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The effect of international energy prices on energy production in Sichuan, China

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Abstract

Sichuan Province is China's leading natural gas and hydropower producer. This article tests for the effects of international energy (nominal) prices on natural gas and hydropower production in Sichuan. Monthly data cover the period from April 2002 to June 2019. This study conducts unit root tests using the standard augmented Dickey–Fuller (ADF) test, the Phillips–Perron (PP) test, and the Dickey–Fuller generalized least squared (GLS) test suggested by Elliott, Rothenberg and Stock (ERS), and the Perron break date innovational outlier (IO) Model C. It tests for long-run equilibrium using the Johansen multivariate method and Phillips–Ouliaris technique. It tests for weak exogeneity and estimates error-correction models (ECMs) and vector-autoregressive models (VARs). Overall, in the long run, both international spot and futures gas prices slightly and positively impacted the production of gas and hydropower. Differences between the spot and futures gas price effects were minor. International crude oil prices had insignificant effects on energy production. Energy production was gas price-inelastic. Long-run spot and futures gas price elasticities of gas output were 0.192 and 0.186, respectively. Given the strong governmental support for energy prices, Sichuan's gas market has partially integrated into the global gas market. We suggest that, in the long run, both international futures and spot gas prices can be considered as an exogenous variable predicting changes in gas production. International futures gas prices can be a short-run factor predicting gas production. Gas production appears to serve as a long-run substitute for hydropower production; accordingly, with the growing gas supply, hydropower oversupply in Sichuan may become increasingly severe in the long run.

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Keywords: Break date; Cointegration; Long-run elasticity; Hydropower; Natural gas; Price; Production; Weak exogeneity

1. Introduction

Sichuan Province is located in southwestern China, in the middle and upper reaches of the Yangtze River. It covers a territorial area of 486,000 square kilometers and holds a population of 83.41 million (2018). Sichuan has played a crucial role in China's natural gas and hydropower supply due to its abundant reserves and high level

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of production in these two primary energies. In 2017, Sichuan's hydropower and natural gas output accounted for 25.4% and 24.1% of China's total, respectively. Its crude oil output was negligible due to a lack of significant oil reserves. Overall, natural gas, hydropower, coal, and crude oil constituted 37.6%, 31.2%, 27.1%, and 0.10% of Sichuan's primary energy production (see Table 1).

Table 1. Profile of Primary Energy Sources, Production, and Consumption in Sichuan Province, China (2017).

	Total	Natural gas	Hydropower	Coal	Crude oil	Wind, solar and nuclear power, bioenergy
Output (Mtce)	119.91	45.12	37.38	32.53	0.12	2.14
of total energy output		37.6%	31.2%	27.1%	0.10%	1.79%
Consumption (Mtce)	170.61	26.46	20.61	67.37	46.46	2.14
of total energy use		15.5%	12.1%	39.5%	27.2%	1.26%
Net imports (Mtce)		0.00	0.00	22.49	46.09	0.00
Net exports (Mtce)		18.62	16.76	0.00	0.00	0.00
Recoverable reserves		14.22[a]	148[b]	5.16[c]		
Proven reserves					426[d]	
Installed capacity			75.64[e]			

Notes: Data calculated based on Sichuan Statistics [1] and NBSC [2], except for recoverable reserves. Mtce: million tons of coal equivalent.

[a] Recoverable reserves: Trillion cubic meters (tcm) by 2015, including conventional natural gas estimated at 9.80 tcm [3] and shale gas 4.42 tcm [4].

[b] Recoverable reserves: Million kW by 2015 [5].

[c] Recoverable reserves: Billion tons by 2017 [6].

[d] Proven reserves: Sichuan lacks crude oil resources. In 2002, the Sichuan Basin had only 426 million tons of proven crude oil reserves [7]. The Sichuan Basin comprises an area of 260 thousand square kilometers, mostly located in central Sichuan and partly on the western edge of Chongqing.

[e] Million kW; figure from North Star Power [8].

China's energy policy and demand have jointly driven primary energy production in Sichuan. China is attempting to reduce its greenhouse gas emissions and build up a sustainable energy supply–demand system by significantly increasing the share of natural gas and non-fossil energy consumption [9,10]. The Chinese government planned for the share of natural gas use in the total primary energy consumption to grow to 7.5% by 2015. In 2017, however, overall gas output contributed to only 4.33% of total energy use. The natural gas supply highly depends on only a few provinces, and the role of Sichuan is crucial. Gas output in Shanxi, Sichuan, and Xinjiang accounted for 28.3%, 24.1%, and 20.7% of the nation's total, respectively [2].

Sichuan had raised the share of its natural gas use to 15.5% of total primary energy consumption by 2017, far exceeding the national average (7.0%). Net natural gas exports from Sichuan to other provinces and Shanghai accounted for 41.3% of its total gas output.

