iym} = d_i + d_y + d_m + d_i \times d_y + d_i \times d_m + \varepsilon_{iym} \tag{2}$$

We include the provincial fixed effect (d_i) to capture time-invariant factors (e.g., local policies and endowment of renewable resources), a year fixed effect (d_y) to capture annual-specific common shocks (e.g., macroeconomic conditions), monthly fixed effect (d_m) to capture seasonal-specific common shocks (e.g., peaks during summer and winter months), the interaction between provincial and year fixed effects ($d_i \times d_y$), as well as the interaction between provincial and monthly fixed effects ($d_i \times d_m$). The interactions allow provincial fixed effects to change over years and months. For example, there was a burst of investment on coal-fired units around 2012–15 when the central government relaxed investment controls. Local governments responded to the relaxation to different extents during this period which could affect their operating hours of coal-fired units differently. ε is the error term.

We next estimate how operating hours of coal-fired units affect their thermal efficiency. Thermal efficiency is measured by the heat rate (*HR*), that is, the energy embodied in the coal needed to produce a unit of electricity. A higher *HR* indicates lower thermal efficiency. Following Chan et al. (2014), we use two heat rate indicators: (i) operating heat rate, *OHR,* that measures energy needed to produce a gross unit of electricity; (ii) gross heat rate, *GHR,* per unit of electricity sold that also includes auxiliary energy requirements at the plant. A simple and intuitive specification for *HR* is a linear function of operating hours:

$$HR_{iym} = \beta \times COHOUR_{iym} + \boldsymbol{\gamma}\mathbf{X}_{iym} + e_{iym} \tag{3}$$

As discussed in the introduction, we expect that $\beta < 0$ since coal-fired units could be less efficient (i.e., higher *HR*) when they have to operate at low loads (i.e., low *COHOUR*). However, β will be biased if other factors in the error term correlating with *COHOUR* also determine the heat rate of coal-fired units (Lin and Li, 2015). For example, it is likely that dispatch operators give hours to less efficient coal-fired units when electricity demand is high, while giving priority to more efficient plants during periods of low demand. In such a case, we may underestimate the negative impact of *COHOUR* on *HR*.

We use an instrumental variable to deal with this endogeneity. Hydropower is an alternative for coal-fired power, so generation from coal-fired units would be crowded out when river flows are particularly suitable for hydro generation.[5] We denote the monthly generating hours of hydropower plants by *HYHOUR*. If river flow is random, *HYHOUR* would not be directly correlated with the heat rate of coal-fired units, and be an exogenous instrument. Accordingly, we estimate following two-stage system:

$$\text{Stage I}: COHOUR_{iym} = \delta \times HYHOUR_{iym} + \boldsymbol{\gamma}\mathbf{X}_{iym} + e_{iym} \tag{4.1}$$

$$\text{Stage II}: HR_{iym} = \lambda \times \widehat{COHOUR}_{iym} + \boldsymbol{\gamma}\mathbf{X}_{iym} + e_{iym} \tag{4.2}$$

In the first stage we regress coal hours on hydro hours and **X**, and in the second stage we put the fitted values of *COHOUR* from (4.1) into (4.2), thus using the exogenous variation from naturally determined *HYHOUR* to identify the causal effect of *COHOUR* on heat rates of coal-fired units. We note that unlike Lin and Li (2015) who used annual data, we extend the data to monthly frequency so that the variation from the instrumental variable is much larger which enables us to get more precise estimates.

Combining eqs. (1) and (4.2), a 1% increase in the share of renewables ($\Delta RENEW = 0.01$) results in the change of the heat rate of coal-fired units by $\widehat{\alpha} \times \widehat{\lambda}\%$.

