Quality & Quantity (2022) 56:285–303
https://doi.org/10.1007/s11135-021-01130-w

Non-linear cointegration between wholesale electricity prices and electricity generation: an analysis of asymmetric effects

Barsha Nibedita[1] · Mohd Irfan[1]

Accepted: 23 February 2021 / Published online: 8 March 2021

Abstract
This study investigates the non-linear cointegrating relationship between wholesale electricity prices (WEP) and electricity generation from conventional sources (EGCS), using data for India. The conventional sources considered in the analysis are thermal, nuclear, and hydro. The dataset is a monthly time series covering the period from April 2012 to April 2019. The existence of a non-linear cointegration between the variables and asymmetric effects of EGCS on WEP are examined by employing a non-linear autoregressive distributed lags modelling framework. Empirical results reveal that a non-linear long-run equilibrium relationship is evident in the WEP-EGCS nexus for India. The findings indicate that in the long-run, electricity generation from nuclear and hydro sources have asymmetric effects on WEP, but thermal source has symmetric effects on WEP. However, only hydro source has asymmetric short-run effects on WEP. The findings of this study suggest that such non-linear relationships between WEP and EGCS are crucial to be accounted for identifying the optimal electricity generation fuel mix in emerging economies, including India.

Keywords Electricity generation fuel mix · Wholesale electricity price · Asymmetric effects · Non-linear autoregressive distributed lags · Conventional sources of electricity

1 Introduction

Over the past many decades, the electricity generation fuel mix (EGFM) of emerging economies has been dominated by fossil fuels, mainly burning of coal (BPSRWE 2019). Increased electricity demand and overdependence on coal have raised concerns about climate change, resource depletion, and energy security issues at the global and regional level (Ali et al. 2019). Therefore, one of the principal goals of energy security policies

✉ Mohd Irfan
irfan@iitism.ac.in

Barsha Nibedita
itzbarsha91@gmail.com

1 Department of Management Studies, Indian Institute of Technology (Indian School of Mines) Dhanbad, Dhanbad, Jharkhand 826004, India

of emerging economies is to diversify the EGFM, which results in promoting the use of alternative electricity generation sources: nuclear, hydro, and renewables (Le and Nguyen 2019). However, it can be argued that since most of the emerging economies have liberalized their electricity market, price effects of changes in electricity generation cannot be left unnoticed due to its impact on the financial and economic viability of electricity generation systems (Gross et al. 2010). Such price effects are also expected to have severe implications on the long-term energy security goals of countries, especially in emerging economies. On the one hand, decrease in wholesale electricity price hamper the market expectations, participants' risk exposure, and future investment decisions (Roques et al. 2008; Gross et al. 2010; Johnson and Oliver 2019). On the other hand, increase in wholesale electricity price reduces the affordability of electricity and therefore weakens the energy security (Sovacool and Brown 2010; Sarangi et al. 2019). Given this, the relationship between electricity generation and wholesale electricity prices is a relevant area of research in the energy economics literature.

The existing empirical studies investigate the effects of supply side factors, particularly, electricity generation from sources on wholesale electricity prices (Humphreys and McClain 1998; Benini et al. 2002; Awerbuch 2006; Roques et al. 2008; Bhattacharyya 2009; Jun et al. 2009; Gelabert et al. 2011; Milstein and Tishler 2011; Forrest and MacGill 2013; Chattopadhyay 2014; Mari 2014; Martinez-Anido et al. 2016; Adom et al. 2017; Worthington and Higgs 2017; Maekawa et al. 2018). However, empirical researches on the impact of electricity generation from conventional sources (EGCS) on wholesale electricity prices (WEP) are scarcely available. Though in some of these studies EGCS is found to be a significant determinant of WEP, there is no common consensus about the positive or negative effects on WEP. Despite this established relationship, several limitations have been observed in the previous studies on EGCS-WEP nexus; specifically, all the studies have assumed that EGCS has linear effects on WEP (Gelabert et al. 2011; Forrest and MacGill 2013; Chattopadhyay 2014; Worthington and Higgs 2017; Gerasimova 2017; Adom et al. 2017). For example, the impacts of both positive and negative shocks in EGCS lead to symmetric changes in WEP. However, it is also argued that electricity generation from hydro and nuclear sources is relatively more flexible than thermal sources, and therefore, responds non-linearly to the shocks arising from market uncertainties (IRENA 2018). Given the degree of this supply-side flexibility, one can expect that non-linearity in EGCS, namely nuclear and hydro, could lead to non-linear (asymmetric) variations in WEP as well (Zachmann and Von Hirschhausen 2008). In addition, it is also well-recognized that electricity consumption is non-linear in characteristic, and assuming a linear effect of EGCS on WEP could undermine the precise nature of the relationship between EGCS and WEP (Shahbaz 2018). Therefore, a clear understanding of the non-linear cointegrating relationship between EGCS and WEP, and the asymmetric effects of EGCS on WEP is inevitable, as price uncertainties have significant implications on the long-term energy transition goals (Gross et al. 2010). Besides, past studies have mainly examined the symmetric effects of EGCS on WEP; to the best of our knowledge, there is no empirical study that has examined the relationship in the context of non-linear cointegration and asymmetric impacts (Gelabert et al. 2011; Forrest and MacGill 2013; Chattopadhyay 2014; Worthington and Higgs 2017; Gerasimova 2017; Adom et al. 2017). Thus, an empirical investigation of such nature may provide an accurate and unbiased picture of the existing relationship between EGCS and WEP. The other limitation of past studies is related to the methodology employed in the analysis, which fails to accommodate the long-run and short-run asymmetric effects of EGCS on WEP. The long-term aspect is essential in empirical analysis, as it covers the indirect impacts of EGCS on future investments (through long-term changes in

WEP) to maintain a continuous supply of electricity (Bluszcz 2017). In particular, a long-term decrease in WEP generates a higher revenue risk and discourages future expansion in the power/electricity sector (Benini et al. 2002; Gross et al. 2010). Similarly, the short-term aspect of EGCS focuses on the affordability dimension of electricity that influences energy security (Sovacool and Brown 2010). In contrast, such a distinction between the long-run and short-run effects of EGCS on WEP is ignored in the existing studies. Nevertheless, the impact of EGCS on WEP is investigated mainly from the perspective of developed economies (Martinez-Anido et al. 2016); thus, the established empirical relationship has limited applicability in emerging economies.

The EGCS-WEP nexus is a matter of concern for many emerging economies, including India, as the countries have adopted a liberalized electricity market to improve the efficiency of the power sector (Rudnick and Velasquez 2018). However, the success is influenced by variations in WEP, in particular, increased price results in lowering the revenue risks and makes diversification in the EGFM more attractive for future expansion and new investments and vice versa (Roques et al. 2008; Gross et al. 2010). One can argue that since EGCS share around 76.5% of total electricity generation capacity in India (MOP 2019), the energy security and transition goals cannot be met unless the underlying effects of EGCS on WEP is well understood. Thus, there is an immediate need to study the existence of non-linear long-run equilibrium relation and asymmetric impacts of EGCS on WEP for India, which could provide an accurate understanding of the existing trade-offs. The existing studies in the Indian context have mainly focused on barriers or drivers of electricity generation and the determination of electricity price; therefore, the EGCS-WEP nexus from non-linear viewpoint is overlooked for a very long time (Shukla and Thampy 2011; Chattopadhyay 2014; Girish et al. 2018).

Based on the preceding discussions, the objective of the present study can be presented as follows: to examine the non-linear cointegration and asymmetric long-run and short-run effects of EGCS on WEP. Thus, this study intends to investigate the non-linear long-run equilibrium relationship, and asymmetric long-run and short-run impacts of electricity generation from thermal, nuclear, and hydro sources on WEP, using data for India. The empirical analysis employs a non-linear autoregressive distributed lags modelling framework on monthly time series data covering the period April 2012–April 2019. The findings show that a non-linear cointegrating relationship exists between EGCS and WEP for India. The asymmetric long-run price effects of nuclear and hydro sources are evident, but asymmetric short-run price effects are observed only for hydro source.