China has to import more and more natural gas from abroad. In 2017, 43% of China's gas use depended on imports. By 2030, the import dependence could rise to 50%–60% [11]. Thus, given China's enormous use of foreign natural gas, we argue that international natural gas prices in key markets will increasingly affect Sichuan's natural gas production. A previous study suggests that energy prices have a significant negative effect on China's industrial output in the short run [12].

Sichuan is the largest hydropower producer in China. In 2017, hydropower installed capacity in Sichuan reached 75.64 million kW [8], accounting for 22.2% of China's total capacity [13]. Sichuan, Yunnan, and Hubei accounted for 25.4%, 20.8%, and 12.5% of China's 1197.87 billion kWh of hydropower output, respectively. Thus, hydropower production and use have played a dominant role in Sichuan's electricity supply–demand scenario. Hydropower output (304.12 billion kWh) accounted for 87.4% of the province's total electricity output. Hydropower use (161.2 million kWh) accounted for 73.1% of its total power use. Sichuan exported 47.0% of its hydropower output to other provinces [1,2]. Significant importers include Shanghai, Zhejiang Province, and Jiangsu Province. It is noteworthy that in the long run, international crude oil prices have resulted in the increase in China's total hydropower consumption [14].

The government has strictly controlled electricity, refined oil products, and gas prices [15,16]. It has enacted the Refined Oil Pricing Mechanism (ROPM) since 2002. ROPM requires that oil product prices adjust to changes in international crude oil prices. It has made great progress in China's market-oriented natural gas pricing mechanism reform. China's gas pricing is now more closely connected to international fuel oil and liquid petroleum gas prices [17]. Market fundamentals, such as economic growth, policies, and other market factors are increasingly affecting China's import gas prices [18]. However, natural gas pricing has provided biased incentives for producers and favors large suppliers. Household users have continued to receive natural gas subsidies [19]. Hence, controlled energy pricing has continued.

This study tests for the effect of international energy spot and futures nominal prices on primary energy production in Sichuan, China. The focus is on how changes in U.S. spot and futures Henry Hub natural gas prices affect changes in natural gas production. We also examine how West Texas Intermediate (WTI) spot and futures crude oil prices affect energy production.

This study contributes to the literature in four ways. First, amid the government's strict management of energy prices, international natural gas prices in a vital market have exhibited a significant long-run effect on natural gas production adjustments in Sichuan. Thus, we suggest that Sichuan has partially integrated into global gas markets, even if China's natural gas market has not yet aligned with the global gas market [20]. Second, we suggest that futures gas prices could be a long-run factor predicting gas production. Third, we show that the long-run price effect is greater than the short-run effect. Fourth, we show that the crude oil price effect is negligible.

The remainder of this paper is organized as follows. Section 2 reviews the literature. Section 3 introduces the study's methods. Section 4 describes the time series of data. Section 5 reports the empirical results. Section 6 discusses the effect of natural gas prices on natural gas and hydropower production. Finally, Section 7 concludes the paper.

2. Literature review

2.1. Natural gas prices and production

Studies have found cointegration between natural gas prices and production. A strong cointegrated relationship existed between natural gas prices and shale gas production in 16 U.S. states from January 2007 to December 2016 [21]. Nevertheless, when the recent shale gas boom is taken into account, there is no reliable cointegration between gas prices and conventional natural gas production [22].

There is growing evidence that natural gas prices and production costs can affect gas production. The undesirable cost of natural gas production in a country may increase gas production in other countries with relatively low extraction costs. If Mexico is unable to keep gas production costs at competitive levels, it will have to seek extra gas supply from Texas and neighboring U.S. states, causing a ripple effect that will increase production in other regions in the U.S. [23]. International gas resources may prove to be less costly than those in the U.S. Hence, the emergence of an integrated global gas market could result in significant U.S. gas imports, which is a production incentive for international net gas exporters [24]. In China, lifting the gas demand price cap would negatively affect the LNG industry, as market players could resort to lower-cost supply pathways [15].

2.2. Integration of natural gas markets

Significant local dynamic neighboring market integrations exist across natural gas markets. The interdependence between European and American gas prices is increasing [25]. Though China's domestic natural gas market has not yet aligned with the global gas market, external natural gas prices were found to have a significant long-term impact on China's natural gas prices [20].

2.3. Natural gas and crude oil prices: Moving together, spillover effects, and decoupling

From 1999 to 2017, there was a long-term equilibrium relationship between crude oil and natural gas returns in the U.S. market when additional factors such as storage and seasonality factors were taken into account [26]. When shifts in the cointegrating vector are controlled for, tests reveal that natural gas and crude oil prices are cointegrated [27]. Moreover, European and Japanese gas prices are cointegrated with Brent oil prices [28].

