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Electricity supply in Ghana: The implications of climate-induced distortions in the water-energy equilibrium and system losses

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ABSTRACT

An important synergy exists between electricity supply security and sustainable economic development. However, distortions in the water-energy equilibrium (especially for electricity systems that heavily depend on hydropower renewable energy) and operational inefficiency in the transmission and distribution networks can affect electricity supply negatively and distort this synergy. Given the irreversible nature of capital investments and the time-dependent nature of learning abilities and information flow, it is critical to delineate the short- and long-run effects of system losses and distortions in the water-energy equilibrium on electricity availability. This study applies an econometric approach to study the case of Ghana from 1970 to 2016. Distortions in the water-energy equilibrium negatively affect electricity supply in the short- and long-run. Investment in storage renewable hydro will ensure operational flexibility and compensate for the variability in water flow. Moreover, storage hydropower is a vital asset for the development of non-flexible renewables (i.e. wind and solar) due to the synergy that exists between them. System losses have a concave effect on electricity supply, with the tolerable rate determined as 6.65%. Current levels suggest that the country should cut down on system losses by 13.35%; this requires a significant investment in transmission and distribution networks and meters.

1. Introduction

Electricity supply and economic growth are closely connected [1]. Therefore, ensuring an uninterrupted supply of electricity is a prerequisite for a nation's sustainable economic growth and development. Globally, hydropower provides about 15% of electricity generation [2], supplies about 71% of renewable electricity [3], and represents about 85% of renewable energy [4]. In most economies, the technology supports more than 50% of the total electricity generated [5]. In Africa, in particular, hydropower generation constitutes 84% of all non-fossil fuel energy use [3]. Among experts, it is believed that large dams can help alleviate Africa from its energy supply insecurity issues. Compared to thermal-based generating sources, hydropower technology provides the least-cost alternative of generating power, and it is environmentally friendly [6]. Moreover, carbon dioxide emissions from the entire lifecycle of construction, operation and decommissioning are far lower than all other renewable technologies. Thus, in terms of addressing the electricity supply security issue while ensuring minimal carbon emissions, hydropower technology leapfrogs other generating technologies. However, because hydropower drives on the power of water, adverse changes in the climate that alter the flow of water distorts the water-energy equilibrium, which poses the risk of exacerbating the problems of electricity supply insecurity.

In addition to the significance of generation technology to energy supply security, achieving operational efficiency in the areas of transmission and distribution also plays a significant role. While developed economies have made significant strife in improving the operational efficiency of electricity generation, developing regions like Africa continue to experience inefficiency in transmission and distribution networks. Consequently, for example, distribution losses as a percent of total electricity generation are in excess of 20%. From the level of 11.9% in 2005, the rate has increased to 21.1% in 2014 [7].

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The implications of climate change and rising system losses have been examined in the literature. Greenleaf et al. [8] examined the effect of climate change policy on energy security in the European Union. They found that extreme weather conditions can temporarily restrain energy infrastructures and consequently energy supply. Van Rheenen et al. [9] examined the impact of climate change on hydropower supply in the central valley and Lake Shasta of Poland. The result showed that hydropower could decrease by 8–11% in Lake Shasta and by 10–12% in the central valley as a whole due to climate change. In the Nordic region, Beldring et al. [10] revealed, based on a simulation model, that, there will be a general increase in river flow and hydropower supply, but the variable winter climate is expected to increase the frequency and fast inflows that may challenge the reservoir capacity of dams. Barnett et al. [11] reported that climate change will reduce hydropower based on the Colorado River by 49% by the middle of the century. Demers and Roy [12] also found that, in the province of Quebec, while water inflows increased, the summer inflows decreased due to climate change. Gaudard et al. [5] investigated the effect of water seasonality and price changes on future revenue distribution and its related uncertainty. They found that the impact of climate change on streamflow will decrease the revenue by 20%. Also, variability in electricity prices increases the uncertainty in revenue. In Africa, few studies have investigated the implications of climate change on energy generation. A report by the Building Nigeria's Response to Climate Change (BNRCC) [13] asserted that climate change will most certainly impact negatively the already limited power supply via its impact on a hydro and thermal generation. Enete and Alaba [14] confirmed that climate change undermines power and energy generation in Nigeria. Zwaan et al. [15] evaluated the prospects of large-scale hydropower development in Ethiopia under different scenarios. Their result showed that there is a high projection for future deployment of hydropower generation notwithstanding the hydrological effects from climate change, domestic water use and irrigated agriculture water demand expansions. However, climate change can impose an important limitation on water use for other purposes, and this might reduce the potential deployment of the hydropower plant. Climate change will cause a decrease of 800 GWh of hydropower electricity generation in 2030 and further to 1200 GWh in 2050. Kwakwa [16] examined the drivers of hydropower generation in Ghana in the long-run. Their result showed a negative impact of environmental degradation on hydropower generation. While the above studies acknowledge the implications of the distortions in the water-energy equilibrium caused by climate change on electricity supply, they provide no clear statistical association either in the long-run or short-run between distortions in the water-energy equilibrium and electricity supply. Given that information flow and learning capabilities differ between the long-run and short-run, it is important to disassociate the short-term and long-term effects of distortions in water-energy equilibrium on electricity supply.