The present study differs from the existing studies in several aspects. This study is the first-ever empirical attempt to examine the non-linear long-run equilibrium relationship between WEP and electricity generation. The past studies have examined the linear cointegrating relationship between these variables (Forrest and MacGill 2013; Adom et al. 2017). In this study, electricity generation from conventional sources, namely thermal, nuclear and hydro are considered in the empirical analysis; however, the previous empirical studies were largely focused on renewable sources. The analysis conducted in this study investigates the asymmetric impacts of electricity generation from conventional sources on WEP, however, existing studies have investigated the effects by assuming symmetric impacts (Gelabert et al. 2011; Forrest and MacGill 2013; Chattopadhyay 2014; Worthington and Higgs 2017; Gerasimova 2017; Adom et al. 2017). The empirical research in this study segregates the long-run and short-run impacts of EGCS on WEP, where past studies rely on either simulation method or standard econometric techniques that fail to accommodate such distinction in their investigation (Gelabert et al. 2011; Forrest and MacGill 2013; Chattopadhyay 2014; Worthington and Higgs 2017; Gerasimova 2017; Adom et al.

2017). Moreover, in this study, data for India is employed in the empirical analysis, which is amongst the major emerging economies that have implemented diversification of EGFM to reduce carbon emissions and achieve long-term energy security in the country (Sarangi et al. 2019). In the existing literature, no such empirical study is conducted from an emerging economy perspective, especially for India. The findings of this study contribute to the existing literature in the following ways. The finding that there exist a non-linear cointegration between EGCS and WEP is first of its kind in the existing literature, and thus provide important inputs for identifying the optimal EGFM considering this non-linear equilibrium relationship. Though the symmetric effects of thermal sources observed in this study is consistent with previous studies, the asymmetric long-run impacts of nuclear and hydro powers are new to the prevailing knowledge of the effects of EGCS on WEP. The asymmetric short-run impacts of hydro on WEP provide empirical evidence to the argument that the hydro generation system has more flexibility compared to other conventional power sources. Such an understanding of asymmetric effects is necessary to develop a comprehensive energy policy for long-term energy planning, which accounts for the sustainability, reliability, and energy security dimensions. The findings presented for India could provide valuable lessons for other emerging economies, where diversification of EGFM is promoted with the assumption of a linear effect of EGCS on WEP. Specifically, in emerging economies including India, as the realization of energy transition through renewable sources is facing a severe challenge of volatility in WEP, identification of optimal EGFM considering the asymmetric effects of power sources could help in achieving long-term energy security.

The remaining part of the paper is structured as follows: Sect. 2 discusses the EGCS-WEP nexus from an Indian perspective and reviews the existing literature. The methodology and data employed in this study are discussed in Sect. 3, and Sect. 4 presents the estimation results. Section 5 discusses the implications of the empirical findings, and Sect. 6 presents the concluding remarks.

2 The EGCS-WEP nexus—Indian perspective and a brief literature review

The Indian economy has experienced significant structural changes in past decades that have led to unprecedented economic growth, rapid urbanization, growth in exports, and increased population density. With the expansion of economic activities and accelerated development, the demand for electricity is expected to rise by manifold in the coming years (Tripathi et al. 2016). In India, most of the electricity demand is currently met through conventional sources: thermal, nuclear, and hydro, and approximately these sources share 76.5% of the total installed capacity for electricity generation (MOP 2019). Nevertheless, India is also expected to reduce the emission intensity by 2030, as it was committed under the Paris Agreement (MNRE 2011). In this situation, the use of low-carbon electricity generation sources such as nuclear, hydro, and renewables is considered to be a plausible strategy. However, the success of this strategy depends on the dynamics of the electricity market, where volatility in wholesale electricity prices is posing a serious threat to the financial and economic viability of low-carbon power generation systems. As such, the positive and negative shocks in the EGCS are expected to have some significant influence on WEP, and subsequently, have vital implications on India's long-term energy security goals.

Increased electricity generation from sources other than coal provides robustness against interruptions of any one fuel source and mitigates the fossil fuel supply shocks (Grubb et al. 2006). The use of alternative electricity generation sources helps in controlling the price risks that come from employing a particular electricity generation source, but it does not act as a necessary feature to make the system more reliable. Moreover, the efficient use of low-carbon energy sources lessens the overall per-unit cost of generating electricity by giving a boost to the alternative sources in the EGFM, and further results in increasing the probability of energy security compared to the EGFM dominated by fossil fuels (Awerbuch 2006). On the contrary, EGCS, such as nuclear and hydro, are relatively more flexible than coal due to their technical characteristics (IRENA 2018). Thus, it is likely that adverse shocks in EGCS could lead to a rise in WEP and influence affordability, which jeopardizes the long-term energy security objectives (Sovacool and Brown 2010). In such circumstances, thus, there exists a dilemma that how does the Indian economy meets its growing electricity demand by relying on alternate low-carbon EGCS, and at the same time, reduce the threat to energy security arising due to the volatility in wholesale electricity prices. This task eventually requires a better understanding of the relationship between EGCS and WEP for India, and thus, there is a need for a more in-depth analysis of the effects of EGCS on WEP for India.

In the existing empirical literature, some of the studies have analyzed the impact of supply side factors, specifically, electricity generation from sources on WEP using diverse set of countries and methodologies (Humphreys and McClain 1998; Benini et al. 2002; Awerbuch 2006; Roques et al. 2008; Bhattacharyya 2009; Jun et al. 2009; Gelabert et al. 2011; Milstein and Tishler 2011; Forrest and MacGill 2013; Chattopadhyay 2014; Mari 2014; Martinez-Anido et al. 2016; Adom et al. 2017; Worthington and Higgs 2017; Maekawa et al. 2018). For instance, Humphreys and McClain (1998) find in their study that increase or decrease in WEP can be reduced by raising the percentage of coal consumption in the EGFM. Since Blazquez et al. (2018) argued that the marginal cost of electricity generation from some sources is almost zero, there is less flexibility in the adjustment of generation capacity of such sources. This, in turn, makes the conventional sources of electricity such as coal, diesel, and gas more prone to the demand shocks and the resultant price risk poses a threat to their financial and economic viability (Johnson and Oliver 2019). Adom et al. (2017) in a study for Ghana find that increase in electricity generation from hydro source causes movements in wholesale electricity prices in both the long-run and short-run. Awerbuch (2006) in an analysis of optimal EGFM portfolio suggested that fuel mix with more concentration of coal sources poses a higher price risk. Thus, a joint criteria is necessary to identify the optimal EGFM: minimisation of risk and maximisation of return. Bhattacharyya (2009) in a study for selected European countries suggested that EGFM dominated by fossil fuels are associated with more vulnerability in electricity supply. Benini et al. (2002) examined the volatilities in wholesale electricity prices for Spain, California and UK. The study argues that movements in wholesale electricity prices are determined by large number of factors including electricity generation from hydro sources. Chattopadhyay (2014) using mathematical modelling approach studied the effect of electricity generation from renewable sources on electricity market in India. The analysis suggests that price movements are related to renewable generation capacity, demand and existing generation capacity of thermal sources. Forrest and MacGill (2013) in a study for Australian electricity market analysed the effect of wind generation on electricity price and electricity generation from coal sources. The analysis using regression method demonstrates that increased electricity generation from wind sources are replacing the electricity generation from coal sources. In another analysis for Australia, Higgs et al. (2015) investigated the impacts of electricity generation from fossil fuels and renewables on wholesale electricity prices. The study shows that generation sources significantly affect the electricity price, where coal sources negatively influence the electricity price and hydro sources positively affect the electricity price. In a recent study for Australia, Worthington and Higgs (2017) examined the effect of diversity in EGFM on wholesale electricity prices. The analysis based on least squares and quantile regression techniques show that electricity prices are lower in the situation when more coal is used in electricity generation. Gelabert et al. (2011) using standard regression method examined the effects of electricity generation from various sources on wholesale electricity prices for Spain. The findings suggest that coal and hydro sources are positively influencing the price, but the effect of nuclear source is insignificant. Gerasimova (2017) in a research for Nordic countries analysed the effects of wind and hydro based electricity generation on electricity price volatility. The study used regression model and the findings show that increased hydro power results in more volatility in wholesale electricity price in Finland, Sweden and Norway, but the effect is significant for Denmark. Jun et al. (2009) in an analysis for South Korea using supply security index suggest that concentration of coal and nuclear electricity generation sources in EGFM increases the probability of price fluctuations. Maekawa et al. (2018) examined the price effects of non-renewable and renewable electricity generation sources for Japan. The conceptual model proposed in the study argues that both demand and supply side factors determine the movements in electricity price in Japan. Mari (2014) using mean variance portfolio model find that nuclear power can be utilised to hedge against the electricity price risk arising from coal and gas sources in the United States. Martinez-Anido et al. (2016) using scenario analysis show that in the United Kingdom, increased electricity generation from conventional sources have positive effect on the electricity price. The findings also suggest that nuclear and hydro sources create less uncertainty in the electricity supply curve compared to solar and wind sources. Milstein and Tishler (2011) using data for Israel find that when electricity demand is met only through conventional electricity generation sources, the electricity prices are higher compared to diversified EGFM. Roques et al. (2008) in a study for European markets find that co-movements in electricity price can lead to an EGFM with more concentration of coal and nuclear sources.