Price spillovers have been found to proceed from crude oil markets to natural gas markets in the United States, Europe, and Japan [28]. In the U.S. market, there was a stable contemporaneous causal flow from crude oil prices to natural gas prices from 1999 to 2017 [26]. Tests using the day-ahead spot price from 2011 to 2014 find that oil prices had a small positive impact on gas prices in the Netherlands [29].

However, there is increasing empirical evidence that natural gas prices have decoupled from oil prices. The long-term relation seen in the early years decoupled in 2006, such that natural gas and crude oil prices are now determined independently [30]. The U.S. gas price has decoupled from oil prices due to natural gas market liberalization and shale gas expansion [28].

2.4. Spot and futures prices of natural gas and crude oil

The literature shows that futures prices may be able to predict spot prices. Changes in spot and futures prices may have occurred as a result of changes in the excess supply of current production, or changes in price expectations [31]. The introduction of futures may improve the speed and quality of information flowing to the spot market [32].

The short-maturity natural gas futures market can significantly predict the spot market [33]. From May 2007 to April 2016, there were significant spillover effects in the natural gas spot, futures, and ETF markets in both the United States and the United Kingdom. Hence, natural gas futures prices might be considered when constructing optimal dynamic hedging strategies for natural gas spot prices [34]. However, tests using daily data for Henry Hub natural gas spot and futures prices suggest that natural gas futures prices do not predict the magnitude of natural gas spot prices with exceptional accuracy [35].

Crude oil spot and futures prices are often cointegrated [36] or tend to move towards equilibrium [37]. In the short run, there is a causal effect between oil spot and futures prices [38]. However, if nonlinear effects are considered, there are no lead–lag relations between the WTI crude oil spot and futures prices [39].

3. Methodology

To examine the relationship between energy production and energy prices, the study tested for cointegration using the Phillips–Ouliaris test [40] and the Johansen trace test [41]. The Johansen test estimates $\Pi = \alpha\beta'$. The cointegration vector β represents the long-run relationship. By imposing a zero restriction on α, we tested for the weak exogeneity of a variable for the long-run relation [42]. Moreover, cointegration implies a valid linear error-correction model (ECM) between $I(1)$ variables. However, a first-differenced VAR is still valid for an $I(1)$, but not cointegrated, variable set [43]. Working with the estimated VAR or ECM, we conducted the Granger causality test using the Wald χ^2-statistic.

We tested for unit roots using the augmented Dickey–Fuller (ADF) [44], Phillips–Perron (PP) [45], and Elliott–Rothenberg–Stock modified Dickey–Fuller tests (ERS) [46]. The ERS test applied the generalized least squares (GLS) to de-trend data and selected the lag length using a modified AIC (MAIC) to avoid power loss and maintain a preferable size [47]. Moreover, we tested for a structural break using the Perron method [48]. We estimated the following Perron IO Model C:

$$y_t = \mu + \theta DU_t + \beta t + \gamma DT_t + \delta D(T_b)_t + \alpha y_{t-1} + \sum_{i=1}^{k} c_i \Delta y_{t-i} + \varepsilon_t \tag{1}$$

The t_α-value on α is used to evaluate the null hypothesis of a unit root ($\alpha = 1$).

4. Data

The National Bureau of Statistics of China (NBSC) publishes monthly primary energy production series for Sichuan Province [49]. These series include the output of coal, crude oil, natural gas, hydropower, coal gas, and coal seam gas. However, energy output series have unidentical numbers of observations. Hence, we defined four energy economic systems from April 2002 to June 2019, which includes natural gas and hydropower output, and one of the above four energy prices.

Sichuan produced only 151 and 81 thousand tons of crude oil in 2010 and 2018, respectively. Thus, crude oil production is trivial, and the system, therefore, did not include the crude oil output series. We also dropped the coal series because it lost many records, and the nuclear, wind, solar power, and bioenergy output series due to the quite small number of their observations.

Energy prices include Henry Hub natural gas and WTI crude oil spot and futures prices [50,51]. Prices are in nominal terms. We defined the following variables: *COAL*: Crude coal output. *GAS*: Natural gas output. *HYDROPOWER*: Hydropower output. *GASPRICE_S*: Nominal natural price — spot. *GASPRICE_F*: Nominal natural gas price — futures. *OILPRICE_S*: Nominal crude oil price — spot. *OILPRICE_F*: Nominal crude oil price — futures.

We seasonally adjusted the output and price series using the X-12 (multiplicative) technique. Data were transformed into logarithms.

The Jarque–Bera statistics show that we can accept the normality for *GAS*, *OILPRICE_S*, and *GASPRICE_S* at the 1% level. However, we rejected the normality for *HYDROPOWER*, *OILPRICE_F*, and *GASPRICE_F* at the 1% level. Hence, various unit root tests are required.

