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Measuring contagion effects of nuclear energy policies and events

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Summary

This paper investigates the contagion effects of five regional nuclear accidents, nuclear expansions, or nuclear phase-out events or policies from 2007 to 2017 on the stock markets of the global nuclear energy markets. Contagion tests based on correlation and higher order comoments are applied to determine how these events or policy shocks affect global nuclear energy stock prices. The empirical results show that the Fukushima nuclear accident had the most significant impact on global nuclear energy markets, followed by the Korean nuclear expansion, while the German, Korean, and French nuclear phase-out policies had the least pervasive contagion. The nonlinear dependence test detected more evidence of contagion than did the linear dependence test, indicating that both asymmetric and extremal dependences are important dimensions of measuring risk contagion in nuclear energy markets.

KEYWORDS

contagion tests, Fukushima nuclear accident, nuclear energy policy, nuclear phaseout, nuclear power markets

1 | INTRODUCTION

In response to the call for energy conservation and reduction of carbon emissions, nuclear energy has become an indispensable and reliable energy source because it emits almost zero greenhouse gases or other harmful gases such as nitrogen oxides or sulfur oxides during power generation. Although the cost of nuclear power plant (NPP) infrastructure is higher than that of thermal power plants, subsequent fuel costs are significantly lower. Moreover, the technical nature of the nuclear power industry means that it is conducive to promoting technological innovation and decreasing rates of unemployment. Thus, numerous countries, particularly those in Asia, have constructed NPPs. In 2008, Korea adopted a new National Energy Basic Plan to increase the amount of electricity generated by NPPs to 59% by 2030.[1]

However, the Fukushima nuclear accident in Japan in March, 2011, has affected public perceptions of nuclear safety. Since then, many countries, especially Japan and European countries, have reviewed their nuclear power programs with a view to phasing out their NPPs. For example, on June 30, 2011, the German Bundestag voted in favor of a nuclear abolition bill, under which 17 NPPs in the country will be shut down by 2022.[2] In July 2015, The French National Assembly passed its *Energy Transition for Green Growth Act*, mandating a reduction of electricity generated by NPPs from 75% to 50% by 2025.[3] The Swiss government aims to phase out nuclear power by 2050.[4] The Canadian government has established an action plan to strengthen the safety of NPPs and other major nuclear facilities.[5] China, the United Kingdom (UK), and the United States (US) have all announced that they will temporarily reject any new nuclear programs.[6]

From an economic perspective, nuclear energy policies or events originated from one country may also affect other countries' policy decisions and guidelines on nuclear energy development,[20] thus having impacts on

the global nuclear energy markets as well as the economies of these countries. Therefore, the aim of this paper is to investigate the impacts of five nuclear accident or nuclear energy policy events on global nuclear energy markets. Furthermore, this work provides an important reference for relevant departments to evaluate and formulate energy policies to maintain energy security and economic development. The sampling period of this paper includes the most important critical period for nuclear power development in the past 10 years. It not only covers the Fukushima nuclear accident, which has the most significant impact on the nuclear power industry, but also covers the most important nuclear power industry policies introduced by various countries in recent years. Therefore, this article has high empirical values and reference significance for reviewing the development of the global nuclear power industry.

To investigate the impacts of nuclear events on global nuclear markets, we adopt four contagion tests: (a) a correlation test; (b) two types of coskewness tests; (c) two types of cokurtosis tests; and (d) a covolatility test. An early contagion test[7] measures linear dependence contagion, defined as a significant increase in cross-market linkages after a shock has occurred to one or more markets. Because Gaussian distributions underpinning traditional correlations are not appropriate for modeling returns on assets, some researchers[8,9] suggest exploring different channels of contagion through higher order comoments. Several authors[10,11] show that coskewness, cokurtosis, and covolatility are important dimensions for measuring contagion risk because investors prefer returns on assets that switch from left-skewed to right-skewed and exhibit leptokurtic behavior in the postevent period compared with the pre-event period. Thus, adopting both correlation and higher order comoment contagion tests enables us to explore an extensive range of spillover effects between the nuclear power markets of seven countries globally.

This paper adopts novel econometric methods to assess the impact of related events and policies on the development of the nuclear power industry in seven countries. Specifically, the contributions of this paper are as follows: First, both linear and nonlinear dependence tests of contagion are examined to identify how events or policy shocks affect global nuclear energy markets by capturing changes in asset-return relationships, including cross-country mean and mean (correlation), cross-country mean and volatility (coskewness), cross-country mean and skewness (cokurtosis), and cross-country volatilities (covolatility). Second, this paper fills the research gap by studying the contagious effects of three events—nuclear disasters, nuclear expansion policies, and nuclear phase-out policies—on nuclear market performance. Finally, based on the use of four test models, this article attempts to find one of the most efficient tools for evaluating the contagion effects of nuclear power policies by investigating the size and power properties of these contagion tests.

In this paper, empirical analysis of nuclear energy markets shows significant and widespread contagion effects on global nuclear energy markets following the five nuclear episodes. Among the five nuclear events, the Fukushima nuclear incident was the most serious, affecting most global nuclear energy markets, followed by the Korean nuclear expansion, with nuclear phase-out policies the least pervasive in causing contagion. In addition, compared with the linear dependence test, nonlinear dependence tests show more evidence of contagion following nuclear incidents and policy changes, indicating that both asymmetric and extremal dependences are essential dimensions in measuring nuclear risk. Finally, the applied contagion tests show good size and power properties based on the empirical study of the pre- and postevent periods.

The paper is structured as follows: Section 2 reviews the related literature on the effects of nuclear accidents and policies on market performance. Section 3 introduces the contagion tests. Section 4 describes five nuclear accident and policy announcements during the period 2007 to 2017. Section 5 provides the economic implications of the results. Section 6 concludes the paper.

2 | LITERATURE REVIEW

Many studies have quantified the contagion effects of a variety of nuclear incidents on stock markets. Early studies examining the effects of nuclear accidents on stock prices focused on the Three Mile Island accident in 1979,[12,13] which had a significant adverse effect on the housing market. More recent works have focused on the impact of the Fukushima nuclear accident on the housing market,[14-16] banking sector,[17] stock market,[18-21] and power sector.[22] Researchers[20] use the event parameter model to test the contagion effects of the Fukushima nuclear accident on the conventional electricity industry, finding a sharp increase in systematic risks in the industry following the event. Researchers in Ref. 14 use the difference-in-differences approach to evaluate the impact of Fukushima on the Swiss housing market, finding that the prices of houses close to NPPs decreased. Researchers in Ref. 15 use the same model to evaluate Chinese housing prices before and after Fukushima, concluding that land prices within 40 km of NPPs dropped by about 18% 1 month following the accident. Researchers in Ref. 16 also use the difference-in-differences model, finding that

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the Fukushima accident reduced the price of houses near NPPs in Germany by 4.9%.

However, little attention has been paid to market and economic instability caused by uncertainties about the future of nuclear power, especially those related to nuclear phase-out policies, which is one of the main scopes of this paper. There is clear evidence for the impact of nuclear phaseout on electricity prices in many countries, including Belgium,[23] France,[3,24,25] Germany,[26-28] Japan,[29] and Switzerland.[30,31] Nuclear phaseout affects not only the electricity sector but also other economic sectors such as manufacturing[32] and renewable energy.[33,34] Researchers in Ref. 31 develop a system dynamics model to analyze the impact of the Swiss nuclear phaseout on its electricity market, concluding that nuclear energy production has been mainly replaced by photovoltaics and imports, increasing electricity prices. Using a quasi-experimental approach, the researcher in Ref. 25 finds that the French nuclear phaseout increased electricity prices in France by 27.1% and in Germany by 3.2% because of cross-border trade.

The final set of literature covers the impact of nuclear expansion on stock market performance. Using contagion tests, researchers in Ref. 35 examine the impact of Chinese nuclear expansion on the performance of nine sectors, finding that nuclear announcement shocks primarily affect the financial sector (48.47%), followed by the energy (29.33%) and industrial (18.59%) sectors. A number of studies find a positive effect of nuclear energy expansion on energy self-sufficiency,[36] electricity grid capacity,[37] and economic growth.[38] However, in the United Kingdom, nuclear energy expansion had a negative effect on environmental and ecological systems.[39]

The abovementioned studies on nuclear accidents and nuclear phase-out and expansion policies provide important reference for the study of nuclear market contagion. However, the research on the development of the nuclear power industry itself in response to relevant policies or events is still very sparse. Therefore, this paper contributes to the existing literature with respect to how regional nuclear policies and events cause contagion to the global nuclear energy markets.

3 | RESEARCH METHODOLOGY

This section provides a brief description of the contagion tests developed by Fry et al and Fry-McKibbin et al.[8,9,40] These contagion tests measure changes in relationships between assets markets through higher order comoments of correlation, coskewness, cokurtosis, and covolatility, deriving Lagrange multiplier test statistics under the assumption that the joint probability distribution of returns on assets is a nonnormal bivariate generalized exponential distribution. The size and power properties of the contagion tests are presented in the last subsection.