It is evident for the above reviewed studies that most of the researchers have assumed a linear relationship between electricity generation and WEP in the analysis. Thus, all these studies have overlooked the possibility of a non-linear relationship between EGCS and WEP as well as asymmetric effects in their analysis. In this regard, one can say that it is now imperative to provide a better understanding of empirical relationship between EGCS and WEP, especially for India, to assist in identification of the optimal EGFM for long-term energy security.

3 Materials and methods

3.1 Conceptual model and research hypotheses

In a liberalized electricity market, fluctuations in WEP are a well-established phenomenon, and it can be explained with the help of a standard demand and supply model. Accordingly, the proposed model is presented in Fig. 1, where both the demand and supply of electricity are considered to be non-linear, as suggested in Gao et al. (2000). The model (in Fig. 1) shows that the intersection of demand (D) and supply (S) of electricity curves determines

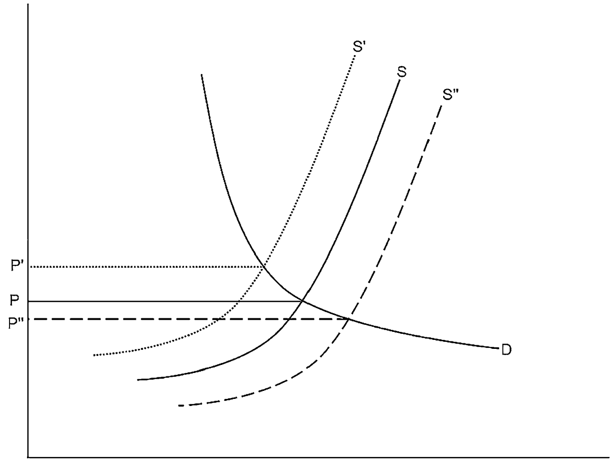

Fig. 1 The relationship between EGCS and WEP

the equilibrium WEP (P) in the electricity market. However, keeping the demand for electricity fixed, increased EGCS results in a rightward shift in the electricity supply curve from S to S". Hence, a new equilibrium WEP (P") is determined, and it is observed that P > P". Similarly, decreased EGCS results in a leftward shift in the electricity supply curve from S to S'. Therefore, a new equilibrium WEP (P') is determined, and in this case, P < P'. The differences between the equilibrium WEPs with respect to changes in EGCS can be expressed as Δ_1 = P"-P and Δ_2 = P'-P, where $|\Delta_2| > |\Delta_1|$. Thus, the relationship between Δ_1 and Δ_2 ($|\Delta_2| > |\Delta_1|$) suggests a possibility of asymmetric (non-linear) price effects of EGCS. Specifically, it can be argued that positive shocks in EGCS result in a relatively smaller change in WEP compared to adverse shocks in EGCS.

The non-linear effect of EGCS on WEP is also discussed in the theoretical work of Johnson and Oliver (2019), but in relation to the intermittent sources of energy and their impacts on WEP volatility. Thus, the conceptual model proposed in this study is distinct in a sense, it considers specifically the non-linear effects of EGCS on WEP. The existing empirical literature on the effects of electricity generation on WEP are vast in numbers, and there is no such study that examines the non-linear effects of EGCS on WEP (Gelabert et al. 2011; Forrest and MacGill 2013; Chattopadhyay 2014; Worthington and Higgs 2017; Gerasimova 2017; Adom et al. 2017). Thus, this study intends to fill these gaps in the existing literature by investigating the non-linear long-run equilibrium relationship between EGCS and WEP and asymmetric long-run and short-run effects of EGCS on WEP. For this purpose, the following two hypotheses are constructed for the empirical verification of the findings suggested in theoretical model (in Fig. 1):

H1 *A non-linear cointegrating relationship exists between EGCS and WEP.*

H2 *The asymmetric long-run and short-run effects of EGCS on WEP exist.*

3.2 Empirical model

In this study, the non-linear cointegrating relationship and asymmetric effects of EGCS on WEP are examined by employing the following econometric specification:

$$WP_t = \alpha + \sum_{i=1}^{3} \left(\theta_i^+ EG_{i,t}^+ + \theta_i^- EG_{i,t}^- \right) + \beta ED_t + \varepsilon_t \tag{1}$$

where t indicates the time, WP denotes the WEP, i corresponds to EGCS (1 = thermal, 2 = nuclear and 3 = hydro), EG_i denotes electricity generated from source i, superscripts + and – on EG_i indicate the positive and negative shocks, ED implies electricity demand and taken as a control variable, and ε is the residual term. The econometric relationship specified in Eq. (1) estimates the non-linear effects (θ^+, θ^-) of positive and negative shocks in EG on WP. The parameters of the model presented in Eq. (1) can be estimated by employing an appropriate time-series econometric technique. Moreover, the positive and negative shocks in EG_i can be calculated by using the partial sum decompositions method proposed in (Shin et al. 2014), and can be expressed in a general form as follows:

$$\begin{aligned} EG_{i,t}^+ &= \sum_{k=1}^{t} \Delta EG_{i,t}^+ = \sum_{k=1}^{t} max(\Delta EG_{i,t}, 0) \\ EG_{i,t}^- &= \sum_{k=1}^{t} \Delta EG_{i,t}^- = \sum_{k=1}^{t} min(\Delta EG_{i,t}, 0) \end{aligned} \tag{2}$$

where $EG_{i,t}^+$ and $EG_{i,t}^-$ denote partial sum decompositions, and Δ is the first difference operator.

3.3 Data

The data utilized in this study is the monthly time series covering the period April 2012–April 2019. WP is calculated by taking an average of the daily day-ahead wholesale electricity price (expressed in Indian rupees per megawatt-hours of electricity) in a month, and it was collected from the Indian Energy Exchange database. The data series for variables EG_i (expressed in GWh, which is equivalent to one million Kilowatt-hours) were extracted from the monthly archives on electricity generation from the Central Electricity Authority of India. Where EG_1 is for Thermal power (*TH*), EG_2 is for Nuclear power (*NU*) and EG_3 is for Hydro (*HY*). *ED* is proxied by the index of industrial output, and the monthly data series for *ED* were collected from the Reserve Bank of India Database. All the data series were transformed into a natural logarithmic form to eliminate outliers and to avoid heteroscedasticity and normality issues in the econometric analysis. The descriptive statistics of the variables are presented in Table 4 in the Appendix.

3.4 Estimation strategy

The estimation strategy employed in this study relies on a two-step procedure: first, the stationary properties of variables are analyzed by using the unit root test with unknown structural break proposed in Vogelsang and Perron (1998). Second, a non-linear autoregressive distributed lag (NARDL) modelling framework is employed to investigate the non-linear cointegration and asymmetric long-run and short-run effects of EGCS on WEP suggested in Shin et al. (2014). The details of each step in the estimation strategy are provided in the following discussion.

3.4.1 Unit root test

The first step in a time series analysis is to examine the presence of unit root in the data series for variables of interest. However, it is often suggested that conventional unit root tests are biased in the presence of a structural break in data series and provide unreliable results (Vogelsang and Perron 1998; Shahbaz et al. 2016). As it can be observed in Fig. 2 (in Appendix), there are several structural breaks in the data series of variables used in this study. Therefore, the employability of unit root test with structural break specification is necessary to make an unbiased conclusion about stationary properties of variables. Hence, Vogelsang and Perron (1998) unit root (VPUR) test with exogenous structural break was employed to identify the unit root properties as well as the optimal break period. The following augmented Dickey-Fuller estimating equation is utilized in VPUR test:

$$x_t = \alpha + \beta t + \theta DU_t(T_b) + \gamma DT_t(T_b) + \varpi D_t(T_b) + \varphi x_{t-1} + \sum_{i=1}^{k} \vartheta_i \Delta x_{t-i} + \varepsilon_t \quad (3)$$

where t denotes the time, x is the variable of interest, DU indicates intercept break, T_b depicts break date, DT denotes trend break, and e is the residual term. VPUR test relies on lag length to correct the higher-order correlation in the series and uses t-Statistic to test the null hypothesis H0: Series has a unit root. VPUR test results are used to identify the order of integration, that is, I(0), I(1) or I(2), and the selection of break period in the data series.