Data have non-zero means. The output of natural gas and hydropower has trended upwards over time (see Fig. 1). Spot and futures natural gas prices and spot and futures crude oil prices appear to move together over time. Natural gas prices have gradually declined since June 2008 whereas natural gas production in Sichuan has kept growing. Hence, domestic gas production has appeared to deviate from external prices over time.

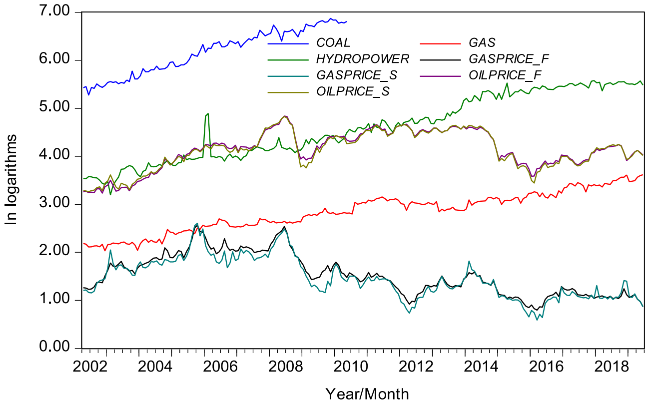

Fig. 1. International natural gas and crude oil prices and primary energy output in Sichuan Province, China.

5. Empirical results

5.1. Unit roots

The ADF, PP, and ERS tests consistently indicated that *GAS* contained a unit root (see Table 2). The Perron test suggested that it had a breakpoint, and $\alpha \approx 1$ (0.69, seeTable 3). Hence, we took *GAS* as a near $I(1)$ process with a structural shift occurring in August 2012.

Table 2. Conventional unit root tests.

	ADF		PP		ERS	
Variable	Level	First diff.	Level	First diff.	Level	First diff.
GAS	−2.12(11)	−5.67(10)***	−5.67(10)***	−22.6(13)***	−4.13(8)***	−4.13(8)***
HYDROPOWER	−1.79(14)	−5.66(13)***	−5.66(13)***	–	−15.6(0)***	−15.64(0)***
GASPRICE_S	−2.70(12)	−5.36(11)***	−5.36(11)***	−12.0(4)***	−5.99(3)***	−5.99(3)***
GASPRICE_F	−3.01(12)	−5.30(11)***	−5.30(11)***	−14.3(3)***	−6.53(3)***	−6.53(3)***
OILPRICE_S	−2.54(2)	−7.84(2)***	−7.84(2)***	−11.2(1)***	−7.76(1)***	−7.76(1)***
OILPRICE_F	−2.09(1)	−5.93(5)***	−5.93(5)***	−11.1(2)***	−8.25(1)***	−8.25(1)***

Notes: Variables in logarithms. As indicated in Fig. 1, data in levels have non-zero means and appear to contain a trend. Test equations contained both the trend and intercept [52]. The lag length k was decided using the t-statistic for the ADF test [53]. For the PP test, k was decided using the Newey–West (NW) bandwidth technique [54]; for the ERS test, k was chosen using the modified Akaike information criterion (AIC) [47]. *, **, and ***denote rejection of the null hypothesis of a unit root at the 10%, 5%, and 1% levels, respectively.

Both the ADF and ERS tests indicated that *HYDROPOWER* had a unit root. The Perron test suggested that it had a breakpoint, and $\alpha = 0.54$. We took *HYDROPOWER* as a near $I(1)$ process with a structural shift occurring in December 2013.

Table 3. Structural break tests using the Perron IO Model C.

Variable	k		Estimate	Standard Error	t-statistic	p-value	T_b
GAS	11	α	0.69	0.08	8.54	0.00	Aug 2012
HYDROPOWER	2	α	0.54	0.08	7.00	0.00	Dec 2013
GASPRICE-S	11	α	0.81	0.06	13.37	0.00	May 2009
GASPRICE-F	7	α	0.87	0.04	20.54	0.00	Feb 2009
OILPRICE-S	2	α	0.89	0.03	34.45	0.00	Oct 2014
OILPRICE-F	6	α	0.98	0.02	48.31	0.00	Dec 2015

Notes: We report only the estimated α to reduce the text space. Variables in logarithms. Test equations contained a slope and an intercept. We selected the lag order k (between 2 and 11) using a general-to-specific recursive procedure. This procedure is data-dependent. The absolute value of a t-statistic on the last lagged term must be greater than or equal to 1.80 [48,53]. The trimming fraction λ was 0.15, which was suggested by [55]. The critical values for a sample size of 100 were −6.21 at the 1% level, −5.55 at the 5% level, and −5.25 at the 10% level [48]. T_b is the break date detected.

The ADF, PP, and ERS tests consistently indicated that *GASPRICE_S*, *GASPRICE_F*, *OILPRICE_S*, and *OILPRICE_F* contained a unit root. The Perron test suggested that they had a breakpoint, and $\alpha \approx 1$. Hence, we took these four variables as a near $I(1)$ process with a structural shift.