Other studies have instead examined the relationship between system losses and electricity supply. Sihombing [17] investigated the effect of energy losses on electricity supply in North Sumatra Indonesia and found a negative effect. Nababan [18] also confirmed the negative effect of energy losses on electricity supply. Opeyemi et al. [19] and Iwayemi [20] both examined the effect of system losses on electricity supply and confirmed a negative relationship. These studies assumed a linear relationship between energy supply and system losses. This may not depict the reality since, engineering-wise, it may not be possible to totally get rid of system losses, but an acceptable level that does not deteriorate electricity generation is still attainable. Though one may be tempted to use the levels in developed countries as a benchmark, the differences in system operating conditions suggest that the acceptable levels of system losses for production may differ from country to country. Thus, by assuming linearity in the relationship, it is impossible to determine the threshold (referred to in this study as “red line in system losses”) which will provide the benchmark for evaluating a country's performance in terms of lowering the losses in the system.

The different strand of the literature has treated the implications of system losses and distortions in the water-energy equilibrium on electricity supply in isolation. This from an econometric point of view can be problematic since the omission of an important variable in a statistical relationship may lead to the wrong representation of the true impact of both system losses and distortions in water-energy equilibrium on electricity supply. The main aim of this study is to provide an econometric investigation into the short- and long-run marginal effect of system losses and distortions in the water-energy equilibrium, using the case of Ghana. This study makes the following contributions to the literature. It provides the first econometric evaluation of the short- and long-run marginal effects of both the distortions in the water-energy equilibrium and system losses on electricity supply in Africa. The paper uses the variability in hydropower source to proxy the climate-induced distortions in the water-energy equilibrium. Climate change is the major source of the variability in the water levels of the dam. Second, the study allows for non-linearity in energy supply – system losses relationship. In other words, it determines the cut-off point in system losses below which energy availability would not be distorted. This is then tested against a linear relationship model to determine which one best describes the data. The determination of the cut-off point provides the benchmark to evaluate performance in terms of lowering system losses.

Ghana owns one of the largest hydropower plant capacity in Africa and hosts 76 feasible small- and medium-sized hydro sites, which have a potential capacity of about 800 MW of power [21]. In the electricity sector, hydropower technology contributes more than 60% of the total electricity generation, which supports economies like Togo, Benin, Burkina Faso, and Cote d'Ivoire, and constitute about 90% of renewable energy. Like most economies in Africa, hydropower technology will remain an important generation source in Ghana's electricity sector for a longer time to come. Given the symmetry that exists in the weather patterns especially in the western part of Africa, the findings based on the data of Ghana will provide useful policy guidance (on the type of renewable hydro plant to develop) for the electricity sector in these economies to enhance electricity supply security.

Section 2 presents the theoretical and empirical specifications and discusses the data. Section 3 provides an overview of the electricity sector. Section 4 discusses the main findings of the study. Section 5 concludes the paper and makes policy recommendations.

2. Method and data

This section of the paper describes the theoretical and empirical models, the econometric method, and the data used in this study.

2.1. Theoretical model

The theoretical model is derived from the neoclassical theory of supply, which specifies the supply of any commodity, in the most general form, as a function of own-price (P), the price of other commodities (P_r) and technology (T). This is shown in Equation (1), where S denotes the supply of a good.

$$S = f(P_o, P_r, T) \tag{1}$$

Relating this theory to the case of electricity supply (*ES*), the electricity supply function is expressed as a function of the price of electricity (P_E), the price of alternative fuel/energy (P_r), and the level of technology. Equally, other factors like weather (*W*) and market size (M_s) also matter. Equation (2) shows the electricity supply equation.