Suppose that the coal price is p_{coal} and coal used in coal-power plants is $E_{coal-fired}$, then the indirect cost of an additional share of renewable energy in raising the amount of fuel use in coal-fired generation can be estimated by:

$$Cost = p_{coal} \times \widehat{\alpha} \times \widehat{\lambda} \times E_{coal-fired} \times \Delta RENEW \tag{5}$$

Furthermore, it is worth noting that if carbon pricing is considered[6] and we assume that the equilibrium price captures the social cost of carbon emissions, such indirect costs of renewables would be higher than that measured by Eq. (5). Assuming that carbon price is *t*, the indirect cost would be:

$$Cost = (p_{coal} + c \times t) \times \widehat{\alpha} \times \widehat{\lambda} \times E_{coal-fired} \times \Delta RENEW \tag{6}$$

where *c* is carbon emission factor of coal combustion.

The carbon prices from China's carbon emission trading scheme (ETS) pilots have been volatile and the forthcoming national ETS could easily generate a very different price. Below, we give an example using an illustrative carbon price.

4. Validity of hydropower instrumental variable: Institutional background

We now describe the electric power system in China to argue the

[4] There are several reasons for the large flexibility needs in China's power system. First, since the electricity capacity in China is much larger than other countries, the associated flexibility needs to maintain balance must be scaled up. Second, gas-fired plants are the main source of flexibility in most power systems, but they account for less than 5% in China which leads to higher flexibility needs. Meanwhile, the rapid increase in wind and solar power during the past decade led to a substantial growth in demand for power system flexibility. Third, the power grids in China are largely operated at the provincial level, and cross-border trade in electricity is limited. It restricts the ability of power grids to optimize across larger regions through interconnections. Finally, electricity prices in China are largely regulated and lack flexibility. The rigid prices do not provide incentives for suppliers to raise output and consumers to adjust demand.

[5] In China, the best season for hydropower is summer because of the rains.

[6] The nationwide carbon emission trading system is going to be implemented for the power sector in 2021.

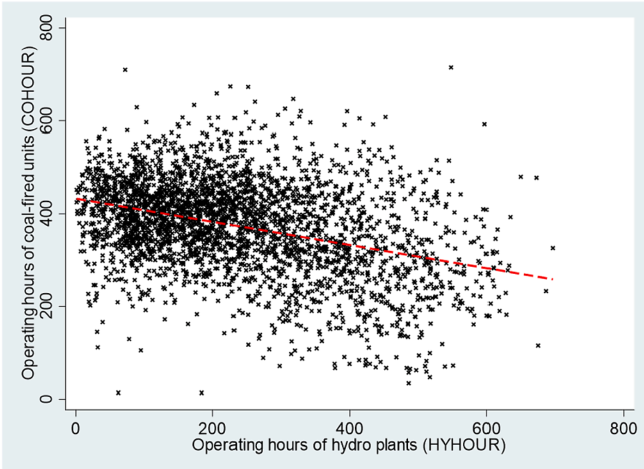

Fig. 3. Relation between provincial average monthly coal-fired hours and hydro hours, 2009–19.

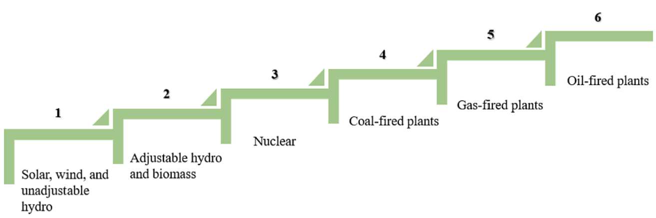

Fig. 4. The dispatchable order for electricity in China.
Note: Adjustable hydro refers to pumped storage hydropower which are constructed to provide power system flexibility. The operation of adjustable hydro is set according to the demand-supply conditions in power systems. Regular hydropower plants have priority over coal units in the dispatch order and are thus non-adjustable. Adjustable biomass plants are the ones that can adjust their output in a cost-effective manner.

validity of using hydropower operating hours as an instrumental variable in eq. (4.1).