3.1 | Correlation test

The correlation test was developed by Fry et al[8] to test for significant changes in correlations between asset markets i and j in the postevent period ($\hat{v}_{y|x_i}$) compared with the pre-event period ($\hat{\rho}_x$). The correlation event test statistic (CR) is:

$$\mathrm{CR}(i \to j) = \frac{\left(\hat{v}_{y|x_i} - \hat{\rho}_x\right)^2}{\mathrm{Var}\left(\hat{v}_{y|x_i} - \hat{\rho}_x\right)}, \tag{1}$$

$$\hat{v}_{y|x_i} = \frac{\hat{\rho}_y}{\sqrt{1 + \delta\left(1 - \hat{\rho}_y^2\right)}}, \tag{2}$$

$$\delta = \left(\sigma_{i,y}^2 - \sigma_{i,x}^2\right) / \sigma_{i,x}^2. \tag{3}$$

The unconditional correlation coefficients of markets i and j in the pre-(x) and postevent (y) periods are $\hat{\rho}_x$ and $\hat{\rho}_y$, respectively. The conditional correlation coefficient in the postevent period is $\hat{v}_{y|x_i}$, where δ is the change in ratio of market volatilities in market i in the postevent period relative to the pre-event period, and $\sigma_{i,x}^2$ and $\sigma_{i,y}^2$ are the respective variances of returns. The variance of CR in Equation (1) is given by:

$$\mathrm{Var}\left(\hat{v}_{y|x_i} - \hat{\rho}_x\right) = \mathrm{Var}\left(\hat{v}_{y|x_i}\right) + \mathrm{Var}(\hat{\rho}_x) - 2\mathrm{Cov}\left(\hat{v}_{y|x_i}, \hat{\rho}_x\right), \tag{4}$$

$$\mathrm{Var}\left(\hat{v}_{y|x_i}\right) = \frac{1}{2}\frac{(1+\delta)^2}{\left[1 + \delta\left(1 - \rho_y^2\right)\right]^3} \times \left[\frac{1}{T_y}\left(\left(2 - \rho_y^2\right)\left(1 - \rho_y^2\right)^2\right) + \frac{1}{T_x}\left(\rho_y^2\left(1 - \rho_y^2\right)^2\right)\right], \tag{5}$$

$$\mathrm{Var}(\hat{\rho}_x) = \frac{1}{T_x}\left(1 - \rho_x^2\right)^2, \tag{6}$$

$$\mathrm{Cov}\left(\hat{v}_{y|x_i}, \hat{\rho}_x\right) = \frac{1}{2}\frac{1}{T_x}\frac{\rho_y \rho_x \left(1 - \rho_y^2\right)\left(1 - \rho_x^2\right)(1+\delta)}{\sqrt{\left[1 + \delta\left(1 - \rho_y^2\right)\right]^3}}. \tag{7}$$

This extends the test developed by Ref. 7 through generalizing the expression of the variance of the test statistic to allow for some dependence between returns on assets in the postevent period compared with the pre-event

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period. Under the null hypothesis, the correlation test statistic is asymptotically distributed as $\mathrm{CR} \xrightarrow{d} \chi_1^2$.

3.2 | Coskewness tests

Coskewness tests capture changes in the asymmetric dependence of asset markets i and j in the pre- and postevent periods derived from the correlation change test.[8] The asymmetry arises from the dependence between expected returns in one market and volatility of returns in another market. There are two forms of coskewness tests, denoted CS_{12} and CS_{21}. The first form measures the dependence between expected returns in market i and squared returns in market j. The coskewness coefficients in the pre-(x) and postevent (y) periods are:

$$\hat{\psi}_x\left(r_i, r_j^2\right) = \frac{1}{T_x}\sum_{t=1}^{T_x}\left(\frac{r_{i,t}-\hat{\mu}_{i,x}}{\hat{\sigma}_{i,x}}\right)\left(\frac{r_{j,t}-\hat{\mu}_{j,x}}{\hat{\sigma}_{j,x}}\right)^2, \tag{8}$$

$$\hat{\psi}_y\left(r_i, r_j^2\right) = \frac{1}{T_y}\sum_{t=1}^{T_y}\left(\frac{r_{i,t}-\hat{\mu}_{i,y}}{\hat{\sigma}_{i,y}}\right)\left(\frac{r_{j,t}-\hat{\mu}_{j,y}}{\hat{\sigma}_{j,y}}\right)^2, \tag{9}$$

The two asset returns (r_i and r_j) in each period are demeaned and standardized using the respective sample means ($\mu_{i,x}$, $\mu_{j,x}$, $\mu_{i,y}$, and $\mu_{j,y}$) and SDs ($\sigma_{i,x}$, $\sigma_{j,x}$, $\sigma_{i,y}$, $\sigma_{j,y}$). T_x and T_y are the sample sizes for each periods.

The coskewness test statistic comparing the first form of coskewness of markets in periods x and y is:

$$\mathrm{CS}_{12}(i \to j) = \frac{\left(\hat{\psi}_y\left(r_i, r_j^2\right) - \hat{\psi}_x\left(r_i, r_j^2\right)\right)^2}{\frac{4\hat{v}_{y|x_i}^2 + 2}{T_y} + \frac{4\hat{\rho}_x^2 + 2}{T_x}}, \tag{10}$$

The second form of coskewness reverses the asymmetric dependence to volatility in asset i and expected returns in asset j. The coskewness statistics are denoted $\hat{\psi}_x\left(r_i^2, r_j\right)$ and $\hat{\psi}_y\left(r_i^2, r_j\right)$. The second coskewness test is:

$$\mathrm{CS}_{21}(i \to j) = \frac{\left(\hat{\psi}_y\left(r_i^2, r_j\right) - \hat{\psi}_x\left(r_i^2, r_j\right)\right)^2}{\frac{4\hat{v}_{y|x_i}^2 + 2}{T_y} + \frac{4\hat{\rho}_x^2 + 2}{T_x}}. \tag{11}$$

Under the null hypothesis, the coskewness test statistics are asymptotically distributed as $\mathrm{CS}_{12}, \mathrm{CS}_{21} \xrightarrow{d} \chi_1^2$.

3.3 | Cokurtosis tests

Cokurtosis tests capture changes in dependence measured in the fourth-order comoments of the joint distribution of asset markets i and j.[9] Three types of cokurtosis tests may be used to capture the dependence between expected returns in one market and skewness in another market and vice versa and volatility dependence across markets, respectively. For convenience, we refer to the final form of cokurtosis as covolatility. The two cokurtosis tests and the covolatility test are denoted CK_{13}, CK_{31}, and CV, respectively.

The first form of cokurtosis measures the dependence between expected returns in market i and the skewness of returns in market j. The cokurtosis coefficients in periods x and y are:

$$\hat{\varphi}_x\left(r_i, r_j^3\right) = \frac{1}{T_x}\sum_{t=1}^{T_x}\left(\frac{r_{i,t}-\hat{\mu}_{i,x}}{\hat{\sigma}_{i,x}}\right)\left(\frac{r_{j,t}-\hat{\mu}_{j,x}}{\hat{\sigma}_{j,x}}\right)^3 - 3\hat{\rho}_x, \tag{12}$$

$$\hat{\varphi}_y\left(r_i, r_j^3\right) = \frac{1}{T_y}\sum_{t=1}^{T_y}\left(\frac{r_{i,t}-\hat{\mu}_{i,y}}{\hat{\sigma}_{i,y}}\right)\left(\frac{r_{j,t}-\hat{\mu}_{j,y}}{\hat{\sigma}_{j,y}}\right)^3 - 3\hat{v}_{y|x_i}, \tag{13}$$

The cokurtosis test statistic comparing the first form of cokurtosis of markets in the pre- and postevent periods is:

$$\mathrm{CK}_{13}(i \to j) = \frac{\left(\hat{\varphi}_y\left(r_i, r_j^3\right) - \hat{\varphi}_x\left(r_i, r_j^3\right)\right)^2}{\frac{18\hat{v}_{y|x_i}^2 + 6}{T_y} + \frac{18\hat{\rho}_x^2 + 6}{T_x}}, \tag{14}$$

The second form of cokurtosis reverses the dependence to skewness in asset i and expected returns in asset j, with the statistics denoted $\hat{\varphi}_x\left(r_i^3, r_j\right)$ and $\hat{\varphi}_y\left(r_i^3, r_j\right)$. The cokurtosis test statistic comparing the second form of cokurtosis of markets in the pre- and postevent periods is:

$$\mathrm{CK}_{31}(i \to j) = \frac{\left(\hat{\varphi}_y\left(r_i^3, r_j\right) - \hat{\varphi}_x\left(r_i^3, r_j\right)\right)^2}{\frac{18\hat{v}_{y|x_i}^2 + 6}{T_y} + \frac{18\hat{\rho}_x^2 + 6}{T_x}}. \tag{15}$$