Thus, from April 2002 to June 2019, *GAS*, *HYDROPOWER, OILPRICE_S*, *OILPRICE_F, GASPRICE_S,* and *GASPRICE_F* were all $I(1)$ variables.

5.2. Structural breaks

5.3. Cointegration tests

The Phillips–Ouliaris test suggests that, at the 5% level, we could reject the null hypothesis of no cointegration for each of the four variable sets or economic systems (see Table 4).

Table 4. Phillips–Ouliaris tests.

Variable sets	Dependent variable	Z_α-statistic	Haug's c.v.*	p**
GAS, HYDROPOWER, GASPRICE_S	*GAS*	−30.15	−36.50	0.02
GAS, HYDROPOWER, GASPRICE_F	*GAS*	−30.23	−36.50	0.02
GAS, HYDROPOWER, OILPRICE_S	*GAS*	−35.92	−36.50	0.01
GAS, HYDROPOWER, OILPRICE_F	*GAS*	−36.43	−36.50	0.01

Notes: Data in logarithms and in first differences. Tests included both the intercept and linear trend as data had non-zero means and appeared to grow over time [52]. The null hypothesis was that the series were not cointegrated. Lags were chosen as per AIC. We selected the lag length from a maximum value of 10 downwards. *Haug's c.v.: Haug provided finite-sample critical values for the Z_α Phillips–Ouliaris test [40]. **p indicates p-value by MacKinnon [56].

However, asymptotically, the Johansen trace test indicated that, at the 5% level, the system (*GAS*, *HYDROPOWER*, *OILPRICE_S*) contained a cointegrating vector (see Table 5). Nonetheless, both the Cheung–Lai critical value and Reinsel–Ahn trace corrections indicated that we could accept the null hypothesis of no cointegration for this system. Hence, *GAS*, *HYDROPOWER*, and *OILPRICE_S* were not cointegrated.

Asymptotically, the Johansen trace test indicated that, at the 5% level, two systems – (*GAS*, *HYDROPOWER*, *GASPRICE_S*) and (*GAS*, *HYDROPOWER*, *GASPRICE_F*) – each contained a cointegrating vector. Moreover, the Cheung–Lai critical value and Reinsel–Ahn trace corrections both indicated one cointegration relationship for these two variable sets. Hence, we concluded that both (*GAS*, *HYDROPOWER*, *GASPRICE_S*) and (*GAS*, *HYDROPOWER*, *GASPRICE_F*) had a cointegrating vector.

The normalized cointegration relationship for (*GAS*, *HYDROPOWER*, *GASPRICE_S*) is

$$GAS = -\underset{(0.28)}{1.319} HYDROPOWER + \underset{(0.11)}{0.192} GASPRICE\_S + \underset{(0.00)}{0.02} t.$$

Table 5. Johansen cointegration tests.

Variable set	r	k	Trace	OL*	CL**	RA***
(*GAS, HYDROPOWER, GASPRICE_S*)	0	3	52.65	42.92	44.68	49.60
	$\leq$1		24.29	25.87	26.93	22.88
	$\leq$2		8.97	12.52	13.03	8.45
			SIC −512	Adj. Q 0.87	LM 0.75	JB 0.00
(*GAS, HYDROPOWER, GASPRICE_F*)	0	3	49.24	42.92	44.68	46.38
	$\leq$1		23.26	25.87	26.93	21.91
	$\leq$2		9.37	12.52	13.03	8.83
			SIC −5.97	Adj. Q 0.66	LM 0.10	JB 0.00
(*GAS, HYDROPOWER, OILPRICE_S*)	0	2	42.95	42.92	44.08	41.29
	$\leq$1		18.67	25.87	26.57	17.95
	$\leq$2		6.70	12.52	12.86	6.44
			SIC −6.21	Adj. Q 0.94	LM 0.78	JB 0.00
(*GAS, HYDROPOWER, OILPRICE_F*)	0	2	42.11	42.92	44.08	40.48
	$\leq$1		17.82	25.87	26.57	17.13
	$\leq$2		5.88	12.52	12.86	5.65
			SIC −6.47	Adj. Q 0.97	LM 0.81	JB 0.00

Notes: r is the null hypothesis of the cointegration rank of at most r. Assumption: IV. *5% Osterwald–Lenum asymptotical critical values [57]. **5% Cheung–Lai finite-sample critical values [58]. ***Reinsel–Ahn finite-sample trace corrections [59]. The lag length k was selected by increasing the absolute values of both AIC and the Schwarz information criterion (SIC) to the extent possible while allowing for serial correlation and multivariate normality. The maximum k was set to 8.

where t-statistics are in parentheses. The estimated coefficients are interpreted as long-run elasticity. Combined with the results of the weak exogeneity tests (see Table 6) showing that, in the long run, both spot and futures gas prices impacted the production of natural gas and hydropower and that gas production impacted hydropower production, we suggest that the long-run spot gas price elasticities of the production of natural gas and hydropower were 0.192 and 0.146, respectively. The long-term elasticity of hydropower production relative to gas production was −0.758 within this system.