First, it should be obvious that there is no direct link between generation hours of hydropower and the heat rate of coal-fired power plants. We now see if there is a possible link between the operating hours of hydropower and coal plants. In Fig. 3, we plot the average operating hours of coal-fired units by province and month against the monthly hours of hydro units over 2009–19. The dashed line is the least-squares fit and shows the negative correlation between them.

The power dispatch system in China is organized by a tier of dispatch organizations where the main decisions are made at the provincial level (see description in Ho et al., 2017). In most cases during this 2009–19 period, the dispatch of coal plants is determined by a "fair allocation" formula that gives all plants a share of total demand, regardless of efficiency. Hydropower is preferred and their hours are largely exogeneous, depending on water flows. In response to worsening environmental conditions and the curtailment of renewable energy in the mid-2000s, China launched a national energy efficiency campaign for energy conservation and emissions reduction. The dispatch of generation was encouraged to reorient towards "energy conservation dispatch" (Ho et al. (2017),section 4.5) where the dispatch order is as shown in Fig. 4. Renewables and hydropower are given priority over fossil-fuel sources. Within the class of coal-fired power, more efficient plants are supposed to be dispatched first. Prioritizing renewables should mean running at their full capacities, and in the case of hydropower this should be based on natural river flows. Coal-fired power plants are operated at less than full capacity, especially during off-peak hours.

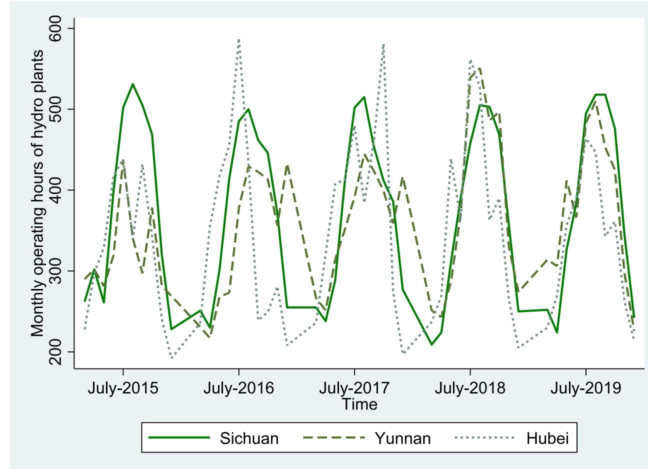

Fig. 5. The seasonal variations of the monthly operating hours of hydro plants.
Note: Sichuan, Yunnan, and Hubei are the three provinces in China that have the largest hydro capacities.

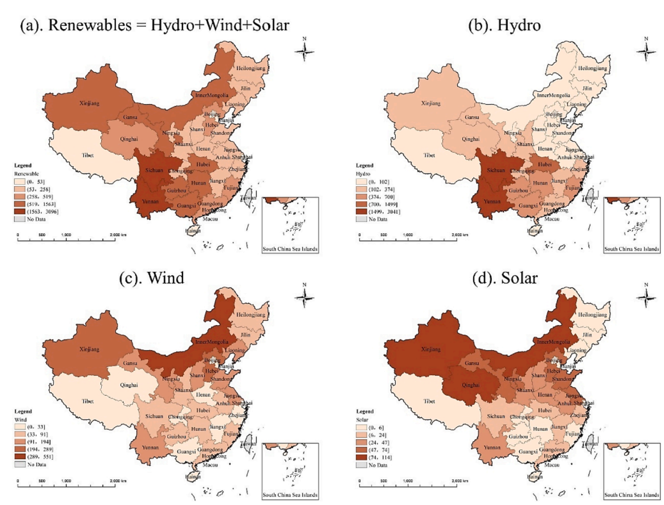

Fig. 6. The spatial distribution of renewable generation in China (2017). The brackets in the color legend denote 10^8 kWh generated in the provinces in 2017.