Covolatility tests measure dependence between the volatility of asset i and the volatility of asset j. Expressions of the covolatility statistics in the pre- and postevent periods are:

$$\hat{\varphi}_x\left(r_i^2, r_j^2\right) = \frac{1}{T_x}\sum_{t=1}^{T_x}\left(\frac{r_{i,t}-\hat{\mu}_{i,x}}{\hat{\sigma}_{i,x}}\right)^2\left(\frac{r_{j,t}-\hat{\mu}_{j,x}}{\hat{\sigma}_{j,x}}\right)^2 - \left(1+\hat{\rho}_x^2\right), \tag{16}$$

$$\hat{\varphi}_y\left(r_i^2, r_j^2\right) = \frac{1}{T_y}\sum_{t=1}^{T_y}\left(\frac{r_{i,t}-\hat{\mu}_{i,y}}{\hat{\sigma}_{i,y}}\right)^2\left(\frac{r_{j,t}-\hat{\mu}_{j,y}}{\hat{\sigma}_{j,y}}\right)^2 - \left(1+2\hat{v}_{y|x_i}^2\right), \tag{17}$$

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The covolatility test statistic comparing the volatility of markets in the pre- and postevent periods is:

$$\mathrm{CV}(i\rightarrow j)=\frac{\left(\hat{\varphi}_y\left(r_i^2,r_j^2\right)-\hat{\varphi}_x\left(r_i^2,r_j^2\right)\right)^2}{\frac{4\hat{v}_{y|x_i}^4+16\hat{v}_{y|x_i}^2+4}{T_y}+\frac{4\hat{\rho}_x^4+16\hat{\rho}_x^2+4}{T_x}}, \tag{18}$$

Under the null hypothesis of no contagion, the cokurtosis and covolatility test statistics are asymptotically distributed as $\mathrm{CK}_{13},\mathrm{CK}_{31},\mathrm{CV}\xrightarrow{d}\chi_1^2$.

3.4 | Size and power properties of contagion tests

To investigate the size and power properties of contagion tests, a range of Monte Carlo experiments are conducted using the data generating process based on the bivariate generalized normal distribution with standardized population means to be zero and variances to be one, giving the joint density function as

$$f\left(r_i,r_j\right)=\exp\left[-\left(\frac{r_i^2+r_j^2-2\rho r_i r_j}{2(1-\rho^2)}\right)+\theta_4 r_i r_j^2+\theta_5 r_i r_j^3+\theta_6 r_i^2 r_j^2-\eta\right]. \tag{19}$$

where η is constant term.

To perform the size property of contagion tests, the Monte Carlo experiment is conducted based on the null hypothesis of no contagion by imposing the restrictions $\rho=0,\ \theta_4=0,\ \theta_5=0,\ \theta_6=0$ on the data generating process. Then, Equation (19) reduces to an independent bivariate normal distribution in the pre- and postevent periods as

$$f\left(r_i,r_j\right)=\exp\left[-\left(\frac{r_i^2+r_j^2}{2}\right)-\eta\right]. \tag{20}$$

To perform the power property of contagion tests, four experiments are conducted based on the alternative hypothesis of contagion through the correlation channel given by

$$f\left(r_i,r_j\right)=\exp\left[-\left(\frac{r_i^2+r_j^2-2\rho r_i r_j}{2(1-\rho^2)}\right)-\eta\right], \tag{21}$$

for experiment I, through the coskewness channel given by

$$f\left(r_i,r_j\right)=\exp\left[-\left(\frac{r_i^2+r_j^2}{2}\right)+\theta_4 r_i^1 r_j^2-0.5 r_i^2 r_j^2-\eta\right]. \tag{22}$$

for experiment II,* and through the cokurtosis channel gives

$$f\left(r_i,r_j\right)=\exp\left[-\left(\frac{r_i^2+r_j^2}{2}\right)-\theta_5 r_i^1 r_j^3-\eta\right]. \tag{23}$$

for experiment III, and through the covolatility channel gives

$$f\left(r_i,r_j\right)=\exp\left[-\left(\frac{r_i^2+r_j^2}{2}\right)-\theta_6 r_i^2 r_j^2-\eta\right]. \tag{24}$$

for experiment VI.

Table 1 presents the results of size and power properties of contagion tests. The sizes for all contagion tests are based on the 5% asymptotic χ_1^2 critical value. The simulation results show that all four tests (CR, CS_{12}, CK_{13}, and CV) are consistent with the empirical sizes approaching the nominal 5% level as the empirical study of the pre-

TABLE 1 Size and power properties of contagion tests

Size tests	Experiment based on Equation (20)				
T_x=	363	298			
CR	0.059	0.058			
CS_{12}	0.047	0.046			
CK_{13}	0.042	0.042			
CV	0.039	0.040			
Power tests	Experiment I based on Equation (21)				
ρ_y=	0	0.1	0.4	0.7	0.9
CR	0.050	0.221	1.000	1.000	1.000
Power tests	Experiment II based on Equation (22)				
$\theta_{4,y}$=	0	0.1	0.4	0.7	0.9
CS_{12}	0.050	0.082	0.381	0.856	0.995
Power tests	Experiment III based on Equation (23)				
$\theta_{5,y}$=	0	0.1	0.4	0.7	0.9
CK_{13}	0.050	0.208	0.732	0.915	0.967
Power tests	Experiment VI based on Equation (24)				
$\theta_{6,y}$=	0	0.1	0.4	0.7	0.9
CV	0.050	0.999	1.000	1.000	1.000

Note: Based on the size property of contagion tests, the postevent sample size is $T_y=365$. Based on the power property, the pre- and postevent sample sizes are $T_x=298$ and $T_y=365$. The number of replications is 50 000.

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and postevent sample sizes are $T_x = 363$, $T_y = 365$ and $T_x = 298$, $T_y = 365$.

The power properties of contagion tests are presented in Table 1. The results of the experiment I reveal that when contagion strength correlation (ρ_y) increases from 0 to 0.4, the correlation test reaches to 100% power in detecting contagion. For experiment II, the coskewness test detects 100% power of contagion when contagion strength coskewness is 0.9. For experiment III, the cokurtosis test detects 100% with 0.9 of contagion strength, while for experiment VI, the covolatility test finds 100% of power with 0.9 of contagion strength. Overall, among the four tests, the cokurtosis test performs the best power of finding contagion, followed by the correlation and covolatility tests, with the coskewness test the least powerful in detecting contagion.

4 | FIVE EPISODES OF NUCLEAR EVENTS

This section describes the data used in the empirical analysis and the dates chosen for each nuclear policy or event, which are then used to analyze contagion.

4.1 | Data

To investigate the contagious effects of major nuclear events from 2007 to 2017 on the nuclear energy returns of various countries, the following major events are compared: (1) the 2008 Korean nuclear expansion policy; (2) the 2011 Fukushima nuclear accident; (3) the 2011 German nuclear abolition policy; (4) the 2013 Korean nuclear reduction policy; and (5) the 2015 French nuclear reduction policy. These five nuclear events were relatively important globally in recent years, reflecting general trends and changes in nuclear energy progress. We investigated their contagion on seven countries listed in the World Nuclear Association (WNA) Index: Canada, France, Germany, India, Japan, Korea, and the United States. The WNA Index, collected from the Bloomberg database, provides the stock prices of nuclear energy companies in the WNA. The WNA Nuclear Energy Index is intended to act as a rational and neutral indicator of the performance of the global nuclear power industry and is made up of a universe of publicly listed firms from all over the world. In order to be included in the index, the performance of a firm must be substantially influenced by the development of the industry and its stock need to pass several screens, including share price and turnover, float, exchange listing, as well as capitalization.[41,42] Thus, the index reflects changes in the development of nuclear energy and signs of spread from the returns of nuclear power indices.

The data consist of the daily nuclear power indices of seven countries over the sample period April 4, 2007 to January 6, 2017. These indices are constructed using the capitalization-weighted index approach for the firms listed in the WNA Index.[43] The WNA Index includes 2 Canadian firms, 1 French firm, 3 German firms, 1 Indian firm, 17 Japanese firms, 3 Korean firms, and 22 US firms.† To observe nuclear market movements associated with incidents and policies, we plot the nuclear market indices (see Figure 1). The shaded areas in Figure 1 denote five nuclear accident or policy episodes. The nuclear indices show an overall upward trend for the period 2008 to 2010, which can be attributable to the implementation of Korea's nuclear power expansion policy in 2008. However, the 2011 Fukushima nuclear accident significantly affected countries that rely on nuclear power, especially Canada, France, Germany, and Korea, causing a sharp decline in nuclear index trends. Subsequently, the trends in most countries have undergone a continual decline from 2012 to 2016, primarily because of nuclear phaseouts and the acceleration of renewable energy production.

Following Ref. 35 we transform the data into logarithmic differences to calculate nuclear returns given by:

$$r_{i,t} = 100 \times (ln(P_{i,t}) - ln(P_{i,t-1})), \tag{25}$$

where $P_{i,t}$ is the daily closing price of index i at time t. Nuclear returns are plotted in Figure 2. The figure indicates that most market returns behave in a similar manner, and most returns exhibit dramatic changes following major events such as the Korean nuclear expansion, the Fukushima accident, and nuclear phase-out policies.