Table 6. Weak exogeneity tests.

Cointegrated systems	H_0: $\alpha = 0$	Wald-χ^2	p-value
(*GAS, HYDROPOWER, GASPRICE_S*)	$\alpha_{11} = 0$	1.57	0.21
	$\alpha_{21} = 0$	12.8	0.00
	$\alpha_{31} = 0$	0.78	0.39
(*GAS, HYDROPOWER, GASPRICE_F*)	$\alpha_{11} = 0$	1.27	0.26
	$\alpha_{21} = 0$	11.8	0.00
	$\alpha_{41} = 0$	0.37	0.54

Notes: α was defined by the estimated cointegrating vector β [60]. p-value was estimated on the basis of [42].

The normalized cointegration relationship for (*GAS*, *HYDROPOWER*, *GASPRICE_F*) is

$$GAS = -\underset{(0.29)}{1.354} HYDROPOWER + \underset{(0.12)}{0.186} GASPRICE\_F + \underset{(0.00)}{0.02} t.$$

Thus, the long-run futures gas price elasticities of the production of natural gas and hydropower were 0.186 and 0.137, respectively. The long-term elasticity of hydropower production relative to gas production was −0.739 for this system.

5.4. Weak exogeneity tests

By imposing a zero restriction on α, we conducted the LR tests for the weak exogeneity of variables for the estimated long-run relationships. Natural gas production, spot, and futures natural gas prices were weakly exogenous relative to the long-run equilibrium.

5.5. Estimation of first-differenced VARs and Granger causality tests

Neither of the two systems including crude oil prices had a cointegrating vector. Thus, we estimated VAR matrices for both of them (see Table 7).

Table 7. Estimation of first-differenced VARs.

Lagged variable	Dependent variable	t		t		t
	GAS		*HYDROPOWER*		*OILPRICE_S*	
OILPRICE_S(−1)	0.04	0.87	0.12	1.25	0.22	3.09
OILPRICE_S(−2)	0.04	0.75	−0.199	−2.05	0.10	1.40
Lag selection:	LR(2) = 33.41	AIC(2) = −6.58	SIC(0) = −6.35	HQ(2) = −6.44	JB 0.00	Adj. Q 8.18
R^2	0.11		0.14		0.08	
	GAS		*HYDROPOWER*		*OILPRICE_F*	
OILPRICE_F(−1)	0.07	1.15	0.18	1.61	0.25	3.56
OILPRICE_F(−2)	0.04	0.67	−0.215	−1.94	0.04	0.56
Lag selection:	LR(2)=31.71	AIC(2)=-6.85	SIC(0)=-6.61	HQ(2)=-6.71	JB 0.00	Adj. Q 6.86
R^2	0.11		0.14		0.08	

Notes: We report only price estimates to reduce the text space. Data in logarithms and first differences. We used both LR and three information criteria: AIC, SIC, and Hannan–Quinn information criterion (HQ) to select the final lag order k, where figures in parentheses are the lag order selected by their respective criterion. The maximum k was set to 8. JB: p-value for multivariate normality Jarque–Bera statistic; normal tests were driven by the square root of correlation [61]. Adj. Q indicates the portmanteau adjusted statistic for no residual autocorrelations.

Based on the estimates of these VARs, we conducted tests on Granger causality between the variables (see Table 8). At the 10% level, both spot and futures oil prices Granger caused *HYDROPOWER*. Thus, regarding the effect of spot oil prices on hydropower production, a statistically significant coefficient was 0.199, with a t-value of −2.05. Regarding the effect of futures oil prices on hydropower production, the statistically significant coefficient was 0.215, with a t-value of −1.94.

Table 8. Granger causality tests in estimated VARs.

Variable sets	Dependent variable	H_0: Variable excluded	Wald-$\chi 2$	p
GAS, HYDROPOWER, OILPRICE_S	*HYDROPOWER*	*OILPRICE_S*	4.79	0.09*
GAS, HYDROPOWER, OILPRICE_F	*HYDROPOWER*	*OILPRICE_F*	5.03	0.08*

Notes: We report only the Granger causal relationships detected to reduce the text space. Variables are those in VARs (see Table 7). H_0: estimated coefficients in VARs = 0. *indicates rejection of the null hypothesis of non-causality at the 10% level.

5.6. Estimation of ECMs and Granger causality tests

The two systems including natural gas prices each had a cointegration relationship. Thus, we estimated ECM matrices for (*GAS*, *HYDROPOWER*, *GASPRICE_S*) and (*GAS*, *HYDROPOWER*, *GASPRICE_F*; see Table 9).