3.4.2 NARDL modelling framework

As per the objectives of this study, the non-linear long-run equilibrium relationship and asymmetric effects depicted in Eq. (1) are investigated by employing a NARDL framework suggested in Shin et al. (2014). The NARDL framework has numerous advantages; for instance, it can be applied to small sample size and also in circumstances where the order of integration of variables is mixed, either I(0) or I(1). Besides, the specifications of NARDL model provide estimated coefficients for error correction term as well the long-run and short-run effects. Thus, the estimated coefficients can be utilized to examine the non-linear cointegration between the variables and the asymmetric long-run and short-run effects of explanatory variables on the dependent variable in each specification (Ghosh 2020). Accordingly, the econometric model depicted in Eq. (1) is formulated in the form of NARDL specification, and can be presented as follows:

$$\begin{aligned}\Delta WP_t = {} & \alpha + \delta t + \xi T_b + \lambda WP_{t-1} + \theta_1^+ TH_{t-1}^+ + \theta_1^- TH_{t-1}^- + \theta_2^+ NU_{t-1}^+ + \theta_2^- NU_{t-1}^- + \theta_3^+ HY_{t-1}^+ + \theta_3^- HY_{t-1}^- \\ & + \sum_{j=1}^{p-1} \gamma_j \Delta WP_{t-j} + \sum_{j=0}^{q-1} \left(\varphi_{1j}^+ \Delta TH_{t-j}^+ + \varphi_{1j}^- \Delta TH_{t-j}^- \right) + \sum_{j=0}^{q-1} \left(\varphi_{2j}^+ \Delta NU_{t-j}^+ + \varphi_{2j}^- \Delta NU_{t-j}^- \right) \\ & + \sum_{j=0}^{q-1} \left(\varphi_{3j}^+ \Delta HY_{t-j}^+ + \varphi_{3j}^- \Delta HY_{t-j}^- \right) + \beta \Delta ED_t + \varepsilon_t \end{aligned} \quad (4)$$

where Δ denotes the first difference value, p and q are the lags, T_b represents the optimal break period (identified from VPUR test results). The specification presented in Eq. (4) can be re-written in the error correction form as follows:

$$\Delta WP_t = \alpha + \delta t + \xi T_b + \lambda\omega_{t-1} + \sum_{j=1}^{p-1}\gamma_j \Delta WP_{t-j} + \sum_{j=0}^{q-1}\left(\varphi_{1j}^{+}\Delta TH_{t-j}^{+} + \varphi_{1j}^{-}\Delta TH_{t-j}^{-}\right) + \sum_{j=0}^{q-1}\left(\varphi_{2j}^{+}\Delta NU_{t-j}^{+} + \varphi_{2j}^{-}\Delta NU_{t-j}^{-}\right) + \sum_{j=0}^{q-1}\left(\varphi_{3j}^{+}\Delta HY_{t-j}^{+} + \varphi_{3j}^{-}\Delta HY_{t-j}^{-}\right) + \beta\Delta ED_t + \varepsilon_t \quad (5)$$

where, $\omega_{t-1} = WP_{t-1} - \eta_1^{+}TH_{t-1}^{+} - \eta_1^{-}TH_{t-1}^{-} - \eta_2^{+}NU_{t-1}^{+} - \eta_2^{-}NU_{t-1}^{-} - \eta_3^{+}HY_{t-1}^{+} - \eta_3^{-}HY_{t-1}^{-}$ is the non-linear error correction term, η^{+} and η^{-} are the long-run coefficients such that $\eta^{+} = -\theta^{+}/\lambda$ and $\eta^{-} = -\theta^{-}/\lambda$.

Similarly, the other specifications of the NARDL model can be expressed as follows:

$$\Delta TH_t = \alpha + \lambda\omega_{t-1} + \delta t + \xi T_b + \sum_{j=1}^{p-1}\gamma_j \Delta TH_{t-j} + \sum_{j=0}^{q-1}\left(\varphi_{1j}^{+}\Delta WP_{t-j}^{+} + \varphi_{1j}^{-}\Delta WP_{t-j}^{-}\right) + \sum_{j=0}^{q-1}\left(\varphi_{2j}^{+}\Delta NU_{t-j}^{+} + \varphi_{2j}^{-}\Delta NU_{t-j}^{-}\right) + \sum_{j=0}^{q-1}\left(\varphi_{3j}^{+}\Delta HY_{t-j}^{+} + \varphi_{3j}^{-}\Delta HY_{t-j}^{-}\right) + \beta\Delta ED_t + \varepsilon_t \quad (6)$$

where,$\omega_{t-1} = TH_{t-1} - \left(\eta_1^{+}WP_{t-1}^{+} + \eta_1^{-}WP_{t-1}^{-} + \eta_2^{+}NU_{t-1}^{+} + \eta_2^{-}NU_{t-1}^{-} + \eta_3^{+}HY_{t-1}^{+} + \eta_3^{-}HY_{t-1}^{-}\right)$

$$\Delta NU_t = \alpha + \lambda\omega_{t-1} + \delta t + \xi T_b + \sum_{j=1}^{p-1}\gamma_j \Delta NU_{t-j} + \sum_{j=0}^{q-1}\left(\varphi_{2j}^{+}\Delta WP_{t-j}^{+} + \varphi_{2j}^{-}\Delta WP_{t-j}^{-}\right) + \sum_{j=0}^{q-1}\left(\varphi_{1j}^{+}\Delta TH_{t-j}^{+} + \varphi_{1j}^{-}\Delta TH_{t-j}^{-}\right) + \sum_{j=0}^{q-1}\left(\varphi_{3j}^{+}\Delta HY_{t-j}^{+} + \varphi_{3j}^{-}\Delta HY_{t-j}^{-}\right) + \beta\Delta ED_t + \varepsilon_t \quad (7)$$

and, $\omega_{t-1} = NU_{t-1} - \left(\eta_1^{+}WP_{t-1}^{+} + \eta_1^{-}WP_{t-1}^{-} + \eta_2^{+}TH_{t-1}^{+} + \eta_2^{-}TH_{t-1}^{-} + \eta_3^{+}HY_{t-1}^{+} + \eta_3^{-}HY_{t-1}^{-}\right)$

$$\Delta HY_t = \alpha + \lambda\omega_{t-1} + \delta t + \xi T_b + \sum_{j=1}^{p-1}\gamma_j \Delta HY_{t-j} + \sum_{j=0}^{q-1}\left(\varphi_{2j}^{+}\Delta WP_{t-j}^{+} + \varphi_{2j}^{-}\Delta WP_{t-j}^{-}\right) + \sum_{j=0}^{q-1}\left(\varphi_{1j}^{+}\Delta TH_{t-j}^{+} + \varphi_{1j}^{-}\Delta TH_{t-j}^{-}\right) + \sum_{j=0}^{q-1}\left(\varphi_{3j}^{+}\Delta NU_{t-j}^{+} + \varphi_{3j}^{-}\Delta NU_{t-j}^{-}\right) + \beta\Delta ED_t + \varepsilon_t \quad (8)$$

and $\omega_{t-1} = HY_{t-1} - \left(\eta_1^{+}WP_{t-1}^{+} + \eta_1^{-}WP_{t-1}^{-} + \eta_2^{+}TH_{t-1}^{+} + \eta_2^{-}TH_{t-1}^{-} + \eta_3^{+}NU_{t-1}^{+} + \eta_3^{-}NU_{t-1}^{-}\right)$.