The tests are conducted before controlling for market fundamentals.[7,44] These are controlled through cross-market interdependencies $\phi(L)$, which always exist in vector autoregressive models, given by:

$$R_t = \phi(L)R_t + u_t, \tag{26}$$

where $R_t = \{x_t, y_t\}'$ is the transposed vector of returns during the pre-event (x) and postevent (y) periods, $\phi(L)$ is a parameter vector of lag L, and u_t is a vector of residuals, which are used as unexpected shocks in the calculation of test statistics in Section 2. Table 2 presents the performance of the lag order selection criteria based on the vector autoregressive model. The results reveal that one lag is selected based on the Schwarz and Hannan-Quinn information criteria.

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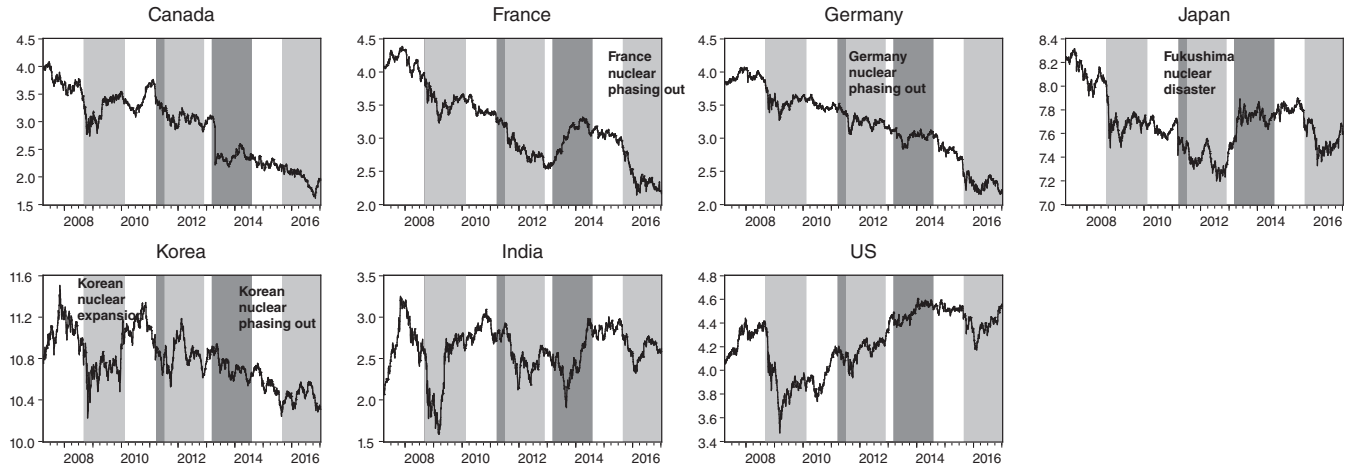


FIGURE 1 Daily indices of the nuclear markets for seven countries (Canada, France, Germany, Japan, South Korea, India, and the United States) from April 4, 2007 to January 6, 2017. Shaded areas represent five episodes of nuclear events: (1) Korean nuclear power expansion (August 27, 2007 to January 19, 2010); (2) Fukushima nuclear disaster (March 14, 2011 to August 3, 2012); (3) German nuclear phaseout (June 30, 2011 to November 21, 2012); (4) Korean nuclear phaseout (February 22, 2013 to July 24, 2014); (5) French nuclear phaseout (August 17, 2015 to January 6, 2017)

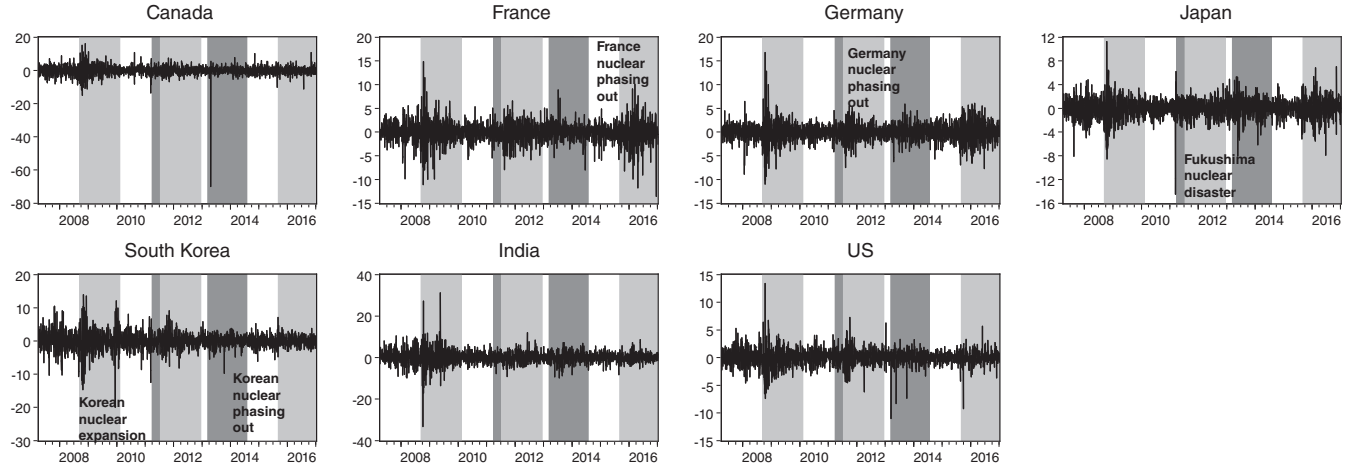


FIGURE 2 Daily percentage returns of the nuclear markets for seven countries (Canada, France, Germany, Japan, South Korea, India, and the United States) from April 4, 2007 to January 6, 2017. Shaded areas represent five episodes of nuclear events: (1) Korean nuclear power expansion (August 27, 2007 to January 19, 2010); (2) Fukushima nuclear disaster (March 14, 2011 to August 3, 2012); (3) German nuclear phaseout (June 30, 2011 to November 21, 2012); (4) Korean nuclear phaseout (February 22, 2013 to July 24, 2014); (5) French nuclear phaseout (August 17, 2015 to January 6, 2017)

4.2 | Nuclear policy and events

This section presents a summary of each policy or event along with the dates of the pre- and postevent periods. Table 3 shows the dates chosen for each event, and Table 4 provides the details of each event. Table 3 summarizes the starting and ending date of each event and its source. For example, the Korean nuclear expansion starts on August 27, 2008 and ends on January 19, 2010. The length of each event is set to 1 year (365 days) as each event has announcement and launch dates. For robustness check, we also allow the length of each event to be 180 days.

With the rapid growth in electricity demand along with the rise in environmental awareness, many countries have expressed interest in nuclear energy, which is considered one of the safest, most reliable, and economically efficient energy sources with a guaranteed long-term supply. Since 2008, Korea has devoted itself solely to the development of nuclear power. In addition, the Korean National Energy Committee announced its new National Energy Basic Plan on August 27, 2008, under

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which the electricity generated by NPPs is set to increase from 35.5% of total electricity production to 59% by 2030.[1,45]

On March 11, 2011, Japan was struck by a devastating earthquake registering 9.1 on the moment magnitude scale, resulting in a major accident at the Fukushima Daiichi NPP.[16,44] The failure of three of the six nuclear reactors at the Fukushima plant on April 12 led to the Nuclear and Industrial Safety Agency assigning the nuclear accident a level 7 on the International Nuclear and Radiological Event Scale.[22] This accident was followed by a series of news and reports, both locally and internationally, causing countries to reconsider their energy and nuclear safety strategies. Since then, many countries, including Germany, Italy, Korea, and France, have reevaluated their nuclear power programs, and even China announced that it would temporarily stop approving new NPPs.[15]

Only 2 months following the Fukushima accident, Germany decided to fully phase out its use of nuclear energy.[2] On June 30, 2011, the German parliament voted to close all of the country's NPPs by 2020, making it the first major nation to implement a drastic nuclear phase-out policy.[46,47] Germany's policy to move to a low-carbon and nuclear-free energy sector is known as the *Energiewende* (meaning "energy transition").[48] Under legislation passed in 2014, specifically the *Renewable Energy Sources Act*, the German government plans to not only reduce Germany's carbon emissions but also increase its investments in renewable energy.[48]

The 2011 Fukushima accident significantly affected countries that rely on nuclear power. Korea, one of the top five nuclear-powered nations, has chosen coal as its major energy source for future national electricity supply.[49] On February 22, 2013, Korea announced its sixth Basic Plan for Long-Term Electricity Supply and Demand (2013-2027), which primarily focuses on the phasing out of nuclear energy and acceleration of renewable energy. Under this plan, Korea's nuclear power generation is expected to reduce to 23.1% by 2025 and to 22.7% by 2027.[50,51]

France's nuclear power sector was also strongly affected in the aftermath of the Fukushima accident. On August 17, 2015, the French National Assembly passed the *Energy Transition for Green Growth Act*, which will reduce the energy generated by nuclear power from 75% in 2015 to 50% by 2025.[3,52] In addition, the Act provides medium- and long-term objectives for national energy production and consumption by enhancing France's energy autonomy, cutting its greenhouse gas emissions, and providing effective tools to all stakeholders to boost green growth.[53]

TABLE 2 Performance of vector autoregressive lag order selection criteria

	Vector autoregressive lag order selection criteria				
Lag	**LR**	**FPE**	**AIC**	**SIC**	**HQ**
0	NA	8250.369	28.883	28.899	28.889
1	661.735	6602.207	28.660	28.789[a]	28.707[a]
2	122.955	6535.758[a]	28.650[a]	28.892	28.738
3	57.331	6639.993	28.666	29.020	28.794
4	78.953	6687.616	28.673	29.140	28.843
5	81.022	6729.438	28.679	29.259	28.890
6	59.821	6828.684	28.694	29.386	28.945
7	54.346	6944.211	28.711	29.516	29.003
8	85.257[a]	6973.890	28.715	29.633	29.048

Abbreviations: AIC, Akaike information criterion; FPE, final prediction error; HQ, Hannan-Quinn information criterion; LR, sequential modified likelihood ratio test statistic; SIC, Schwarz information criterion.
[a]Denotes the optimal lag order selected by the criterion.