Based on estimates of these ECMs, Table 10 reports the results of the Granger causality tests for the variable pairs in the estimated ECMs using Wald-χ^2. At the 10% level, *GASPRICE_F* Granger caused *GAS*, but *GASPRICE_S* did not. *GAS* Granger caused *HYDROPOWER*. Furthermore, neither *GASPRICE_F* nor *GASPRICE_S* Granger caused *HYDROPOWER*.

Hence, regarding the effect of futures gas prices on gas production, the statistically significant coefficients were 0.095 on the lagged-one term and −0.094 on the lagged-three term. Hence, the short-run (one-month) elasticity of gas production relative to futures gas prices was 0.095.

Regarding the effect of gas production on hydropower production, within the system (*GAS*, *HYDROPOWER*, *GASPRICE_S*), the statistically significant coefficients were 0.277 and 0.292. Within the system (*GAS*, *HYDROPOWER*, *GASPRICE_F*), the statistically significant coefficients were 0.278 and 0.282. Overall, we suggest that the short-run (two-month) elasticity of hydropower production relative to gas production was 0.283.

Table 9. Estimation of ECMs.

Lagged variable	Dependent variable	*t*		*t*		*t*
	GAS		*HYDROPOWER*		*OILPRICE_S*	
EC term	−0.04	−1.50	−0.23	−5.20	0.06	1.20
GASPRICE_S(−1)	0.01	0.28	−0.02	−0.34	0.01	0.08
GASPRICE_S(−2)	0.00	0.08	−0.06	−1.05	0.00	0.06
GASPRICE_S(−3)	−0.05	−1.34	−0.09	−1.51	0.06	0.83
Lag selection:	Log likelihood=630.3	AIC(2)=-5.73	SIC(0)=-5.16	Adj. Q 0.87	LM 0.75	JB 0.00
R^2	0.12		0.24		0.03	
	GAS		*HYDROPOWER*		*OILPRICE_F*	
EC term	−0.03	−1.39	−0.22	−4.99	0.03	0.84
GASPRICE_F(−1)	0.095	1.87	−0.01	−0.06	0.17	2.28
GASPRICE_F(−2)	0.02	0.41	−0.05	−0.55	0.05	0.71
GASPRICE_F(−3)	−0.094	−1.83	−0.01	−0.10	0.03	0.43
Lag selection	Log likelihood=715.9	AIC(2)=-6.57	SIC(0)=-6.02	Adj. Q 0.66	LM 0.10	JB 0.00
R^2	0.14		0.23		0.05	

Notes: We report only price estimates to reduce the text space. The lag length k was selected by increasing the log-likelihood and the absolute values of both AIC and SIC to the extent possible while allowing for serial correlation and multivariate normality. The maximum k was set to 8. Adj. Q: p-value for a portmanteau adjusted statistic for no residual autocorrelation. LM: p-value for LM statistic for no serial correlation. JB: p-value for Jarque–Bera multivariate normality statistic. Normality tests were driven by the square root of correlation.

Table 10. Granger causality tests in estimated ECMs.

Variable sets	Dependent variable	H_0: Variable excluded	Wald-χ2	p
GAS, HYDROPOWER, GASPRICE_S	*HYDROPOWER*	*GAS*	7.21	0.07*
GAS, HYDROPOWER, GASPRICE_F	*GAS*	*GASPRICE_F*	6.80	0.08*
	HYDROPOWER	*GAS*	6.73	0.08*

Notes: We report only the Granger causal relationships detected to reduce the text space. Variables are those in ECMs (see Table 9). H_0: estimated coefficients in ECMs = 0. *indicates rejection of the null hypothesis of non-causality at the 10% level.

6. Discussion

During the April 2002 to June 2019 period, we observe a cointegrating relation between gas, hydropower, and either spot or futures natural gas prices.

Hence, gas production, hydropower production, and energy prices displayed a long-run equilibrium. Gas prices were weakly exogenous for this long-run relation.

In the long run, both spot and futures gas prices slightly and positively impacted the production of gas and hydropower. The long-run spot and futures gas price elasticities of gas output were 0.192 and 0.186, respectively. Although China's natural gas market has not yet aligned with the global gas market [20], we suggest that as a significant natural gas producer in China, Sichuan has gradually integrated into global gas markets and accordingly established a similar price-production relationship with key international markets [21,22]. Our findings support the increasing interdependence between natural gas markets [25].

Moreover, the difference between the long-run effects of spot and futures gas prices on either gas or hydropower production was generally insignificant, which may reflect significant spillover effects in the natural gas spot and futures markets [34].