To examine the non-linear cointegration among the variables, as depicted in ω_{t-1}, in Eqs. (5)–(8), the NARDL bounds test can be applied (Shin et al. 2014; Ghosh 2020). Particularly, the NARDL bounds test utilizes the F-test for joint statistical significance of coefficients with the H0: $\lambda = \eta^{+} = \eta^{-} = 0$ (no non-linear cointegration exists in the model). The calculated F_{PSS}-statistic is used to accept or reject the H0. Furthermore, the H0: $\lambda = 0$ against $\lambda \neq 0$ can also be tested by using t_{BDM}-statistic as well. In this study, any concrete conclusions about the non-linear cointegration are drawn only when the results of both the test statistics are consistent. Since the NARDL bounds test results only provide evidence on the existence of a long-run equilibrium relationship in the estimated model, the estimated value of the coefficient λ is used to interpret the speed of adjustment in the dependent variable with respect to the short-run shocks in explanatory variables in each specification given in Eqs. (5)–(8), but the estimated value must lie between − 1 and 0.

After the confirmation of a non-linear cointegrating relationship among the variables, the next step is to examine the asymmetric long-run and short-run effects of *TH, NU* and

HY on *WP* (Eq. 5). The standard Wald-test for the long-run and short-run symmetry is employed for this purpose (Shin et al. 2014; Shahbaz 2018). Particularly, the rejection of H0: $\eta_1^+ = \eta_1^- = 0$ in the Wald-test implies a presence of asymmetric long-run effects of *TH* on *WP*. In a similar fashion, Wald-test can be applied to examine the asymmetric long-run effects of *NU* and *HY* on *WP*. For the asymmetric short-run effects, the rejection of H0: $\theta_j^+ = \theta_j^- = 0$ in the Wald-test implies the existence of asymmetric short-run effects of the respective explanatory variable. Similarly, for other specifications given in Eqs. (6)–(8), the Wald-test can be conducted to examine the asymmetric long-run and short-run effects of explanatory variables on the dependent variable.

4 Results

4.1 Unit root test results

VPUR test results are reported in Table 1. The estimated values of *t*-Statistic suggest that the H0: data series has a unit root can be rejected at the 1% level of statistical significance for variables *TH, TH*$^+$*, NU, HY, HY*$^+$in their level form. Similarly, for the rest of the other variables, H0 cannot be rejected at the 1% level of statistical significance in their level form. However, after taking the first difference of data series, H0 cannot be rejected at the 1% level for all the variables. The results of VPUR tests suggest that the data series of variables are integrated of order, I(0) or I(1), but none of them are found to be I(2). Moreover, the results show the optimal break period (*Tb*) employed in the unit root tests. In this study,

Table 1 VPUR test results

Variable	At level		After first difference	
	t-Statistic	T_b	*t*-Statistic	$_b$
WP	– 4.77	July, 2017	– 11.44***	Oct, 2018
WP^+	– 3.81	May, 2016	– 10.56***	Aug, 2018
WP^-	– 3.42	Dec, 2016	– 11.68***	Oct, 2018
TH	– 7.09***	Aug, 2013	– 8.91***	Sep, 2014
TH^+	– 6.11***	June, 2014	– 12.22***	Oct, 2018
TH^-	– 4.78	March, 2014	– 11.86***	June, 2017
NU	– 6.05***	Aug, 2017	– 11.46***	Aug, 2017
NU^+	– 4.04	Aug, 2017	– 10.21***	March, 2017
NU^-	– 4.72	March, 2017	– 11.04***	Aug, 2017
HY	– 8.68***	Sep, 2014	– 8.73***	April, 2016
HY^+	– 8.07***	Oct, 2014	– 8.25***	April, 2014
HY^-	– 3.38	Aug, 2015	– 11.62***	Oct, 2017
ED	– 3.11	March, 2015	– 9.28***	Oct, 2017

***Denotes statistical significance at the 1% level. The test statistic for testing the null hypothesis in VPUR test is H0: series has a unit root. The T_b is assumed to be exogenously determined, and the optimal T_b is selected using the criteria proposed in Vogelsang and Perron (1998). The optimum number of lags in VPUR test is selected automatically using the Schwarz Information Criterion with maximum lags of 11 the selection of *Tb* for subsequent estimations is based on the criteria that the data series of a variable should be I(0). The findings from VPUR tests also indicate that the use of NARDL model specification to examine the asymmetric effects is justified in the present study, as it can be applied in cases where a mixed order of integration is observed, I(0) or I(1) (Shin et al. 2014).

4.2 Estimated coefficients of NARDL specifications

The next step in the empirical examination is to estimate the long-run and short-run coefficients of the specifications given in Eqs. (5)–(8). The estimated coefficients are reported in Table 2. In Table 2, the estimated results of specification (ΔWP_t as a dependent variable) given in Eq. (4) show that the coefficients for TH^+_{t-1},TH^-_{t-1}, NU^-_{t-1}, HY^-_{t-1} are 1.154, 1.417, − 0.832, 0.303, and these coefficients are statistically significant at the 5%, 5%, 1% and 5% level. This result suggests that in the long-run, the effects of both positive and negative shocks in *TH* on *WP* are evident, but only negative shocks in *NU* and *HY* influence *WP*. Furthermore, the estimated coefficients for ΔTH^+_t,ΔTH^-_t and ΔHY^+_t are 1.652, 1.527 and − 0.407, and these coefficients are statistically significant at the 1%, 1% and 5% level, respectively. These findings suggest that in the short-run, both positive and negative shocks in *TH* influence *WP*, but only positive shocks in *HY* influence *WP*. The results of specification (ΔTH_t as a dependent variable) given in Eq. (5) depict that the estimated coefficients for WP^+_{t-1}, WP^-_{t-1}, ΔWP^+_t and ΔWP^-_t are 0.127, 0.153, 0.115 and 0.257, and these coefficients are statistically significant at the 5%, 1%, 10% and 1% level. This finding shows that in both the long-run and short-run, positive and negative shocks in *WP* have significant effect on *TH*. The coefficients for ΔHY^+_t and ΔHY^-_t are 0.168 and − 0.154, and these coefficients are statistically significant at the 1% level. This result suggests that in the short-run, both positive and negative shocks in *HY* influence *TH*. In the estimated results of specification (ΔNU_t as a dependent variable) given in Eq. (6), the coefficient for ΔWP^+_t is − 0.413, and it is statistically significant at the 5% level. This finding suggests that in the short-run, only positive shocks in *WP* have an effect on *NU*. The results of specification (ΔHY_t as a dependent variable) given in Eq. (7) demonstrate that the estimated coefficients for TH^+_{t-1}, ΔTH^+_{t-1}, ΔTH^-_{t-1} and ΔNU^-_{t-1} are 1.010, − 1.107, − 2.112 and − 0.662, and these coefficients are statistically significant at the 10%, 5%, 1% and 10% level, respectively. This result suggests that in the long-run, only positive shocks in *TH* influence *HY* but in the short-run both negative and positive shocks in *TH* influence *HY*. Moreover, negative shocks in *NU* influence *HY* only in the short-run. These findings show that there is a possibility of non-linear cointegration in each specifications given in Eqs. (5)–(7), and therefore this can be confirmed from the results of NARDL bounds test of non-linear cointegrating relationship.

4.3 Non-linear cointegration and asymmetric effects analyses results

The results of non-linear cointegration and asymmetric effects analyses are presented in Table 3. In Table 3, the results of bounds test for non-linear cointegration show that the estimated value of *F*-statistic (t_{BDM}-statistic) are 4.62 (− 5.12) for the specification having ΔWP_t as a dependent variable (in Eq. 6), and these test statistics are statistically significant at the 5% level. Hence, the H0 in the bounds test is rejected for the estimated model and implies that there exists a non-linear long-run equilibrium relationship between the variables of the estimated model. Since the cointegration relationship is