TABLE 3 Pre-event and postevent period dates

Pre- and postevent periods	Source	Start of period	End of period	Obs.
Postevent dates				
Korean nuclear expansion	Korea	August 27, 2008	January 19, 2010	365
Fukushima nuclear disaster	Japan	March 14, 2011	August 3, 2012	365
German nuclear phaseout	Germany	June 30, 2011	November 21, 2012	365
Korean nuclear phaseout	Korea	February 22, 2013	July 24, 2014	365
French nuclear phaseout	France	August 17, 2015	January 6, 2017	365
Pre-event dates				
Pre-Korean nuclear expansion		April 4, 2007	August 26, 2008	
Pre-Fukushima nuclear disaster		January 20, 2010	March 11, 2011	

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TABLE 4 Five major nuclear energy policies and events from 2007 to 2017

Policy and events	Details
Korean nuclear power expansion policy	The National Energy Committee announced its new National Energy Basic Plan on August 27, 2008, under which the electricity generated by nuclear power plants is to increase from the current 35.5% of total electricity production to 59% by 2030. The addition of 10 nuclear power plants with a 1400 MWe capacity is required to facilitate this increase.[1,43]
Fukushima nuclear accident	On March 11, 2011, a nuclear accident in Fukushima, Japan, was triggered by an earthquake of 9.1 magnitude, resulting in a 15-m-high wave and tsunami.[44] The accident resulted in significant economic losses following the closure of the power plant in the following days.[60] Related news and reports spread locally and internationally, leading countries to rethink their energy and nuclear safety strategies.[61,62]
German nuclear phaseout	On June 30, 2011, the German government announced a phaseout of nuclear power, with all nuclear power stations to close by 2022.[2] The policy to progress to a nuclear-free energy sector is known as the *Energiewende*.[46] Moreover, the Germany government set carbon emission reduction targets of 40% by 2020, 55% by 2030, 70% by 2040, and 80-95% by 2050.[63]
Korean nuclear phaseout	On February 22, 2013, South Korea announced its sixth Basic Energy Plan, focusing mainly on nuclear phaseout and acceleration of renewable energy. Under this plan, nuclear power generation is expected to reduce to 23.1% by 2025 and to 22.7% by 2027.[48]
French nuclear phaseout	In August 2015, the French National Assembly passed the *Energy Transition for Green Growth Act*, which reduces the share of nuclear power to electricity supply from of 75% to 50% by 2025.[3,50]

5 | EMPIRICAL RESULTS AND DISCUSSION

5.1 | Descriptive statistics

Table 5 shows descriptive statistics on the returns of seven nuclear markets in the pre-event period (top panel) and the period following the Fukushima nuclear disaster (bottom panel). The data suggest that all returns, except for those in Korea, decreased, while market volatility, measured by SDs, was higher following the Fukushima nuclear accident than in the pre-event period. In addition, the probability distribution of returns is skewed more to the left (negative) in the postevent period compared with the pre-event period, suggesting that the series have more extreme losses than they do gains in the crisis period. Further, all returns possess fat tail features because kurtosis is greater than three during both periods. The Jarque-Bera test strongly rejects the null hypothesis of normality for all series at the 5% significance level, indicating that all returns deviate from normal distributions.

An attempt is also made to compute the market comoments between returns for the seven nuclear-powered countries for the two periods. Table 6 shows that the correlation ranges from 0.095 (Canada) to 0.401 (US) in the pre-event period, and from 0.123 (India) to 0.415 (Korea) in the postevent period. The correlation between selected countries and the Japanese nuclear market surprisingly decreased in the postevent period, implying that correlation is not suitable for modeling asset-returns relationships, especially following extreme events. However, it is evident that nonlinear dependence—coskewness—is an alternate means to model market dependence. In addition, both forms of coskewness—mean returns and volatility—have higher negative values in the postevent period than in the pre-event period, suggesting that joint return series have a longer left tail (more negative returns) than a right tail (more positive returns) in the postcrisis period.

Extremal dependences, measured by cokurtosis and covolatility, can better capture market dependence compared with linear dependence[9] because joint return series often yield asymmetric and fat-tailed behaviors. This phenomenon is evidenced by an increase in cokurtosis and covolatility between the Japanese nuclear market and selected countries in the postaccident period. Taking the first form of cokurtosis as an example, there were lower values of cokurtosis_{13} in the pre-event period, ranging from 0.655 (US) and 3.223 (Japan), and higher values of cokurtosis_{13} in the postevent period, ranging from 0.488 (US) to 22.349 (Japan). An increase in cokurtosis_{13} indicates that returns in the Japanese nuclear market are low, with a positive skewness of returns in other countries, thus increasing the contagion risk in the postcrisis period. Similarly, an increase in covolatility suggests high volatility (risk) in returns of both countries in the postcrisis period.

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TABLE 5 Descriptive statistics for each daily return series in pre- and postevent periods

Market	Mean	SD	Skewness	Kurtosis	JB test
Pre-event period (January 20, 2010 to March 11, 2011)					
Canada	0.044	1.917	0.542	7.492	265.094*
France	−0.102	1.348	−0.174	4.991	50.718*
Germany	−0.060	1.118	−0.335	3.695	11.558*
Japan	−0.021	1.018	−0.261	3.223	3.999
Korea	−0.050	2.232	−0.142	5.045	52.950*
India	−0.019	2.078	0.170	3.650	6.678*
United States	0.069	1.189	0.100	3.678	6.203*
Post-Fukushima nuclear disaster period (March 14, 2011 to August 3, 2012)					
Canada	−0.154	2.397	−0.435	5.911	140.413*
France	−0.169	2.129	−0.260	3.543	8.586*
Germany	−0.064	1.831	−0.102	3.825	10.988*
Japan	−0.126	1.689	−2.408	22.349	6046.915*
Korea	−0.040	2.393	−0.303	6.393	180.639*
India	−0.088	2.422	0.181	4.897	56.736*
United States	0.009	1.473	0.065	5.829	121.963*

Abbreviations: JB, Jarque-Bera test; SD, standard deviation.
*Denotes 5% significance level.

TABLE 6 Second- to fourth-order comoments of returns for seven nuclear-powered countries during the pre- and postevent periods

Market (*j*)	Correlation	Coskewness_{12}	Coskewness_{21}	Cokurtosis_{13}	Cokurtosis_{31}	Covolatility
Pre-event period (January 20, 2010 to March 11, 2011)						
Canada	0.095	−0.066	−0.073	0.919	0.295	0.779
France	0.214	−0.187	−0.176	0.745	0.887	1.228
Germany	0.243	−0.222	−0.200	1.017	0.812	1.121
Japan	1.000	−0.261	−0.261	3.223	3.223	3.223
Korea	0.193	−0.221	−0.060	0.784	0.609	1.319
India	0.136	−0.017	−0.110	0.655	0.499	1.146
United States	0.401	−0.091	−0.173	1.645	1.359	1.610
Post-Fukushima nuclear disaster period (March 14, 2011 to August 3, 2012)						
Canada	0.232	−0.460	−0.635	3.465	4.450	5.102
France	0.172	−0.073	−0.482	0.787	3.241	1.678
Germany	0.213	−0.091	−0.678	0.701	5.295	2.197
Japan	1.000	−2.408	−2.408	22.349	22.349	22.349
Korea	0.415	−0.769	−1.394	4.388	11.298	7.050
India	0.123	0.030	−0.056	0.751	0.916	0.809
United States	0.242	−0.156	−0.291	0.488	2.349	1.002

Note: Correlation = returns of the Japanese nuclear power market and market *j*; coskewness_{12} = returns of the Japanese nuclear power market and square returns of market *j*; coskewness_{21} = square returns of the Japanese nuclear power market and returns of market *j*; cokurtosis_{13} = returns of the Japanese nuclear power market and cubed returns of market *j*; cokurtosis_{31} = cubed returns of the Japanese nuclear power market and returns of market *j*; covolatility = square returns of the Japanese nuclear power market and square returns of market *j*.