One possible violation for the exogeneity of hydropower is the class of dispatchable hydro (2nd-stage in Fig. 4). However, this is not a serious problem for two reasons. First, such dispatchable hydro plants account for less than 10% of hydropower, e.g., in 2018 the capacity of dispatchable hydro is 30 GW out of the 350 GW total. Second, the non-adjustable hydro plants have priority over coal units in the dispatch order and their operating hours depend essentially on the exogenous river flows.

To sum up, the instrument using hydropower operating hours is essentially exogenous since the dispatch of most of the hydropower depends on river flows which are randomly assigned by nature, and thus is not directly correlated with the heat rate of coal-fired power plants.

Another merit of this instrumental variable is the large variation of river flows over seasons. Fig. 5 shows how the monthly hydropower hours fluctuate over the year and thus avoid the weak instrument problem. This is confirmed by the *F*-statistics reported in Section 6 below.

5. Data

We estimate our models presented above using a panel of provincial electricity generation data at monthly frequency over 2009–19 in mainland China, obtained from the Wind Economic Database.[7] The province level is the proper resolution for this study since electricity is largely dispatched at the provincial level as we noted above.[8] Further, the large spatial variation of renewables across provinces, as shown by the generation maps in Fig. 6, allows us to estimate the effects more precisely.

We choose 2009–19 as our sample period for two reasons. First, wind and solar power account for less than half a percent of the electricity mix before 2009. Second, the feed-in tariff for wind power was introduced in 2009, after which wind power increased rapidly. This rapid increase in renewables (especially wind) induced more flexibility needs in power systems. Coal-fired power plants are dispatched to achieve the balancing, leading to the indirect cost associated with the intermittent renewables.

We assemble a panel dataset across 30 provinces, Tibet is excluded due to missing data. Because of the big slowdown in economic production during the Chinese Spring Festival, data in January and/or February are usually not reported by the statistical departments for most variables. In order to eliminate the influence caused by the Spring Festival, and thus ensure the comparability of the data, we drop these two months and keep only data from March to December of each year.

There are four groups of variables which are constructed as follows.

➢ Renewable energy generation

The monthly data on hydropower, wind, and solar, and total generation are given in the Wind Economic Database. The unit is 10^8 kWh. We add these three sources to get total renewable energy generation and calculate the share of renewables in total generations.

➢ Operating hours

The monthly provincial average operating hours of coal-fired units and hydro plants are calculated separately. The Wind Economic Database reports cumulative operating hours from the beginning of each year. For example, the number in July-2018 is the cumulative operating hours from January to July of 2018. We obtain the monthly hours by differencing the cumulative totals.

➢ Thermal efficiency of coal-fired units

As noted in section 7, we calculate two indicators of thermal efficiency following Chan et al. (2014) – operating heat rate (*OHR*) and gross operating heat rate (*GHR*). The *GHR* includes energy used for the auxiliary operations of the power plants. These two indicators in the Wind Economic Database are measured by grams of standard coal equivalent per kilowatt hour, gce/kWh.

Like operating hours, these two indicators for thermal efficiency of coal-fired units are also reported by the cumulative average heat rate (*CHR*) from the beginning of each year. For example, the heat rate in July-2018 is the average heat rate from January to July of 2018. Fortunately, the database also provides monthly coal-fired generation (*E*), which enables us to calculate the (gross or operating) heat rate of month *T* from the cumulatively average heat rate, as:

$$HR_T = \left(CHR_T \times \sum_{t=1}^{T} E_t - CHR_{T-1} \times \sum_{t=1}^{T-1} E_t \right) \Big/ E_T \tag{7}$$

➢ Demand side

The Wind Economic Database provides the monthly electricity demand (in 10^8 kWh) for each province which we can use directly.

Table 1 gives the summary statistics of these variables. There are 30 provinces, and 10 months per year for 11 years giving 3300 observations. The mean monthly generation share for hydro is 18.6% compared

Table 1
Variable descriptions and summary statistics.