$$ES = f(P_E, P_r, M_S, T, W) \tag{2}$$

Equation (2) is purely deterministic. To account for the stochastic component, Equation (2) is augmented with the stochastic term (ε). Further, Equation (2) is augmented with an '*A*' term which captures knowledge acquisition or experience. Equation (3) is the general electricity supply equation.

$$ES = Af(P_E, P_r, M_S, T, W, \varepsilon) \tag{3}$$

The effect of the weather (induced by climate change) on electricity supply depends on the structure of production. An electricity system that is heavily driven by fossil fuel-powered thermal technology is less likely to experience serious distortions from the variability in the weather. However, a system which has a higher share of renewable in total generation is more likely to be affected by the variability in the weather. In Ghana, for example, where hydro-based renewable constitutes a significant share of total production, adverse changes in the weather, such as drought caused by climate change significantly distorts the water flow and levels in the dams**.** This increases the variability in power generation from hydropower sources and distorts the water-energy equilibrium. Thus, in the case of Ghana, the variability in renewable hydro energy production is the main transmission channel through which climate-induced distortions in the water-energy equilibrium will impact on electricity supply. On the policy front, this relationship has an important implication on the type of hydro dam to construct. For instance, in the case of higher variability that decreases electricity supply, constructing a hydropower storage might be recommended. It will ensure operational flexibility and compensate for the variability in water flow. Moreover, storage hydropower is a vital asset for the development of non-flexible renewables (i.e. wind and solar) due to the synergy that exists between them. Thus, Equation (3) can be re-written as Equation (4), where H_V denotes the variability in hydropower renewable energy production which captures the climate-induced distortions in the water-energy equilibrium.

$$ES = Af(P_E, P_r, M_s, T, H_V, \varepsilon) \tag{4}$$

2.2. Empirical model

In order to estimate Equation (4), empirically, the Cobb-Douglas production function is assumed in Equation (5), where '*e*' denotes the exponential notation. A linear log transformation of Equation (5) produces Equation (6), where$\alpha_0 = \ln A$.

$$ES_t = AP_{E,t}^{\beta} P_{r,t}^{\chi} M_s^{\sigma} T_t^{\phi} H_{V,t}^{\gamma} e^{\varepsilon_t} \tag{5}$$

$$lnES_t = \alpha_0 + \beta lnP_{E,t} + \chi lnP_{r,t} + \delta lnM_{s,t} + \phi lnT_t + \gamma lnH_{v,t} + \varepsilon_t \tag{6}$$

The average end-user tariff of electricity captures the own-price effect. The price of crude oil (P_O) is used to capture the cost of alternative fuel or energy. Real gross domestic product per capita (*Y*) is used as a proxy for the number of buyers/market size. An increase in market size should increase electricity supply, all things being equal. The inclusion of real gross domestic product per capita follows from both the theoretical model and empirical works like Zeshan [22], Liu et al. [23] and Opeyemi et al. [20]. In order to capture technological investment in the sector, this study uses two indicators: gross fixed capital formation (*IV*) and total system losses (*SL*). Total system losses show the level of operational and managerial efficiency and thus indicate the extent of technological penetration into the sector. It is expected that rising system losses should negatively impact electricity availability. This is motivated by Sihombing [17], Nababan [18], and Iwayemi [20]. Higher variability in hydropower production (H_V) distorts the water-energy equilibrium significantly, which is expected to affect electricity availability negatively. The variability in hydropower is calculated as the standard deviation in renewable hydropower generation. The inclusion of the variability in hydropower is motivated by studies like Zwaan et al. [15], Gaudard et al. [5] and Demers and Roy [12], and Khan et al. [24]. Based on the above, Equation (6) is reformulated as Equation (7), which is the baseline model.

$$\ln ES_t = \alpha_0 + \beta \ln P_{E,t} + \chi \ln P_{O,t} + \delta \ln Y_t + \varphi_1 \ln SL_t + \varphi_2 \ln IV_t + \gamma \ln H_{V,t} + \varepsilon_t \tag{7}$$

In the baseline model, a linear relationship between electricity supply and system losses is imposed. This presupposes a zero tolerance rate for system losses in electricity generation. However, engineering-wise, this might not be the case since losses may be tolerable up to a certain level that is not deemed deteriorating to electricity supply. Thus, the relationship is likely to be non-linear, which suggests the existence of a threshold in system losses in the generation of electricity. This study hypothesizes an inverted U-shaped relationship. The square of system losses is further included in Equation (8) to capture the non-linear effect of system losses. Equation (8) is novel when compared to previous attempts that assumed linearity in the effect. This study evaluates both the non-linear and linear equations, using different model diagnostics.