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TABLE 7 Contagion from source to recipient country (*j*) during five nuclear episodes

Country (*j*)	CR	CS_{12}	CS_{21}	CK_{13}	CK_{31}	CV	Country (*j*)	CR	CS_{12}	CS_{21}	CK_{13}	CK_{31}	CV
(A) Korean nuclear expansion (source country: Korea)							(D) Korean nuclear phaseout (source country: Korea)						
Canada	0.52	0.00	12.85*	1.74	12.67*	1.72	Canada	0.05	7.86*	0.79	18.32*	1442.86*	0.00
France	0.68	5.48*	12.63*	46.25*	19.87*	0.88	France	0.02	0.36	0.23	0.11	0.31	31.73*
Germany	0.62	3.39	27.62*	132.32*	0.35	3.54	Germany	0.06	3.31	0.24	5.82*	1.05	4.02*
Japan	1.89	4.03*	18.01*	109.54*	79.87*	4.42*	Japan	0.55	2.65	6.17*	3.01	0.10	3.86*
India	1.33	0.05	0.05	15.72*	160.86*	5.36*	India	2.84	3.12	8.79*	4.20*	19.60*	5.22*
United States	9.29*	8.31*	9.77*	214.41*	600.69*	16.76*	United States	0.00	6.86*	15.90*	4.33*	178.21*	50.86*
(B) Fukushima nuclear disaster (source country: Japan)							(E) French nuclear phaseout (source country: France)						
Canada	0.58	21.16*	57.94*	759.54*	107.91*	859.68*	Canada	3.48	17.35	0.11	2.31	1.10	0.01
France	1.73	0.13	9.47*	8.72*	4.09*	146.65*	Germany	46.52*	0.42	0.63	0.46	3.26	1.18
Germany	0.94	0.82	26.40*	48.49*	0.79	731.30*	Japan	1.17	7.49*	1.66	6.97*	34.98*	5.37*
Korea	0.53	26.11*	145.66*	1250.92*	298.82*	3377.29*	Korea	0.87	5.15*	1.44	0.09	0.08	5.69*
India	5.18*	0.14	0.54	1.03	0.25	33.02*	India	1.96	2.38	2.21	0.14	17.62*	0.51
United States	13.50*	0.34	3.20	1.22	13.18*	66.61*	United States	17.03*	2.89	1.81	1.38	31.50*	2.41
(C) German nuclear phaseout (source country: Germany)													
Canada	0.13	1.18	0.68	1.29	1.00	3.79							
France	6.45*	2.84	2.28	1.27	0.54	7.61*							
Japan	3.02	0.82	2.89	4.32*	0.10	4.29*							
Korea	0.20	0.42	1.49	0.17	5.34*	2.71							
India	4.23*	0.52	0.09	1.10	4.32*	1.47							
United States	1.86	4.62*	10.04*	5.37*	51.37*	0.36							

Note: CR = correlation test in (1); CS_{12} and CS_{21} = coskewness tests in (10) and (11); CK_{13} and CK_{31} = cokurtosis tests in (13) and (14); CV = covolatility test in (17).
*Denotes the 5% significance level.

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5.2 | Evidence of contagion during the five episodes

The contagion tests presented in Section 3 are applied to test for contagion linkages between the nuclear markets of different countries following the five nuclear power events shown in Table 7. Each event shows the results of contagion test-based changes in correlation, coskewness, cokurtosis, and covolatility, with the source being the country in which the event occurred. For example, if the Korean nuclear expansion policy is the event, Korea is the source country. Under the null hypothesis of no contagion, the critical value for each test is 3.84 at the 5% significance level.

Panel A of Table 7 shows that the Korean nuclear expansion policy caused significant contagion from the Korean nuclear market to all six other nuclear-powered countries—Canada, France, Germany, Japan, India, and the United States—through either correlation, coskewness, cokurtosis, or covolatility channels. Among the six countries, Japan and the United States were the most affected by the Korean nuclear expansion policy, followed by India and France. A possible explanation for these four countries being most affected by nuclear power expansion is the widespread herd behavior of countries with similar nuclear development paths.[54] Japan was one of the countries most affected by policy contagion because it implemented its nuclear energy innovative technology plan in 2008, which was the same year that Korea implemented its nuclear expansion plan.[55,56]

Panel B of Table 7 shows that contagion appeared to be widespread from the Japanese nuclear energy market to all six nuclear-powered countries following the Fukushima nuclear disaster through the correlation and higher order comoment channels. Among the six countries, Canada and Korea were most exposed to contagion risk from the Japanese nuclear market because all higher order transmission channels (i.e., coskewness, cokurtosis, and covolatility) were in operation, while India was less exposed to contagion risk because only two channels—correlation and covolatility—were in operation. These results are expected because both the Canadian and Korean nuclear safety commissions responded immediately to the Fukushima accident with several actions, including the improvement of reactor defenses, emergency responses, and regulatory frameworks and licensing.[57,58]

Panel C of Table 7 presents the results of the contagion tests following Germany's nuclear phaseout. There was weak evidence of contagion to nuclear power markets, which occurred in France and India through the correlation channel; the United States through the coskewness channel; Japan, Korea, India, and the United States through cokurtosis channels; and France and Japan through the covolatility channel. Following the Fukushima accident, nuclear policies issued by countries influenced other nuclear-dependent countries, with the United States being the most affected. This may have been attributable to the US government announcing a new Department of Energy program in 2012 in response to the German nuclear phaseout, moving its budget from large reactors to small modular reactors, which have advantages in terms of safety, construction, and packaging.[56]

Panel D of Table 7 shows the results of the contagion tests following the Korean nuclear phase-out policy. There is no evidence of contagion through the correlation channel, but strong evidence of contagion through higher order comoments. In addition, the United States was the most affected, with all higher order comoment channels in operation, followed by Canada and India with three channels. France was the least affected following the Korean nuclear phaseout. These findings are expected because of the strong nuclear trade links between the United States and Korea, with Korea exporting nuclear technology and equipment to the United States.[59]

Panel E of Table 7 shows the results of the contagion tests following the French nuclear phaseout. There is significant evidence of contagion from the French nuclear market to all nuclear-powered countries following the French nuclear phaseout, but the contagion effect is relatively weak because some countries were only affected by one channel, either correlation or higher order comoments. It is interesting that among the six countries, Japan was most affected by the French nuclear phaseout through four of the six contagion channels. A possible explanation for this may be Japan's Strategic Energy Plan issued in 2018 following the reduction of energy supplied by nuclear power from 11% in 2010 to 0% in 2016. This indicates that Japan continues having zero nuclear power development because of the impact of the French nuclear reduction policy.[60]

Overall, among the five event and policy episodes, we find that the Japanese Fukushima nuclear accident is the most serious event affecting global nuclear energy markets through 22 contagion links. The Korean nuclear expansion is the second most significant event affecting global nuclear energy markets, as evidenced by the detection of 20 contagion links. Nuclear phase-out policies are the least likely to cause contagion. These findings are consistent with the phenomenon of the asymmetric effect in which bad news (eg, nuclear accidents) tends to cause greater risks to the market than does good news (eg, nuclear expansion).[61] In addition, the impact of Fukushima on market performance gradually decreased

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TABLE 8 Contagion from source to recipient country (*j*) during five nuclear episodes based on the postevent period to be 180 days

Country (*j*)	CR	CS_{12}	CS_{21}	CK_{13}	CK_{31}	CV	Country (*j*)	CR	CS_{12}	CS_{21}	CK_{13}	CK_{31}	CV
(A) Korean nuclear expansion (source country: Korea)							(D) Korean nuclear phaseout (source country: Korea)						
Canada	0.52	0.00	12.85*	1.74	12.67*	1.72	Canada	0.11	5.58*	0.93	15.79*	542.67*	0.09
France	0.68	5.48*	12.63*	46.25*	19.87*	0.88	France	0.05	0.42	0.43	0.72	1.85	30.42*
Germany	0.62	3.39	27.62*	132.32*	0.35	3.54	Germany	0.05	2.91	0.77	7.36*	2.08	9.91*
Japan	1.89	4.03*	18.01*	109.54*	79.87*	4.42*	Japan	0.36	1.06	3.51	4.44*	0.26	4.35*
India	1.33	0.05	0.05	15.72*	160.86*	5.36*	India	1.26	0.40	5.15*	3.34	17.00*	5.23*
United States	9.29*	8.31*	9.77*	214.41*	600.69*	16.76*	United States	0.00	10.76*	15.32*	0.77	127.51*	60.18*
(B) Fukushima nuclear disaster (source country: Japan)							(E) French nuclear phaseout (source country: France)						
Canada	0.52	20.39*	43.86*	483.89*	98.56*	449.93*	Canada	3.48	17.35	0.11	2.31	1.10	0.01
France	2.20	0.00	8.24*	5.89*	3.65*	87.71*	Germany	46.52*	0.42	0.63	0.46	3.26	1.18
Germany	1.09	1.09	21.69*	23.67*	1.36	403.56*	Japan	1.17	7.49*	1.66	6.97*	34.98*	5.37*
Korea	0.43	29.70*	131.58*	774.69*	226.51*	1844.01*	Korea	0.87	5.15*	1.44	0.09	0.08	5.69*
India	5.90*	2.89	0.11	0.06	2.18	25.67*	India	1.96	2.38	2.21	0.14	17.62*	0.51
United States	14.20*	0.80	1.74	3.70	5.64*	34.48*	United States	17.03*	2.89	1.81*		31.50*	2.41
(C) German nuclear phaseout (source country: Germany)													
Canada	0.00	0.81	0.32	0.23	0.15	1.23							
France	7.42*	3.81	2.34	0.00	0.03	1.33							
Japan	3.29	1.22	2.49	12.18*	0.01	4.77*							
Korea	0.11	0.57	2.84	1.64	3.68	1.08							
India	5.95*	0.08	0.00	1.00	1.32	0.72							
United States	2.74	3.90*	7.69*	1.16	32.90*	0.05							