Variable	Description	Obs.	Mean	Min	Max
	Panel A: Renewable share of generation (Units: %)				
RENEW	Share of renewables	3300	21.55	0.00	96.26
SOLAR	Share of solar power	3300	0.53	0.00	23.55
WIND	Share of wind power	3300	2.41	0.00	22.46
HYDRO	Share of hydropower	3300	18.62	0.00	93.49
	Panel B: Monthly operating hours (units: hours)				
COHOUR	Operating hours of coal-fired units	3285	373.51	13.80	715.00
HYHOUR	Operating hours of hydro plants	3026	237.91	1.00	701.00
	Panel C: Thermal efficiency (Units: gce/kWh)				
OHR	Operating heat rate	3043	302.11	203.82	436.74
GHR	Gross heat rate	3048	322.65	200.02	478.34
	Panel D: Log of demand side (Units: 10^4 kWh)				
ED	Monthly electricity demand	3300	14.01	10.86	15.82

Table 2
The impact of renewables on operating hours of coal-fired units.

	Dependent variable: Operating hours of coal-fired units (COHOUR)			
	(1)	(2)	(3)	(4)
RENEW	−6.369***	−5.744***	−6.757***	−6.444***
	(0.181)	(0.137)	(0.132)	(0.141)
Log (ED)	302.943***	181.037***	305.312***	313.111***
	(17.829)	(9.111)	(9.064)	(11.834)
constant	−3743.430***	−2096.062***	−3830.849***	−3919.238***
	(245.800)	(123.352)	(125.769)	(163.058)
d_i	YES	YES	NO	YES
d_y	YES	YES	NO	YES
d_m	YES	YES	NO	YES
$d_i \times d_y$	YES	NO	YES	YES
$d_i \times d_m$	YES	NO	NO	NO
N	3285	3285	3285	3285
adj. R^2	0.837	0.693	0.776	0.787

Notes: Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3
The impact of renewable types on operating hours of coal-fired units.

	Key explanatory variable: x			
	HYDRO	WIND	SOLAR	WIND+SOLAR
	(1)	(2)	(3)	(4)
Renew (x)	−6.305***	−7.983***	2.202	−5.256***
	(0.188)	(0.996)	(1.728)	(0.853)
Log (ED)	310.291***	429.674***	437.290***	432.286***
	(18.067)	(20.825)	(21.045)	(20.920)
constant	−3844.214***	−5486.469***	−5590.954***	−5522.377***
	(249.085)	(287.144)	(290.175)	(288.445)
N	3285	3285	3285	3285
adj. R^2	0.832	0.767	0.762	0.765

Notes: Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Province, year, month, and the interactions between province and year/month are all controlled for.

[7] The database is described at: https://www.wind.com.cn/NewSite/edb.html.

[8] There are two state-owned grid companies in China that accounts for almost all electricity transmission, distribution, and dispatch. The subsidiaries of these two companies operate and dispatch at the provincial level with only limited cross-province electricity trade. This is called “*Sheng Wei Shi Ti*” (*省为实体*) in Chinese – province as executor (Li and Lin, 2017).

Table 4
The impact of operating hours of coal-fired units on their heat rates.

	OLS		Instrumental variable (IV)		
	Dependent variables:				
	OHR	GHR	COHOUR 1st-stage	OHR 2nd-stage	GHR 2nd-stage
	(1)	(2)	(3)	(4)	(5)
COHOUR	−0.019***	−0.032***		−0.063***	−0.090***
	(0.004)	(0.005)		(0.009)	(0.010)
Log (ED)	−5.894*	−0.542	362.849***	8.559**	18.633***
	(3.251)	(3.820)	(11.625)	(4.337)	(5.135)
HYHOUR			−0.322***		
			(0.011)		
constant	394.038***	343.354***	−4350.200887***	251.430***	155.139**
	(44.291)	(52.038)	(158.549)	(55.544)	(65.761)
N	3031	3036	3015	2762	2767
adj. R^2	0.549	0.584	0.678	0.528	0.560

Notes: OHR: operating heat rate; GHR: gross heat rate. Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Since we use the seasonal variations of river flow, we do not control monthly dummies here. Province, year, and the interactions between province and year are controlled for.

to 2.4% for wind and only 0.5% for solar.