$$\ln ES_t = \alpha_0 + \beta \ln P_{E,t} + \chi \ln P_{O,t} + \delta \ln Y_t + \varphi_1 \ln SL_t + \varphi_{11} \ln SL_t^2 + \varphi_2 \ln IV_t + \gamma \ln H_{V,t} + \varepsilon_t \tag{8}$$

2.3. Econometric method: autoregressive distributed lag method

This study employs the autoregressive distributed lag (ARDL) method proposed by Pesaran and Shin [25] and Pesaran et al. [26] to estimate Equations (7) and (8). In contrast to the conventional cointegrating approaches, the ARDL method does not impose strict restrictions on the level of integration required for the variables included in the model. It permits the inclusion of I(0) or I(1) or mutually cointegrated variables [27]. In terms of sample properties, the ARDL method possesses desirable finite sample properties. The long-run estimates remain unbiased even under the assumption of endogeneity of some regressors. Thus, the method assumes the regressors are weakly exogeneous.

An important requirement for the ARDL method is that there should be cointegration. To confirm this, the paper applied the Bounds cointegrating approach, which permits 1(0), I(1) or mutually cointegrated variables. The Bounds test estimates an unrestricted error correction model expressed in Equation (9).

$$\Delta lnES_t = \alpha_0 + \sum_{l=1}^{k} \kappa_i \Delta lnES_{t-i} + \sum_{l=1}^{k} \beta_i \Delta lnP_{E,t-i} + \sum_{l=1}^{k} \chi_i \Delta lnP_{0,t-i} + \sum_{l=1}^{k} \delta_i \Delta lnY_{t-i} + \sum_{l=1}^{k} \phi_i \Delta lnSL_{t-i} + \sum_{l=1}^{k} \phi_{2i} lnIV_{t-i} + \sum_{l=1}^{k} \gamma_i lnH_{V,t-i} + \kappa lnES_{t-1} + \beta lnP_{E,t-1} + \chi lnP_{0,t-1} + \delta lnY_{t-1} + \phi lnSL_{t-1} + \phi_2 lnIV_{t-1} + \gamma lnH_{V,t-1} + \varepsilon_t \tag{9}$$

The test then restricts the coefficients of the lag level variables to zero, which is an indication of no long-run relationship. The null and alternative hypotheses are expressed in Equations (10) and (11).

$$H_O : \kappa = \beta = \chi = \delta = \phi = \phi_2 = \gamma = 0 \tag{10}$$

$$H_A : \kappa = \beta = \chi = \delta = \phi = \phi_2 = \gamma \neq 0 \tag{11}$$

The test generates two critical values which provide the bound that describes the different classifications of the regressors as I(0), I(1) or mutually cointegrated. There are three possible conclusions that can emerge from the test. First, there exists cointegration when the calculated F-statistic exceeds the upper critical value at any significance level. Second, there is no cointegration when the calculated F-statistic falls below the lower bound critical values at some significance level. Third, the decision becomes inconclusive if the calculated F-statistic falls within the lower and upper bound critical values. In such a case, Kremers et al. [28] suggest the use of the significance of the error correction term, while Pesaran et al. [26] suggest the determination of the number of cointegrating ranks. Based on the evidence of cointegration, the study proceeds to estimate the long- and short-run models associated with the ARDL method. These are respectively expressed in Equations (12) and (13).

$$\theta(L,P)ES_t = \sum_{i=1}^{K} \psi_i(L,P)X_{it} + \pi w_t + \varepsilon_t \tag{12}$$

$$\Delta ES_t = \phi(1,P)ECT_{t-1} + \sum_{i=1} \psi_{i0}\Delta X_{it} + \pi \Delta w_t - \sum_{j=1}^{P-1} \eta_j^* \Delta ES_{i,t-j} - \sum_{i=1}^{K} \times \sum_{j=1}^{q-1} \psi_{ij}^* \Delta X_{i,t-j} + \varepsilon_t \tag{13}$$

where 'X' denotes a (n x 1) vector of regressors, η^* and ψ^* denote the short-run dynamics of the models' convergence to equilibrium; ψ_{i0} denotes short-run coefficients, and $\phi(1,P) = 1 - \phi_1 - \ldots - \phi_p$ denotes the adjustment term.