Note: CR = correlation test in (1); CS_{12} and CS_{21} = coskewness tests in (10) and (11); CK_{13} and CK_{31} = cokurtosis tests in (13) and (14); CV = covolatility test in (17).
*Denotes the 5% significance level.

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over time, as evidenced by the weak contagion effects of three nuclear phase-out episodes.

Since the contagion tests are dependent on the selection of the pre- and postevent periods, we modify the length of the postevent period for robustness test. In the base analysis, we define the length of the postevent period to be 1 year (365 days) in Table 3. We modify the length of the postevent period to be 180 days for sensitivity test. In addition, the ending date of the postevent is on May 5, 2009 for the Korean nuclear expansion, November 18, 2011 for the Fukushima nuclear disaster, March 7, 2012 for the German nuclear phaseout, October 31, 2013 for the Korean nuclear phaseout, and April 22, 2016 for the French nuclear phaseout. The contagion tests are applied based on the new length of postevent period, and the results are shown in Table 8, suggesting that the modified length does not affect the central results.

6 | CONCLUSIONS

This paper investigates the impact of five nuclear event and policy episodes on global nuclear energy markets using the correlation test in Ref. 7, coskewness tests in Ref. 8, and cokurtosis and covolatility tests in Ref. 9. From 2007 to 2017, a series of significant nuclear events affected the global nuclear energy market, including the Korean nuclear expansion, the Fukushima accident in Japan, and nuclear reduction policies in Germany, Korea, and France. Data were based on the equity indices of nuclear energy firms in seven countries listed in the WNA Index, constructed using the capitalization-weighted index approach. Contagion tests were applied to explore how nuclear events and polices affect global nuclear markets through second- and higher order comoment channels.

The main findings of this research are as follows: First, among the five nuclear energy incidents and policies, the Fukushima accident in Japan was the most serious, affecting all other nuclear energy markets globally, followed by the Korean nuclear expansion policy. The nuclear phase-out policies of Germany, Korea, and France had the least impact on nuclear energy markets. The results indicate that global nuclear energy markets exhibit asymmetric effects, where market volatility responds more to negative news, such as the nuclear disasters, than to positive news, such as the nuclear expansion policies. Second, higher order comoment contagion tests revealed linkages between global nuclear markets that were not previously detected when using the correlation contagion test, indicating that asymmetric and extremal dependences of nuclear power markets are significantly higher in the postpolicy period compared with the prepolicy period. Overall, the applied contagion tests show good size and power properties. In addition, among the four tests, the cokurtosis test performs the best power of finding contagion.

These empirical findings enable the identification of contagion across nuclear energy markets of different countries and may help global policymakers obtain a greater understanding of market risks arising from various nuclear events and policies. In addition, the findings of contagion between nuclear energy markets are important for investors, arbitrageurs, and traders to identify how energy shocks in one market transmit to other markets and ultimately affect stock markets. Finally, the ability to forecast nuclear energy risks following nuclear accidents may be important for governments, especially for energy producer and consumer industries that are particularly vulnerable to nuclear market price volatility.

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ENDNOTES

* To ensure the distribution to be bounded, the covolatility contagion parameter is kept constant at a value of $\theta_{6,y} = -0.5$.

† Data on nuclear power firms are collected from Bloomberg. The nuclear power indices are based on the equity prices of the following firms. Canada: NexGen Energy (NXE CT Equity) and Cameco (CCO CN Equity); France: EDF Energy (EDF FP Equity); Germany: RWE Group (RWE GR Equity), E.ON Energy (EOAN GR Equity) and SGL Carbon Group (SGL GR Equity); India: Larsen & Toubro Ltd (LTOD LI Equity); Japan: Toyo Engineering (6330 JP Equity), Toshiba Plant Systems & Services (1983 JP Equity), Taihei Dengyo Kaisha (1968 JP Equity), Toshiba (6502 JP Equity), JGC (1963 JP Equity), IHI (7013 JP Equity), Hokuriku Electric Power (9505 JP Equity), Japan Steel Works (5631 JP Equity), Mitsubishi Heavy Industries (7011 JP Equity), Sumitomo Electric Industries (5802 JP Equity), Kyushu Electric Power (9508 JP Equity), Hitachi (6501 JP Equity), Yokogawa Electric (6841 JP Equity), Shikoku Electric Power (9507 JP Equity), Hokkaido Electric Power (9509 JP Equity), Tokyo Electric Power (9501 JP Equity), and Kansai Electric Power (9503 JP Equity); Korea: KEPCO Engineering & Construction (052690 KS Equity), Doosan Infracore (034020 KS Equity), Korea Electric Power (015760 KS Equity): US: Emerson Electric (EMR US Equity), Nextera Energy (NEE US Equity), Federal Signal (FSS US Equity), Entergy (ETR US Equity), First Energy (FE US Equity), Parker-Hannifin (PH US Equity), Duke Energy (DUK US Equity), MKS Instruments (MKSI US Equity), Circor International (CIR US Equity), Team (TISI US Equity), Belden (BDC US Equity), SPX (SPXC US Equity), MSA Safety (MSA US Equity), Kirby (KEX US Equity), Ametek (AME US Equity), General Electric (GE US Equity), Flowserve (FLS US Equity), Curtiss-Wright (CW US Equity),

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Leidos Holdings (DOS US Equity), Exelon (EXC US Equity), Fluor (FLR US Equity), McDermott International (MDR US Equity).

DATA AVAILABILITY STATEMENT

Data are available upon request.