6. Results

In Table 2, we show the results of estimating eq. (1) for operating hours of coal plants. The main coefficients of interest here are for *RENEW*. Column (1) controls the most of fixed effects, including province, year, month, and the interactions between province and year/month. It suggests that a 1 percentage point increase in the share of renewable generation would reduce monthly coal hours by 6.4 h, compared to the 374 mean hours. In addition, the coefficients on Log (*ED*) imply that higher electricity demand leads to larger *COHOUR*, with magnitudes of about 3 h per 1% increase in electricity demand. The magnitude of these effects changes little with different combinations of fixed effects, as shown in columns (2)–(4); the smallest difference occurs in column (2) when we ignore the interaction terms.

In Table 3 we report the estimates using hydro, wind and solar generation separately instead of the total renewable in Table 2; the full set of fixed effects are used in each column. Columns (1)–(2) show that hydropower and wind energy both crowd out the operating hours of coal-fired units. The impact of hydropower is similar to the average results of renewables in Table 2, which is likely explained by its dominant share of total renewables. Of particular interest is that in column (2), the increase in the share of wind power tends to have larger negative impacts on the generation of coal-fired power. There is a mismatch in time between wind generation and electricity peak demand because wind farms generate more electricity at night. In column (3), the effect of solar energy is not statistically significant, most likely due to the very low volume during the early years of this period. If we combine wind and solar together in column (4), their negative impact is smaller than that in column (2) of wind energy alone. Wind usually blows stronger at night while solar power is generated during daylight hours, thus their combination could provide reciprocal load smoothing for each other and reduce the dispatch demand for coal-fired units. Generally, Table 3 shows that generation of different renewable types reduces *COHOUR*.

We next report the estimates of eqs. (3) and (4), showing how operating hours of coal-fired units affect their heat rates. In columns (1)–(2) of Table 4, OLS regression shows that the coefficient on *COHOUR* is −0.019 for *OHR* and is −0.032 for *GHR*. Taking *GHR* as an example, this means a 100-h reduction in *COHOUR* is associated with a 3.2 gce/kWh increase of *GHR*. The average *GHR* in the sample is 323 gce/kWh, so this is a 1% reduction, which is quite tiny. As discussed in Section 6, the OLS results may suffer from underestimation due to the endogeneity of *COHOUR*.

Columns (3)–(5) of Table 4 present the results using the IV. Recall that hydro hours, *HYHOUR*, is the exogenous instrument, which works through naturally determined river flows and its dispatch priority. This provides evidence on causal effects about how changes in coal hours, *COHOUR* (which could be induced by changes in renewables) affects heat rates. The first-stage regression in column (3) shows that 1 h increase in *HYHOUR* is associated with 0.3 h decrease in *COHOUR*. The *F*-statistic of the first stage is 857.7 (with *t*-statistic of 29.3 on *HYHOUR*), which is greater than the critical value of 10 that Stock et al. (2002) and Andrews et al. (2019) suggest for tests of weak instruments. Columns (4)–(5) present the second-stage results on the heat rates, *OHR* and *GHR*, respectively. The coefficients on *COHOUR*, at −0.063 and − 0.090, are three times larger than those in OLS regression and are more precisely estimated. They suggest a 100-h reduction in *COHOUR* is associated with a 9.0 (6.3) gce/kWh increase of *GHR* (*OHR*) compared to the mean of 323 (302) gce/kWh.

Based on the estimates above, we calculate the indirect cost associated with the expansion of renewables in China. Between 2009 and 2019 there was a rapid growth of renewables and Δ*RENEW* is 12.2% in our sample, so the annual *COHOUR* decreases by 932 (=6.4*12.2*12) hours due to renewables. We note that it may not be reasonable to extrapolate this effect for future rises in the renewable share because the flexibility demand for dispatching renewables could change in a non-linear way and a richer specification using a longer and updated sample is required.