2.4. Further robustness checks

The assumption of weak exogeneity imposed by the ARDL technique is a strong one. The supply model estimated in this study is not immune to endogeneity and serial correlation problems. Therefore, this study does not rule out the possible problems of endogeneity and serial correlation which could bias the results. As a further robustness check, the study applied the Fully-modified ordinary least square (FM-OLS) by Phillip and Hansen [29] and the dynamic ordinary least square (DOLS) by Stock and Watson [30]. These methods deal with the problems of endogeneity and serial correlation. They both transform the data, albeit in a distinctive way, to make the long-run model (e.g. 7 and 8) mimic a strict exogeneous case. The Stock and Watson approach introduces optimal leads and lags of the first difference of the regressors to deal with the problems of serial correlation and endogeneity, respectively. The Phillip-Hansen approach rather performs a transformation on both the data and the variables and then proceeds to remove any existing nuisance in the parameter estimates.

2.5. Data

This study used annual time series data covering 1971–2016. Electricity supply is defined as the total electricity generated in kilowatt hours. Electricity price is measured as the average end-user tariff in local currency per kilowatt hours. This imposes the unusual assumption that supply decisions are made at averages and not at the margin. However, the lack of data on marginal electricity prices makes this assumption necessary for this study [27]. The total system loss, which is the sum of distribution and transmission losses, is measured as total electricity losses as a percent of the total electricity generated. The real crude oil price is the nominal world crude oil price deflated by the US implicit GDP deflator. Income is measured using the real GDP per capita. Gross fixed capital formation as a percent of GDP is used to measure investment. The data on electricity price was obtained from the Volta River Authority, Electricity Company of Ghana, and Energy Commission, Ghana [31,32]. Crude oil price data was sourced from the BP statistical review of world energy [33]. The data on electricity production, gross domestic product per capita, hydropower production, gross fixed capital formation, and system losses in the electricity sector were sourced from the World Bank development indicator database [34].

3. Overview of the electricity sector in Ghana

This section discusses the structure of the electricity generation mix, the trends in the water levels of the Akosombo dam, electricity price, and renewable energy development in the electricity sector.

3.1. Installed capacity and electricity generation

Hydro and thermal are the two major electricity generation sources in Ghana. Table 1 shows the total installed capacity (in MW) visa-vie the plant generation (in GWh). A significant addition to the generation capacity occurred in 2010, 2013, and 2015. Most of these capacity additions were thermal-based. In 2015, total installed capacity stood at 3656 MW [31]. Hydro constituted 1580 MW (representing 43.2%), thermal constituted 2053 MW (representing 56.2%), and solar constituted 22.5 MW (representing 0.6%) [31]. This confirms the claim that there is a phenomenon of thermalization in Ghana's electricity sector [35].

Between 2008 and 2014, Ghana experienced a consistent rise in total electricity generation. However, in 2015, there was a significant drop from 12,963 GWh in 2014 to 11,942 GWh in 2015 [31]. This represented a difference of 1021 GWh. The major cause was the fall in generation from the hydro plant at Akosombo. Power generated from the hydro source declined from 8387 GWh in 2014 to 5845 GWh in 2015 [31], which represented a loss of 2542 GWh. This loss was partially compensated for, by increasing the generation from thermal sources by about 1072 GWh in 2015, which was not enough to avert the shortage experienced in power supply in 2015. The shortage recorded in total electricity generation caused a serious energy problem in the country. Power supply became very unstable, and this contributed immensely to the household name 'dumsor' to wit an unstable supply of power. The negative impact, both socio-economic and psychological, of the energy challenge was significantly felt in major energy-driven sectors. Kwabla [36] and Adom et al. [37] revealed that the power crisis had negative effects on the industrial sector. On health, Ibrahim et al. [38] revealed that the crises affected the health of tertiary students in Ghana. The experience in 2015 has renewed the national interest to find ways to boost the supply of electricity in a much sustainable way in the country. Though electricity generated from the hydro source declined in 2016 and 2017, total electricity production bounced back in 2016 and 2017 due to the increase in electricity generated from thermal plants. The contribution of other renewables, which included Safisana Biogas, Volta River Authority solar and BXC solar, also saw a significant improvement from 3 GWh in 2015 to 28.08 GWh in 2017 [31].