Table 2 Estimated coefficients of NARDL specifications

	ΔWP_t	ΔTH_t	ΔNU_t	ΔHY_t
Variable	Coeff.	Coeff.	Coeff.	Coeff.
ω_{t-1}	− 0.606***	− 0.951***	− 0.607***	− 0.240***
WP^{+}_{t-1}	–	0.127**	− 0.105	− 0.150
WP^{-}_{t-1}	–	0.153***	− 0.179	− 0.107
TH^{+}_{t-1}	1.154**	–	0.218	1.010*
TH^{-}_{t-1}	1.417**	–	0.390	0.631
NU^{+}_{t-1}	0.012	− 0.186**	–	0.317
NU^{-}_{t-1}	− 0.832***	0.052	–	0.067
HY^{+}_{t-1}	− 0.086	− 0.044	− 0.016	–
HY^{-}_{t-1}	0.303**	− 0.077	0.188	–
ΔWP_{t-1}	0.019	–	–	–
ΔWP^{+}_{t}		0.115*	− 0.413**	− 0.097
ΔWP^{+}_{t-1}		0.027	0.084	− 0.052
ΔWP^{-}_{t}		0.257***	0.047	− 0.241
ΔWP^{-}_{t-1}		− 0.083	0.003	0.175
ΔTH_{t-1}	–	0.287**	–	–
ΔTH^{+}_{t}	1.652***	–	0.205	− 0.940
ΔTH^{+}_{t-1}	− 0.260	–	0.163	− 1.107**
ΔTH^{-}_{t}	1.527***	–	− 0.272	0.917
ΔTH^{-}_{t-1}	0.064	–	0.140	− 2.112***
ΔNU_{t-1}	–	–	0.208	–
ΔNU^{+}_{t}	− 0.369	− 0.149	–	0.299
ΔNU^{+}_{t-1}	− 0.112	0.140	–	− 0.091
ΔNU^{-}_{t}	− 0.250	− 0.021	–	− 0.184
ΔNU^{-}_{t-1}	0.426	− 0.138	–	− 0.662*
ΔHY_{t-1}	–	–	–	0.554***
ΔHY^{+}_{t}	− 0.407**	0.168***	0.004	–
ΔHY^{+}_{t-1}	− 0.116	0.053	− 0.170	–
ΔHY^{-}_{t}	0.244	− 0.154***	0.022	–
ΔHY^{-}_{t-1}	0.170	− 0.026	− 0.013	–
ΔED_t	− 0.070	0.800***	1.270**	0.214
T	0.003	0.009	0.013	− 0.023
T_b	− 0.129**	0.047**	0.076	− 0.036
Constant	5.457*	6.705***	− 1.052	1.335

Each specification is estimated with $p=2$ and $q=2$, and the optimal lags were selected automatically by using the Schwarz Information Criterion with maximum lags of 4.

***, **, and *denote statistical significance at the 1%, 5%, and 10% level

confirmed for the estimated model, it can be said that any short-run shocks in explanatory variables (specified in Eq. 5) lead to non-linear movements in *WP* to restore its long-run equilibrium position. The estimated value of coefficient ω_{t-1} is − 0.606 (in Table 2), and the coefficient is statistically significant at the 1% level. This result suggests that approximately 60% variation in *WP* is accounted from the shocks in

Table 3 Non-linear cointegration and asymmetric effects test results

Variable	ΔWP_t	ΔTH_t	ΔNU_t	ΔHY_t
L_{WP^+}	–	0.133** (5.46)	– 0.174 (0.98)	– 0.627 (0.62)
L_{WP^-}	–	– 0.161*** (12.17)	0.30 (2.26)	0.447 (0.20)
L_{TH^+}	1.903*** (7.61)	–	0.360 (0.24)	4.216 (1.60)
L_{TH^-}	– 2.338*** (8.68)	–	– 0.643 (0.48)	– 2.631 (0.35)
L_{NU^+}	0.020 (0.004)	– 0.196** (6.69)	–	1.321 (1.27)
L_{NU^-}	1.372***(20.77)	– 0.055 (0.277)	–	– 0.279 (0.04)
L_{HY^+}	– 0.142 (0.32)	– 0.046 (0.561)	– 0.026 (0.01)	–
L_{HY^-}	– 0.500** (5.61)	0.081 (2.22)	– 0.310 (2.32)	–
F_{PSS}	4.62**	7.51***	3.85*	2.83
t_{BDM}	– 5.12**	– 6.97***	– 4.71**	– 2.81
W_{LR}^{WP}	–	0.43	0.31	0.04
W_{SR}^{WP}	–	0.04	1.07	0.02
W_{LR}^{TH}	0.64	–	0.12	0.24
W_{SR}^{TH}	0.05	–	0.35	0.54
W_{LR}^{NU}	69.25***	15.47***	–	0.55
W_{SR}^{NU}	1.29	0.52	–	1.89
W_{LR}^{HY}	2.71*	0.11	0.80	–
W_{SR}^{HY}	6.66**	10.74***	0.26	–

L denotes the long-run effects of respective independent variable on the dependent variable and corresponding *F*-statistic is reported in parentheses. W_{LR} and W_{SR} are the Wald-test statistics for long- run symmetry and additive short-run symmetry, respectively.

***Denotes significance at the 1% level. *Denotes significance at the 10% level. ***, **, and *Denote statistical significance at the 1%, 5%, and 10% level. The non-linear bounds test has H0: no non-linear cointegration exists. The critical values of F_{PSS}-statistic (t_{BDM}-statistics) for $k=6$ are – 4.90 (– 5.31), 4.00 (– 4.69) and 3.59 (– 4.37) at the 1%, 5% and 10% level, respectively, and these critical values are borrowed from Pesaran et al. (2001)

explanatory variables of the estimated model. Similarly, for other specifications depicted in Eqs. (6, 7), the estimated value of *F*-statistic (t_{BDM}-statistic) are statistically significant at the 1% level and therefore, the null of no non-linear cointegration is rejected for the estimated models. The estimated coefficient for ω_{t-1} is – 0.951 (in the specification having ΔTH_t as a dependent variable) and – 0.607 (in the specification having ΔNU_t as a dependent variable), and these values are statistically significant at the 1% level. Thus, the speed of adjustment in *TH* and *NU* with respect to short-run changes in the explanatory variables is approximately 95% and 60%, respectively. However, in the case of specification given in Eq. (8), the estimated value of both *F*-statistic and t_{BDM}-statistic are statistically insignificant and thus, the null of no non-linear cointegration cannot be rejected. These findings suggest that except for the specification having ΔHY_t as a dependent variable, all other specifications have a presence of non-linear long-run equilibrium relationship between the dependent and explanatory variables.

In the results of Wald-test for long-run and short-symmetry of coefficients, for the specification-ΔWP_t as a dependent variable, the estimated value of W_{LR}^{NU} and W_{LR}^{HY} are 69.25 and 2.71, and these test statistics are statistically significant at the 1% and 10% level, respectively. In the case of short-run, only the estimated value of W_{SR}^{HY} (6.66) is statistically significant at the 5% level. Furthermore, for the other specification-ΔTH_t as a dependent variable, the estimated value of W_{LR}^{NU} and W_{SR}^{HY} are 15.47 and 10.74, and these test statistics are statistically significant at the 1% level. In the case of the rest of the other specifications, none of the Wald -test statistics for the long-run and short-run symmetry are statistically significant. These findings suggest that there is a presence of asymmetric long-run effects of electricity generation from nuclear and hydro sources on WEP, but only hydro sources have asymmetric short-run effects on WEP. In addition, there is an existence of asymmetric long-run effects of nuclear sources on thermal sources, but only hydro sources have asymmetric short-run effects on thermal sources. Such findings are new to the existing knowledge of the effects of EGCS on WEP and provide important inputs for the identification of optimal EGFM to achieve long-term energy security. A detailed discussion on the findings is provided in the following subsequent section.

5 Discussion and implications

The non-linear bounds test results in this study provide evidence of a non-linear cointegration in the specification-ΔWP_t as a dependent variable, and thus, the H1 is accepted for India. This finding shows that a non-linear long-run equilibrium relationship exists between EGCS and WEP for India, and it is consistent with the previous studies on linear cointegration (Forrest and MacGill 2013; Adom et al. 2017). Thus, it can be said that any short-run positive and negative shocks in EGCS lead to movements in WEP to restore its long-run equilibrium position. Interestingly, it is observed that approximately 60% variations in WEP are occurring due to the shocks in EGCS and rest are related to the other market uncertainties. This result has important implication for modelling and forecasting of WEP purposes. It is suggested that movements in WEP can be efficiently understood only by considering the non-linear long-run equilibrium relationship between EGCS and WEP. The finding also suggests that any policy which is focused on regulation or deregulation of electricity generation from conventional sources should accommodate its non-linear impact on WEP in the formulation and evaluation process. Specifically, the limited understanding of long-run implications of EGCS on WEP as well as its volatility could also be threatening to the financial and economic viability of the electricity generation projects (Roques et al. 2008; Gross et al. 2010; Johnson and Oliver 2019). Moreover, an empirical evidence on non-linear cointegration between WEP and EGCS is crucial for an emerging economy like India, as the identification of optimal EGFM can be more unbiased and efficient after accommodating this non-linear long-run equilibrium relationship in the investigation.