Using the IV estimates, the associated *GHR* is expected to increase by 7.0 gce/kWh (=6.4*12.2*0.09). Using eq. (5), we calculate that the indirect cost due to the thermal efficiency loss in coal-fired units is 4.77 billion US dollars in 2019.[9] Considering a carbon price of 50 USD/ tCO_2 (Li et al., 2018) and a carbon emission factor of 2.64 tCO_2/tce (Zheng et al., 2020), the indirect cost of renewables due to thermal efficiency loss is 9.44 billion US dollars in 2019.

7. Conclusion

In this paper, we provide empirical evidence for a major concern about intermittent renewables – their need for backup power, which is coal power in China with very few gas units. We describe a mechanism that induces a high indirect cost of renewable energy due to its impact on the heat rate of fossil-fuel power plants. We introduce a compelling instrumental variable to establish the causal effect. The empirical analysis is conducted using the provincial data in China at monthly

[9] Here, the average coal price is 585 Chinese Yuan/ton (Li and Sun, 2018), converting factor of coal is 0.68 in China (Liu et al., 2015), and exchange rate is 6.392 on average from China Premium Database. China's total generation of coal-fired units is 5.05 trillion kWh in 2019. The web link of China Premium Database is: https://www.ceicdata.com/zh-hans.

frequency over 2009–19.

We find that the large-scale expansion of renewables decreases the operating hours of coal-fired units by 932 h, and further increases the gross heat rate by 7.0 gce/kWh. This effect seems modest, moving from the gross heat rate of 323 gce/kWh on average to the counterfactual 316 gce/kWh. However, given the huge level of coal-fired generation, this is associated with a considerable indirect cost. We estimate that the efficiency loss from higher heat rates leads to 4.77 billion US dollars of indirect cost of renewables in China in 2019. This rises to 9.44 billion US dollars when we include the social cost of carbon emissions. These sizeable indirect cost cannot be ignored in designing energy policies.

The findings of this paper have implications for both energy analysts and policy makers. Few studies have paid explicit attention to the causal link between renewable energy and the thermal efficiency of fossil-based technologies. This link is implicit in bottom-up electricity models, but it is important to discuss this explicitly. This paper enhances our understanding of this issue. The estimated indirect costs here suggest that improving large-scale storage options is critical to providing reliable, cost-effective and dispatchable back-up capacity for renewables. Also, demand-response measures, such as time-of-use pricing, should be seriously pursued as alternative sources to provide the flexibility in electric power systems. These alternatives would reduce the reliance on fossil-based plants and thus reduce the indirect costs of renewable energy.

China, like other countries, needs to find ways to integrate intermittent renewables (Zhou et al., 2020). The current ideas include demand management, storage, carbon sequestration for fossil-based plants, and having larger, integrated, dispatchable regions. Making these feasible at a competitive cost is the big technological and managerial challenge for the world. China has its own specific system that needs additional reforms, including pricing and distribution reforms.

CRediT authorship contribution statement

Jianglong Li: Conceptualization, Investigation, Experiment design and data analytical methods, Funding acquisition, Project administration, Methodology, Writing - review & editing.

Mun Sing Ho: Investigation, Experiment design and data analytical methods, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2021.105778.

References

Andrews, I., Stock, J.H., Sun, L., 2019. Weak instruments in instrumental variables regression: theory and practice. Ann. Rev. Econom. 11, 727–753.

Antweiler, W., 2016. Cross-border trade in electricity. J. Int. Econ. 101, 42–51.

Babatunde, O.M., Munda, J.L., Hamam, Y., 2020. Power system flexibility: a review. Energy Rep. 6, 101–106.

Chan, H.S.R., Cropper, M.L., Malik, K., 2014. Why are power plants in India less efficient than power plants in the United States? Am. Econ. Rev. 104 (5), 586–590.