3.2. Total system losses

Total system losses give an indication of the operational/managerial efficiency of the utility. Systemic losses contribute greatly to the energy problem in Ghana. Between 1971 and 1999, system losses were below 12% of the total electricity generated. The rate has significantly increased beyond 20% from 2000 [34]. As shown, in Table 2, total losses (i.e. the sum of distribution and transmission losses) for the period 1990–1995 and 1995–2000 averaged 3% and 5%, respectively. Technically, what this implies is that, during these periods, on annual basis, the country lost between 3 and 5% of the total electricity generated. This, by all standards, compared very well with the acceptable international standard of 4–12%. However, after 2000, a significant upward shift in total losses occurred. For the period 2000–2005, Ghana lost averagely 23% of the power produced annually. This dropped marginally to 22% in 2004–2010 and increased marginally to 22.4% in 2010–2015 [31]. By all standards, the current levels are unacceptable, especially for a country that strives to achieve a sustainable economic development and Sustainable Energy for All (SE4ALL).

Majority of these losses have been recorded in the distribution sector. Thus, beginning in 2000, the operational efficiency of the distribution company has worsened significantly. Two possible factors could explain this phenomenon; the lack of investment (due to the distribution company's inability to collect bills for electricity supplied) and managerial inefficiency. These losses represent significant economic losses to the country and require a country-wide perspective on the subject. The security of the electricity sector, in the future, will crucially, therefore, depend on the country's ability to reduce these losses to the appreciable levels.

3.3. Water levels of the Akosombo dam

Hydro provides the parent power supply source for the country. There are three major dam sites in Ghana that supply electricity. They include the Akosombo dam (with an installed capacity of 1020 MW at the end of 2015), the Bui dam (with an installed capacity of 400 MW at the end of 2015), and the Kpong dam (with an installed capacity of 160 MW at the end of 2015). Due to the importance of hydro, the security of electricity supply heavily depends on the water levels and flow in the dams. One of the critical challenges, in the case of Ghana, has been the adverse effects of the weather on the levels and flow of water in the dams.

Drought caused serious distortions in the water-energy equilibrium during the periods of 1981–1983 [39] and 1993–1995 [40]. This situation with hydropower led to the installation of the Takoradi Power Station thermal plant with a capacity of 300 MW in 1999. In fact, the drought had occurred again in 1998 but the effect this time was not that severe as in previous periods. The government was forced to acquire an emergency diesel power of 60 MW from Cummins Limited (30 MW) and Messrs Aggreko Limited (30 MW) [41]. Despite the installation of additional thermal plants

Table 1
Trends in total installed capacity (MW) and generation by plants (2008–2015). Source: Author's own construction with data from Energy Commission Ghana [31].

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Installed capacity (MW)	1981	1970	2165	2170	2280	2831	2831	3656	3795	4398
Total electricity generated[a] (GWh)	8324	8958	10,167	11,200	12,024	12,871	12,963	11,492	13,022	14,069
Hydro (GWh)	6195	6873	6996	7561	8071	8233	8387	5845	5561	5616
Thermal (GWh)	2129	2081	3171	3639	3953	4635	4572	5644	7435	8424
Other renewables (GWh)	–	–	–	–	–	3	4	3	26.54	28.08

[a] The sum of hydro, thermal and other renewables.

Table 2
Trends in total system losses as a percent of total electricity generated (5-year average).

Year	1990–1995	1995–2000	2000–2005	2005–2010	2010–2015
System losses % total electricity generated	3	5	23	22	22.4

Source: Author's own construction with data from Energy Commission Ghana [31].