The Wald-test results for symmetric long-run effects demonstrate that the nuclear and hydro sources have asymmetric impacts on WEP and thus, imply that positive and negative shocks in electricity generation from these sources create dissimilar impacts on WEP. Similarly, the Wald-test for additive short-run symmetry shows only the positive and negative short-run shocks in electricity generation from hydro source. Accordingly, the H2 is accepted for India, in other words, the results suggest that EGCS have asymmetric long-run and short-run effects on WEP. In particular, increased electricity generation from nuclear and hydro sources are causing less volatility in WEP as compared to decreased electricity generation from hydro in the long-run. These findings have important suggestion for electricity generation planners, as an understanding of such asymmetric effects allow for a better prediction of variation in WEP which helps in reducing the impact of price volatility on renewable electricity sources. The estimated long-run coefficient values (in Table 3) suggest that a 1% increase in positive shocks in electricity generation from thermal source lead to 1.9% rise in WEP, but the same increase in negative shocks lead to a fall in WEP by − 2.3% in the long-run. This finding is in contrast to the past studies where it is observed that increase in electricity generation from thermal source reduces WEP (Gelabert et al. 2011; Maekawa et al. 2018). One possible explanation of such contradictory result is the fact that electricity generation from thermal sources are relatively less flexible and thus, nuclear and hydro sources are forced to respond quickly by reducing their electricity generation. In the case of nuclear sources, a 1% increase in only negative shocks cause a rise in WEP by 1.3%. This result is in line with the conceptual model proposed in this study and suggests that a decline in electricity generation from nuclear source resulted in a rise in WEP in the long-run. Thus, it is suggested that though nuclear sources are dominated by other sources in India's EGFM, the asymmetric effects of nuclear sources cannot be ignored in the determination of optimal EGFM. The findings also show that a 1% increase in negative shocks in hydro source lead to fall in WEP by 0.5%. This result implies that a fall in electricity generation from hydro source is fully compensated by increased electricity generation from other sources. It is also observed that WEP is the determining factor for electricity generation from thermal sources, which are relatively more flexible than renewable sources (such as solar, wind, biogas, and mini-hydro). Thus, it can be said that increased volatility in WEP can compel the thermal sources to adjust their production capacity according to the market conditions. In the case of a diversity in EGFM, it is recognized that the sources of electricity considered in this study contribute around 76.5% of the total electricity generated (MOP 2019). Therefore, it is possible that any deviations from existing EGFM certainly influences the supply of electricity in the market and brings about a change in the volatility of wholesale electricity prices. These findings opine that to enhance energy security for India, and there is now a need to reduce the price volatility in the wholesale electricity market, which can be achieved through designing the optimal power generation mix that accounts for non-linear cointegration and asymmetric effects of EGCS on WEP.

6 Concluding remarks

This study examines the non-linear cointegration between electricity generation from three conventional sources, namely thermal, nuclear and hydro, and wholesale electricity prices for India during the study period of April 2012–April 2019. The asymmetric long-run and short-run effects of electricity generation from these sources on wholesale electricity prices are also investigated in this study. The dataset is a monthly time series collected from multiple sources: Indian Energy Exchange, Central Electricity Authority of India, and Reserve Bank of India. The empirical analysis was based on a non-linear autoregressive distributed lags modelling framework. The result of the non-linear bounds test confirms that there is a presence of non-linear long-run cointegrating relationship between the variables. In particular, wholesale electricity prices adjust non-linearly towards its long-run equilibrium position in response to any short-run shocks from the electricity generation from conventional sources. The estimated coefficient for the error correction term shows that around 60% variation in wholesale electricity prices are explained by deviations in electricity generation from conventional sources. The asymmetric long-run effects of nuclear and hydro sources on wholesale electricity prices are evident, but only asymmetric short-run effects of hydro is observed. The findings in this study have presented some new and interesting facts on the nexus between electricity generation from conventional sources and wholesale electricity prices for India. The findings suggest that an optimal diversity in electricity generation fuel mix could be an effective way to contain the volatility in wholesale electricity prices, provided that non-linearity in the effects are accounted for in the analysis.

Appendix

See Fig. 2 and Table 4.

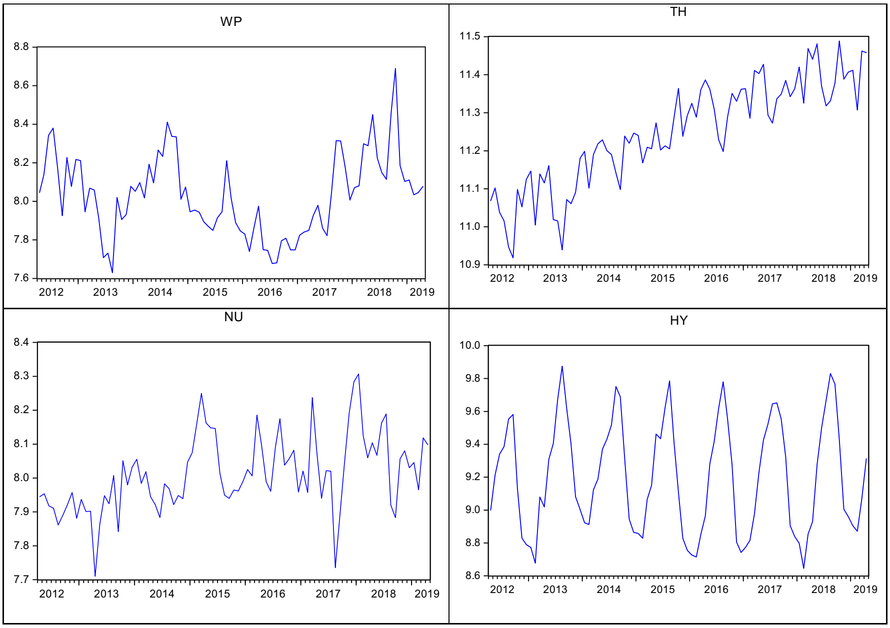

Fig. 2 Time series plots of variables (after natural logarithmic transformation)

Table 4 Descriptive statistics

Variable	Mean	Median	Maxi-mum	Mini-mum	Std. Dev.	Skew-ness	Kurtosis	Jarque–Bera	Probability
WP	8.03	8.03	8.69	7.63	0.21	0.41	2.98	2.40	0.30
WP^+	2.40	2.49	4.66	0.00	1.25	0.04	2.19	2.32	0.31
WP^-	− 2.42	− 2.52	0.00	− 4.63	1.24	0.18	2.19	2.77	0.25
TH	11.25	11.25	11.49	10.92	0.14	− 0.36	2.35	3.30	0.19
TH^+	1.29	1.33	2.57	0.00	0.73	− 0.07	1.96	3.90	0.14
TH^-	− 1.11	− 1.03	0.00	− 2.18	0.60	0.01	2.03	3.30	0.19
NU	8.01	8.01	8.31	7.71	0.11	0.26	3.33	1.36	0.51
NU^+	1.46	1.26	3.29	0.00	1.00	0.28	1.95	5.05	0.08
NU^-	− 1.39	− 1.24	0.00	− 3.14	0.95	− 0.36	1.98	5.52	0.06
HY	9.20	9.19	9.87	8.64	0.34	0.19	1.79	5.67	0.06
HY^+	3.64	3.66	7.27	0.00	2.08	0.01	1.84	4.73	0.09
HY^-	− 3.44	− 3.55	0.00	− 6.95	2.09	− 0.01	1.82	4.92	0.09
ED	4.75	4.75	4.97	4.59	0.09	0.17	2.27	2.28	0.32

Supplementary Information The online version of this article contains supplementary material available at (https://doi.org/10.1007/s11135-021-01130-w)

Authors contributions The first author has conceptualized the idea and collected the data. The second author has helped in analysing the data and writing the manuscript.

Funding Not Applicable.

Data availability The data series for daily day-ahead wholesale electricity price can be accessed from the Indian energy exchange portal from the following link: https://www.iexindia.com/marketdata/areaprice.aspx

The data series for electricity generated from coal, hydro, gas, oil, and nuclear can be extracted from the monthly generation reports available at the Central Electricity Authority, Government of India from the following link: http://cea.nic.in/monthlyarchive.html

The data series for monthly index of industrial production can be accessed from the Indian energy exchange portal from the following link: https://dbie.rbi.org.in/DBIE/dbie.rbi?site=statistics

Code availability Available on request.

Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

References

Adom, P.K., Insaidoo, M., Minlah, M.K., Abdallah, A.M.: Does renewable energy concentration increase the variance/uncertainty in electricity prices in Africa? Renew. Energy **107**, 81–100 (2017)

Ali, S., Xu, H., Al-amin, A.Q., Ahmad, N.: Energy sources choice and environmental sustainability disputes: an evolutional graph model approach. Qual. Quant. **53**(2), 561–581 (2019)

Awerbuch, S.: Portfolio-based electricity generation planning: policy implications for renewables and energy security. Mitig. Adapt. Strateg. Glob. Change **11**(3), 693–710 (2006)

Benini, M., Marracci, M., Pelacchi, P., Venturini, A.: Day-ahead market price volatility analysis in deregulated electricity markets. In: IEEE Power Engineering Society Summer Meeting 3, Chicago, pp. 1354–1359 (2002). https://ieeexplore.ieee.org/abstract/document/1043596

Bhattacharyya, S.C.: Fossil-fuel dependence and vulnerability of electricity generation: case of selected European countries. Energy Policy **37**(6), 2411–2420 (2009)

Blazquez, J., Fuentes-Bracamontes, R., Bollino, C.A., Nezamuddin, N.: The renewable energy policy paradox. Renew. Sustain. Energy Rev. **82**, 1–5 (2018)

Bluszcz, A.: European economies in terms of energy dependence. Qual. Quant. **51**(4), 1531–1548 (2017)

BPSRWE-BP Statistical Review of World Energy: 68th Edition (2019). https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf

Chattopadhyay, D.: Modelling renewable energy impact on the electricity market in India. Renew. Sustain. Energy Rev. **31**, 9–22 (2014)

Forrest, S., MacGill, I.: Assessing the impact of wind generation on wholesale prices and generator dispatch in the Australian national electricity market. Energy Policy **59**, 120–132 (2013)

Gao, F., Guan, X., Cao, X.R., Papalexpoulos, A.: Forecasting power market clearing price and quantity using a neural network method. In: IEEE Power Engineering Society Summer Meeting 4, Seattle, pp. 2183–2188 (2000). https://ieeexplore.ieee.org/abstract/document/866984

Gelabert, L., Labandeira, X., Linares, P.: An ex-post analysis of the effect of renewables and cogeneration on Spanish electricity prices. Energy Econ. **33**, S59–S65 (2011)

Gerasimova, K.: Electricity price volatility: its evolution and drivers. Aalto University School of Business (2017). https://aaltodoc.aalto.fi/bitstream/handle/123456789/28725/master_Gerasimova_Kseniia_2017.pdf?sequence=1%20%20(2017)

Ghosh, S.: Impact of economic growth volatility on income inequality: ASEAN experience. Qual. Quant. **54**(3), 807–850 (2020)

Girish, G.P., Rath, B.N., Akram, V.: Spot electricity price discovery in Indian electricity market. Renew. Sustain. Energy Rev. **82**, 73–79 (2018)

Gross, R., Blyth, W., Heptonstall, P.: Risks, revenues and investment in electricity generation: why policy needs to look beyond costs. Energy Econ. **32**(4), 796–804 (2010)

Grubb, M., Butler, L., Twomey, P.: Diversity and security in UK electricity generation: the influence of low-carbon objectives. Energy Policy **34**(18), 4050–4062 (2006)
Higgs, H., Lien, G., Worthington, A.C.: Australian evidence on the role of interregional flows, production capacity, and generation mix in wholesale electricity prices and price volatility. Econ. Anal. Policy **48**, 172–181 (2015)
Humphreys, H.B., McClain, K.T.: Reducing the impacts of energy price volatility through dynamic portfolio selection. Energy J. **19**(3), 107–131 (1998)
IRENA-International Renewable Energy Agency: Power system flexibility for the energy transition. Abu Dhabi (2018). https://www.irena.org/publications/2018/Nov/Power-system-flexibility-for-the-energy-transition
Johnson, E.P., Oliver, M.E.: Renewable generation capacity and wholesale electricity price variance. Energy J. **40**(5), 143–168 (2019)
Jun, E., Kim, W., Chang, S.H.: The analysis of security cost for different energy sources. Appl. Energy **86**(10), 1894–1901 (2009)
Le, T.H., Nguyen, C.P.: Is energy security a driver for economic growth? Evidence from a global sample. Energy Policy **129**, 436–451 (2019)
Maekawa, J., Hai, B.H., Shinkuma, S., Shimada, K.: The effect of renewable energy generation on the electric power spot price of the Japan electric power exchange. Energies **11**(9), 2215 (2018)
Mari, C.: Hedging electricity price volatility using nuclear power. Appl. Energy **113**, 615–621 (2014)
Martinez-Anido, C.B., Brinkman, G., Hodge, B.M.: The impact of wind power on electricity prices. Renew. Energy **94**, 474–487 (2016)
Milstein, I., Tishler, A.: Intermittently renewable energy, optimal capacity mix and prices in a deregulated electricity market. Energy Policy **39**(7), 3922–3927 (2011)
MNRE-Ministry of New and Renewable Energy: Strategic plan for new and renewable energy sector for the period 2011–17. New Delhi (2011). https://smartnet.niua.org/content/01fff686-a969-4137-a6d7-8a3fedfc6894
MOP-Ministry of Power: Power Sector at a Glance ALL INDIA. Government of India, https://powermin.nic.in/en/content/power-sector-glance-all-india (2019)
Pesaran, M.H., Shin, Y., Smith, R.J.: Bounds testing approches to the analysis. J. Appl. Econ. **16**(3), 289–326 (2001)
Roques, F.A., Newbery, D.M., Nuttall, W.J.: Fuel mix diversification incentives in liberalized electricity markets: a mean-variance portfolio theory approach. Energy Econ. **30**(4), 1831–1849 (2008)
Rudnick, H., Velasquez, C.: Taking stock of wholesale power markets in developing countries: a literature review. Policy Research Working Paper, 8519, World Bank, Washington D.C. (2018). http://documents.worldbank.org/curated/en/992171531321846513/pdf/WPS8519.pdf Accessed 23 Jan 2019
Sarangi, G.K., Mishra, A., Chang, Y., Taghizadeh-Hesary, F.: Indian electricity sector, energy security and sustainability: an empirical assessment. Energy Policy **135**, 110964 (2019)
Shahbaz, M.: Current issues in time-series analysis for the energy-growth nexus (EGN); asymmetries and nonlinearities case study : Pakistan. In: Menegaki, A.N. (ed.) The Economics and Econometrics of the Energy-Growth Nexus, pp. 229–253. Cambridge Academic Press, Cambridge (2018)
Shahbaz, M., Sherafatian-Jahromi, R., Malik, M.N., Shabbir, M.S., Jam, F.A.: Linkages between defense spending and income inequality in Iran. Qual. Quant. **50**(3), 1317–1332 (2016)
Shin, Y., Yu, B., Greenwood-Nimmo, M.: Modelling asymmetric cointegration and dynamic multipliers in a nonlinear ARDL framework. In: Sickles, R.C., Horrace, W.C. (eds.) Festschrift in Honor of Peter Schmidt Econometric: Methods and Applications, p. 409. Springer, New York (2014)
Shukla, U.K., Thampy, A.: Analysis of competition and market power in the wholesale electricity market in India. Energy Policy **39**(5), 2699–2710 (2011)
Sovacool, B.K., Brown, M.A.: Competing dimensions of energy security: an international perspective. Annu. Rev. Environ. Resour. **35**(1), 77–108 (2010)
Tripathi, L., Mishra, A.K., Dubey, A.K., Tripathi, C.B., Baredar, P.: Renewable energy: an overview on its contribution in current energy scenario of India. Renew. Sustain. Energy Rev. **60**, 226–233 (2016)
Vogelsang, T.J., Perron, P.: Additional tests for a unit root allowing for a break in the trend function at an unknown time. Int. Econ. Rev. **39**(4), 1073–1100 (1998)
Worthington, A.C., Higgs, H.: The impact of generation mix on Australian wholesale electricity prices. Energy Sour. Part B Econ. Plan. Policy **12**(3), 223–230 (2017)
Zachmann, G., Hirschhausen, C.V.: First evidence of asymmetric cost pass-through of EU emissions allowances: examining wholesale electricity prices in Germany. Econ. Lett. **99**(3), 465–469 (2008)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.