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REFERENCES

1. Ko WI, Kwon EH. Implications of the new National Energy Basic Plan for nuclear waste management in Korea. *Energy Policy*. 2009;37(9):3484-3488.
2. Robert R, McCauley D. Security, justice and the energy crossroads: assessing the implications of the nuclear phase-out in Germany. *Energy Policy*. 2016;88:289-298.
3. Malischek R, Trüby J. The future of nuclear power in France: an analysis of the costs of phasing-out. *Energy*. 2016;116:908-921.
4. Eser P, Chokani N, Abhari R. Trade-offs between integration and isolation in Switzerland's energy policy. *Energy*. 2018;150:19-27.
5. CNSC. *Canada's Response to Fukushima*. Canada: The Canadian Nuclear Safety Commission (CNSC); 2016.
6. Nam H. Impact of nuclear phase-out policy and energy balance in 2029 based on the 8th basic plan for long-term electricity supply and demand in South Korea. *Renew Sustain Energy Rev*. 2009;122:109723.
7. Forbes K, Rigobon R. No contagion, only interdependence: measuring stock market con-movements. *J Finance*. 2002;57(5):2223-2261.
8. Fry RA, Martin VL, Tang C. A new class of tests of contagion with applications. *J Bus Econ Stat*. 2010;28(3):423-437.
9. Fry-McKibbin R, Hsiao CY. Extremal dependence tests of contagion. *Econom Rev*. 2018;37(6):626-649.
10. Harvey CR, Siddique A. Conditional skewness in asset pricing tests. *J Finance*. 2000;55(3):1263-1295.
11. Kostakis A, Muhammad K, Siganos A. Higher co-moments and asset pricing on London Stock Exchange. *J Bank Financ*. 2012;36(3):913-922.
12. Nelson JP. Three Mile Island and residential property values: empirical analysis and policy implications. *Land Econ*. 1981;57(3):363-372.
13. Gamble HB, Downing RH. Effects of nuclear power plants on residential property values. *J Reg Sci*. 1982;22(4):457-478.
14. Boes S, Nüesch S, Wüthrich K. Hedonic valuation of the perceived risks of nuclear power plants. *Econ Lett*. 2015;133:109-111.
15. Zhu H, Deng Y, Zhu R, He X. Fear of nuclear power? Evidence from Fukushima nuclear accident and land markets in China. *Reg Sci Urban Econ*. 2016;60:139-154.
16. Bauer TK, Braun ST, Kvasnicka M. Nuclear power plant closures and local housing values: evidence from Fukushima and the German housing market. *J Urban Econ*. 2017;99:94-106.
17. Brei M, Mohan P, Strobl E. The impact of natural disasters on the banking sector: evidence from hurricane strikes in the Caribbean. *Q Rev Econ Finance*. 2019;72:232-239.
18. Betzer A, Doumet M, Rinne U. How policy changes affect shareholder wealth: the case of the Fukushima Daiichi nuclear disaster. *Appl Econ Lett*. 2013;20(8):799-803.
19. Ferstl R, Utz S, Wimmer M. The effect of the Japan 2011 disaster on nuclear and alternative energy stocks worldwide: an event study. *Bus Res*. 2012;5(1):25-41.
20. Basse Mama H, Bassen A. Contagion effects in the electric utility industry following the Fukushima nuclear accident. *Appl Econ*. 2013;45(24):3421-3430.
21. Lopatta K, Kaspereit T. The cross-section of returns, benchmark model parameters, and idiosyncratic volatility of nuclear energy firms after Fukushima Daiichi. *Energy Econ*. 2014;41:125-136.
22. Kawashima S, Takeda F. The effect of the Fukushima nuclear accident on stock prices of electric power utilities in Japan. *Energy Econ*. 2012;34(6):2029-2038.
23. de Frutos Cachorro J, Willeghems G, Buysse J. Exploring investment potential in a context of nuclear phase-out uncertainty: perfect vs. imperfect electricity markets. *Energy Policy*. 2020;144:111640.
24. Bianco V, Scarpa F. Impact of the phase out of French nuclear reactors on the Italian power sector. *Energy*. 2018;150:722-734.
25. Rinne S. Radioinactive: do nuclear power plant outages in France affect the German electricity prices? *Energy Econ*. 2019;84:104593.
26. Hoster F. Impact of a nuclear phase-out in Germany: results from a simulation model of the European power systems. *Energy Policy*. 1998;26(6):507-518.
27. Nestle U. Does the use of nuclear power lead to lower electricity prices? An analysis of the debate in Germany with an international perspective. *Energy Policy*. 2012;41:152-160.
28. Bruninx K, Madzharov D, Delarue E, D'haeseleer W. Impact of the German nuclear phase-out on Europe's electricity generation—a comprehensive study. *Energy Policy*. 2013;60:251-261.
29. Nakata T. Analysis of the impacts of nuclear phase-out on energy systems in Japan. *Energy*. 2002;27(4):363-377.
30. Andersson B, Hådén E. Power production and the price of electricity: an analysis of a phase-out of Swedish nuclear power. *Energy Policy*. 1997;25(13):1051-1064.
31. Osorio S, van Ackere A. From nuclear phase-out to renewable energies in the Swiss electricity market. *Energy Policy*. 2016;93:8-22.
32. Rogge KS, Johnstone P. Exploring the role of phase-out policies for low-carbon energy transitions: the case of the German Energiewende. *Energy Res Soc Sci*. 2017;33:128-137.
33. Park NB, Yun SJ, Jeon EC. An analysis of long-term scenarios for the transition to renewable energy in the Korean electricity sector. *Energy Policy*. 2013;52:288-296.
34. de Frutos Cachorro J, Willeghems G, Buysse J. Strategic investment decisions under the nuclear power debate in Belgium. *Resour Energy Econ*. 2019;57:156-184.
35. Hsiao CYL, Chen HH. The contagious effects on economic development after resuming construction policy for nuclear power plants in Coastal China. *Energy*. 2018;152:291-302.

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36. Teräväinen T, Lehtonen M, Martiskainen M. Climate change, energy security, and risk—debating nuclear new build in Finland, France and the UK. *Energy Policy*. 2011;39 (6):3434-3442.
37. dos Santos RLP, Rosa LP, Arouca MC, Ribeiro AED. The importance of nuclear energy for the expansion of Brazil's electricity grid. *Energy Policy*. 2013;60:284-289.
38. Cho I, Oh S, Kim S, Ardin F, Heo E. Determinants of nuclear power expansion in Indonesia. *Nucl Eng Technol*. 2020;53(1): 314–321.
39. McKie RE. An environmental harm perspective to examine our understanding of UK nuclear energy expansion. *Extr Ind Soc*. 2020;7(2):556-564.
40. Fry-McKibbin R, Hsiao CYL, Martin VL. Joint tests of contagion with applications. *Quant Finance*. 2019;19(3):473-490.
41. LaCorte J. WNA Nuclear Energy Index: New Index Tracks World's Nuclear Energy Stocks; Official Index of the World Nuclear Association; 2008. https://www.businesswire.com/news/home/20080129006105/en/WNA-Nuclear-Energy-Index-New-Index-Tracks-Worlds-Nuclear-Energy-Stocks-Official-Index-of-the-World-Nuclear-Association. Accessed July 3, 2020.
42. LaCorte J. Three New Nuclear Stocks Added; Two Stocks Deleted from WNA Nuclear Energy Index in Quarterly Rebalancing; 2010. https://www.prnewswire.com/news-releases/three-new-nuclear-stocks-added-two-stocks-deleted-from-wna-nuclear-energy-index-in-quarterly-rebalancing-87315567.html. Accessed July 3, 2020.
43. Broby D. Equity index construction. *J Index Investing*. 2011;2 (2):36-39.
44. Fry-McKibbin R, Hsiao CYL, Tang C. Contagion and global financial crises: lessons from nine crisis episodes. *Open Econ Rev*. 2014;25(3):521-570.
45. KMKE. National Energy Basic Plan. Korean Ministry of Knowledge Economy (KMKE), Press Release; August 28, 2008.
46. ICL. Greens' anti-nuclear hysteria amnesties capitalism. International Communist League (ICL), fourth internationalist, Spartacist, Germany, May, No. 188; 2011. https://www.icl-fi.org/english/wv/983/germany.html
47. Scherwath T, Wealer B, Mendelevitch R. Nuclear decommissioning after the German nuclear phase-out an integrated view on new regulations and nuclear logistics. *Energy Policy*. 2020;137:111125.
48. Murray L. The need to rethink German nuclear power. *Electr J*. 2019;32(6):13-19.
49. Shim C, Hong J. Impact of a national plan for future electricity supply on ambient air quality in South Korea. *Energy Policy*. 2016;88:278-288.
50. KMKE. The sixth Basic Plan for long-term electricity supply and demand (BPE) (2013-2027). Korean Ministry of Knowledge and Economy (KMKE); 2013. http://www.kpx.or.kr/eng/selectBbsNttView.do?key=328&bbsNo=199&nttNo=10737&searchCtgry=&searchCnd=all&searchKrwd=&pageIndex=1&integrDeptCode
51. Kim P, Kim J, Yim M. How deliberation changes public opinions on nuclear energy: South Korea's deliberation on closing nuclear reactors. *Appl Energy*. 2020;270:115094.
52. Mauger R. Forced nuclear energy reactors shutdown in France: the energy transition Act's mechanisms. *J World Energy Law Bus*. 2018;11(3):270-281.
53. VIG. *Energy Transition*. Valls III's Government, France; 2016. https://www.gouvernement.fr/en/energy-transition. Accessed July 21, 2020.
54. Thomas HF. Modeling contagion in policy systems. *Cogn Syst Res*. 2017;44:74-88.
55. Valentine SV, Sovacool BK. The socio-political economy of nuclear power development in Japan and South Korea. *Energy Policy*. 2010;38(12):7971-7979.
56. WNA. US nuclear power policy. World Nuclear Association (WNA); 2020. https://www.world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power-policy.aspx
57. CNSC. *Fukushima Task Force Report*. Canada: Canadian Nuclear Safety Commission (CNSC); 2011.
58. CNPP (2012). *Republic of Korea*. Country Nuclear Power Profiles (CNPP), Korea. https://www-pub.iaea.org/MTCD/Publications/PDF/CNPP2012_CD/countryprofiles/KoreaRepublicof/KoreaRepublicof.htm. Accessed July 21, 2020.
59. Kim SC. Endangering alliance or risking proliferation?: US–Japan and US–Korea nuclear energy cooperation agreements. *Pac Rev*. 2017;30(5):692-709.
60. NUMO (2018). *Japan's Strategic Energy Plan*. Nuclear Waste Management Organization of Japan (NUMO), Japan. https://www.numo.or.jp/topics/1-1Nakanishi.pdf. Accessed July 21, 2020.
61. Qin Y, Hong K, Chen J, Zhang Z. Asymmetric effects of geopolitical risks on energy returns and volatility under different market conditions. *Energy Econ*. 2020;90:104851.
62. Soni A. Out of sight, out of mind? Investigating the longitudinal impact of the Fukushima nuclear accident on public opinion in the United States. *Energy Policy*. 2018;122:169-175.
63. Goodfellow MJ, Williams HR, Azapagic A. Nuclear renaissance, public perception and design criteria: an exploratory review. *Energy Policy*. 2011;39(10):6199-6210.

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