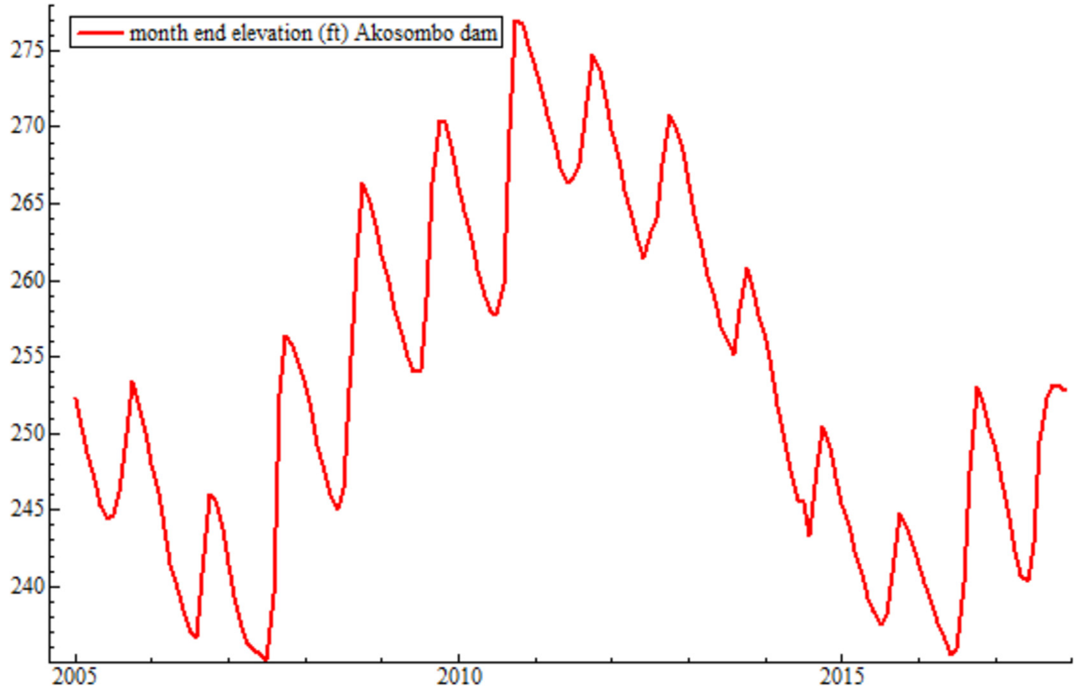

Fig. 1. Plot of month-ending water elevation levels of Akosombo dam (2005–2015). Source: Author's own construction with data from Energy Commission Ghana [31].

in subsequent periods, the droughts that occurred in 2006/2007 and 2015 caused serious distortions in the water-energy equilibrium which negatively affected electricity availability and security.

Fig. 1 shows the plot of the end of the month elevation of water levels (in feet) from the Akosombo dam. The first impression is that the water levels have been very unstable in 2005–2017. For a significant part of the 2006/2007 and 2015 periods, the country recorded the lowest water levels in the Akosombo dam. Fig. 1 also reveals evidence of periodicity in the cyclicality of the monthly water levels of the Akosombo dam. On average, the level rises in the first month; reduces from February to June, and then rises afterward. The period of low levels coincides with the dry periods while the period of the rise coincides with the wet periods.

The instability in the water flows and levels have often plunged the country into prolonged periods of power crisis. The economic cost of these power crises has been estimated to range between $320 and $920 million per annum according to the Institute of Statistical, Social and Economic Research (ISSER), Ghana. The World Bank [42] also estimated the cost to the gross domestic product at 1%. As indicated by the Wholesale Power Reliability Report in 2010, inadequate and unreliable electricity supply cost the nation between 2 and 6% of her gross domestic product [43]. The severe nature of the power crisis often forced the government to import power from Cote d'Ivoire and secure an emergency power plant, which people later raised a lot of red flags about the procurement process and value for money of the project. Renewable hydropower will continue to prove a very important generation source in the country's total electricity generation mix. Developing mini hydro plants is seriously being considered in the national energy agenda given the huge potential of the country in mini-hydro. In this regard, it is important to understand the implications of the climate-induced distortions in the water-energy equilibrium on electricity availability.

3.4. Electricity prices in Ghana

Electricity prices in Ghana for a long time was administratively fixed [27] to protect the poor and industries. The government expenditure on subsidies in the electricity sector grew to an astronomical level and threatened the fiscal position of the country [27]. Moreover, due to the regulation of prices by the government, the end-user tariff did not reflect the market developments. This was problematic for the utility providers who purchased fuels and plants at the market rate. Consequently, the debt levels began to ascend due to the below marginal cost pricing rule and the inability of the Electricity Company of Ghana to collect bills for electricity supplied. As shown, in Table 3, the average price of electricity in 1990–1995 averaged GH₵ 0.009/kWh. There was the need to balance the interests of both producers and consumers and this motivated the institution of the Public Utility Regulatory Commission (PURC) in 1994. The core mandate of the Commission is to set optimal electricity prices that will balance the mutual interests of producers and consumers, using an automatic price adjustment model.

Soon after the coming in of PURC, the price of electricity began to adjust upwards. In 1995–2000, the average end-user tariff averaged GH₵ 0.0195/kWh, which represented an increase of 116.7%. The upward adjustments in the price of electricity have

Table 3
Historical trends in electricity prices (5-year average) in Ghana.