However, in the short run, futures gas prices Granger-caused gas output, but spot gas prices did not. The short-run (one-month) futures gas price elasticity of gas production was 0.095. Neither spot nor futures gas prices Granger-caused hydropower output. Gas production impacted hydropower production but not vice versa; the short-run (two-month) elasticity of hydropower output relative to gas output was 0.283. Therefore, we suggest that, in the short run, futures gas prices slightly and positively impacted gas production first and then the effect may have been transmitted to hydropower production.

The long-run gas price effect appears to be greater than the short-run effect, perhaps due to the slow and awkward response of giant energy equipment, complicated energy production processes, and planned schedules to energy price changes over the short term.

By contrast, crude oil prices did not impact gas production in the long run. Due to negligible oil reserves and oil production, nearly 100% of Sichuan's crude oil use depended on imports. Thus, Sichuan has a minimum demand for crude oil products. This part of energy demand has fully incorporated crude oil price information and accordingly changes in external crude oil prices have little impact on the minimum or fixed demand for refined oil products. Even if international crude oil prices grow, neither natural gas nor hydropower use could substitute for crude oil use in various sectors. As a result, the natural gas output will not adjust according to the change in crude oil prices. Our finding may not support the integration between gas and crude oil prices [27] and the price spillovers proceeding from crude oil markets to natural gas markets [28]. However, it may provide a new clue to the decoupling of gas prices from oil prices [30].

The empirical evidence shows that gas production appears to have provided a long-run substitution for hydropower production. Gas production impacted hydropower production but not vice versa, with an average long-term elasticity of hydropower output relative to the gas output of -0.749. Intuitively, the substitution occurred due to the differential responses of changes in gas and hydropower output to gas price changes. The long-run spot and futures gas price elasticities of hydropower output were 0.146 and 0.137, respectively. Hence, gas output responded to both spot and futures gas prices more (an average of 33% more) quickly than hydropower output did. As indicated above, natural gas demand in China is substantial and is expected to expand quickly. Gas use heavily depends on imports. Gas supply is subject to international gas prices in some vital gas markets. Growing prices would provoke gas producers to increase their output. In theory, power and natural gas can readily substitute for each other. If gas prices grow but power prices decline or remain stable, a household may use more power than usual for cooking, bathing, and heating. Thus, given the growth in international natural gas prices, hydropower demand in China may increase, and its output may then grow. However, the dynamics of hydropower supply and demand come from the internal market. Although a decline in power prices would lead to an increase in hydropower demand and growth in output, this seldom occurs because the State Grid Corporation of China determines power prices in 27 of China's 31 provinces. The relatively fixed power prices, in line with hydropower output surplus, imply that hydropower production is difficult to adjust according to international energy prices. Sichuan's hydropower supply potential has far exceeded demand. In 2016 and 2017, it had to cut as much as 50 billion kWh of hydropower output [5,62]. The reasons for this excess supply include huge installed capacity, seasonal changes in river water volume, disputes over hydropower prices between Sichuan and importing provinces, and below-standard transmission grid equipment.

7. Conclusions

Sichuan Province holds abundant natural gas and hydropower reserves and is thus a leading producer of these two energies in China. However, its coal reserves are limited, and its crude oil reserves are insignificant. The government has encouraged the development and use of natural gas and hydropower. Currently, natural gas is in short supply in Sichuan, while hydropower is coming under increasing pressure due to a supply surplus. Meanwhile, other provinces are increasingly importing gas from Central Asia, the Middle East, Southeast Asia, and Australia. Thus, given the government's strictly planned energy prices, Sichuan's energy production will be increasingly impacted by the global energy market. This study tested for the effect of Henry Hub natural gas and WTI crude oil prices on natural gas and hydropower production in Sichuan. The tests suggested two cointegrating relations.

Both spot and futures gas prices slightly and positively impacted gas and hydropower output. The long-run spot and futures price elasticities of gas output were 0.192 and 0.186, respectively. The long-run spot and futures price elasticities of hydropower output were 0.146 and 0.137, respectively. Thus, the differences between the effects of spot and futures prices were insignificant. The long-run price effect appeared to be greater than the short-run effect.

Although spot and futures gas prices slightly and positively impacted both gas and hydropower output, in the long run, gas output responded to both spot and futures gas prices faster (by nearly 33%) than hydropower output did. Hence, we suggest that gas production could provide a long-run substitution for hydropower production. We find that the average long-term elasticity of hydropower output relative to gas output was -0.749. With the continuous increase of natural gas output, the hydropower surplus may become increasingly severe.

Given the government's strictly planned crude oil and natural gas pricing mechanisms, representative external spot and futures natural gas prices can be a long-run determinant of Sichuan's natural gas production. This could imply that Sichuan's natural gas markets have been integrating into the international key energy market.

International crude oil prices had insignificant effects on energy production due to the negligible oil reserves and production, the minimum demand for refined oil products, and possibly the decoupling of global gas prices from oil prices.

We suggest that using longer-period data may allow us to estimate the energy price effect on energy production with more accuracy.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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