Dong, Y., Jiang, X., Liang, Z., Yuan, J., 2018. Coal power flexibility, energy efficiency and pollutant emissions implications in China: A plant-level analysis based on case units. Resour. Conserv. Recycl. 134, 184–195.

Energy Information Agency (EIA). Electricity generation with wind. Available from: https://www.eia.gov/energyexplained/wind/electricity-generation-from-wind.php (accessed at September-10, 2020).

Ho, M.S., Wang, Z., Yu, Z., 2017. China's Power Generation Dispatch. Resources for the Future (RFF), Washington, DC, USA.

International Energy Agency (IEA), 2017. World Energy Outlook 2017. France, Paris.

International Energy Agency (IEA), 2020. World Energy Outlook 2020. Paris, France.

La Monaca, S., Ryan, L., 2017. Solar PV where the sun doesn't shine: estimating the economic impacts of support schemes for residential PV with detailed net demand profiling. Energy Policy 108, 731–741.

Lew, D., Brinkman, G., Kumar, N., Besuner, P., Agan, D., Lefton, S., 2012. Impacts of wind and solar on fossil-fueled generators (No. NREL/CP-5500-53504). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Li, J., Huang, J., 2020. The expansion of China's solar energy: challenges and policy options. Renew. Sust. Energ. Rev. 132, 110002.

Li, J., Lin, B., 2017. Environmental impact of electricity relocation: a quasi-natural experiment from interregional electricity transmission. Environ. Impact Assess. Rev. 66, 151–161.

Li, J., Sun, C., 2018. Towards a low carbon economy by removing fossil fuel subsidies? China Econ. Rev. 50, 17–33.

Li, M., Zhang, D., Li, C.T., Mulvaney, K.M., Selin, N.E., Karplus, V.J., 2018. Air quality co-benefits of carbon pricing in China. Nat. Clim. Chang. 8 (5), 398–403.

Lin, B., Li, J., 2015. Does China's energy development plan affect energy conservation? Empirical evidence from coal-fired power generation. Emerg. Mark. Financ. Trade 51 (4), 798–811.

Liu, H., Mauzerall, D.L., 2020. Costs of clean heating in China: evidence from rural households in the Beijing-Tianjin-Hebei region. Energy Econ. 90, 104844.

Liu, Z., Guan, D., Wei, W., Davis, S.J., Ciais, P., Bai, J., Andres, R.J., 2015. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. Nature 524 (7565), 335–338.

Martinot, E., 2016. Grid integration of renewable energy: flexibility, innovation, and experience. Annu. Rev. Environ. Resour. 41, 223–251.

Sargent, Lundy, 2014. Coal fired power plant heat rate reduction – NRECA. Available from: https://www.cooperative.com/programs-services/government-relations/regulatory-issues/Documents/SL%20HRI%20study_Final.pdf (accessed on August 27, 2020).

Stock, J.H., Wright, J.H., Yogo, M., 2002. A survey of weak instruments and weak identification in generalized method of moments. J. Bus. Econ. Stat. 20 (4), 518–529.

Verdolini, E., Vona, F., Popp, D., 2018. Bridging the gap: do fast-reacting fossil technologies facilitate renewable energy diffusion? Energy Policy 116, 242–256.

Zhang, M., Liu, L., Wang, Q., Zhou, D., 2020. Valuing investment decisions of renewable energy projects considering changing volatility. Energy Econ. 92, 104954.

Zheng, X., Lu, Y., Yuan, J., Baninla, Y., Zhang, S., Stenseth, N.C., Chen, D., 2020. Drivers of change in China's energy-related CO2 emissions. Proc. Natl. Acad. Sci. 117 (1), 29–36.

Zhou, D., Chong, Z., Wang, Q., 2020. What is the future policy for photovoltaic power applications in China? Lessons from the past. Res. Policy 65, 101575.