Year	1990–1995	1995–2000	2000–2005	2005–2010	2010–2015
Electricity price (GHs/kWh)	0.0093	0.0195	0.0557	0.1258	0.3333

Source: Author's own construction with data from Energy Commission Ghana [31].

been consistent. In 2000–2005, 2005–2010 and 2010–2015, the country recorded average end-user tariffs of GH₵ 0.056/kWh (representing an increase of 187.2% when compared to the average tariff in 1995–2000), GH₵ 0.126/kWh (representing an increase of 125% when compared to the average tariff in 2000–2005, and GH₵ 0.333/kWh) (representing an increase of 164% when compared to the average tariff in 2005–2010). In 2016, the average end-user tariff was GH₵ 0.871/kWh but declined to GH₵ 0.764 in 2017 following the public outcry in the election period [31]. The primary drivers of the rise in the average end-user tariff have been the high cost of production (due to current production structure) and the high energy debt (which necessitated the implementation of the Energy Sector Levy). Further, the developments in the macroeconomy have also contributed to the recent trends in the electricity price [35]. Though consumers have complained about the recent levels of electricity prices and are demanding for a reduction in price from the government, from the point of view of the electric power producers, the current level is still below the marginal cost of producing electricity in the country. At the moment, opinions remain divided about whether the country should allow the producers to charge the realistic tariffs or reduce tariffs paid by the end-users.

3.5. Renewable energy utilization in the electricity sector

Ghana has a great potential in renewable energy resources particularly in hydro, solar, wind, biogas and photovoltaic. The country's hydro capacity is one of the largest in the continent [21]. In terms of other renewables (i.e. solar and wind), Ghana has the highest concentrating solar power and second largest wind power potentials in West Africa [44]. Out of the total renewable energy project in West Africa, Ghana controls about 11.5% [35]. However, these renewable energy potentials remain underdeveloped, partly, due to the lack of any proper regulatory framework for renewable energy development. In 2011, the government of Ghana through the Energy Commission enacted the Renewable Energy Act, Act 832, which, among other things, targets to increase the share of other renewable energy development (excluding hydro) in total electricity generation to 10% by 2020 [21]. Other complementary initiatives, such as the feed-in tariff for renewables, the exemption of tax on renewables (i.e. solar and wind), the Renewable Energy Fund, and the Renewable Energy Purchase Obligation have been implemented to foster renewable energy development. These initiatives provide a conducive market environment for renewable energy development in the country.

However, in the presence of these initiatives, the integration of other renewables excluding hydro in the generation of electricity has been very slow. The first integration of other renewables that excluded hydro materialized in 2013. Table 4 contains information on the total installed renewable electricity capacity (in kW) from 2013 to 2017. On-grid installed renewable capacity constitutes the largest, with a share in the total installed renewable capacity of 82.19% [31]. This is followed by mini-grid renewable energy, with a share of 17.05% in the total installed renewable electricity capacity [31]. The share of off-grid renewable energy in the total installed renewable electricity capacity is less than 1% [31].

In terms of the amount of electricity generated from renewable energy sources, hydro continues to dominate. In 2013, out of the 12,870 GWh of total electricity generated for consumption, renewable energy contributed 8236 GWh and thermal contributed 4635 GWh [31]. This represented a renewable energy share in total electricity generation of 64% of which hydro energy constituted 99.96% and other renewables constituted 0.04%. In 2014, the share of renewable energy in total electricity generation increased marginally to 64.7% (hydro constituted 99.95% and other renewables constituted 0.05%). In 2015, the percentage share of renewable in total electricity generation decreased to 51%[2] (hydro contributed 99.95% and other renewables contributed 0.05%) [45]. Though electricity produced from other renewables increased in 2016 and 2017 to 26.54 GWh and 28.08 GWh, respectively [31], the percentage share in total renewable electricity generation still remains at 0.05%.[3] It, thus, still remains doubtful if the target set for other renewable energies in the Renewable Energy Act may be achieved by 2020. In all, in terms of renewable energy utilization in the electricity sector, hydropower will still prove crucial in decades to come. The country currently hosts about 76 feasible small to medium hydro sites with a potential capacity of 800 MW [21].

Table 4
The Historical trends in the total installed renewable electricity capacity (kW).

Year	Off-Grid		On-Grid				Mini-Grid		Total
	Solar	Wind	D.SPV	US	W-E	Hydro	Solar	Wind	
2013			495	2500					2995
2014	1350		443						1793
2015	4003	20	700	20,000	100	4000	256	11	29,090
2016	1238		2626						3865
2017	678		4266				58		5002
Total	7269	20	8530	22,500	100	4000	314	11	42,744

Source: Energy Commission Ghana [31].

4. Results and discussion

This section presents and discusses the main findings of the study. It begins with a preliminary test of the data and then proceeds to discuss the main findings of the study.

4.1. Preliminary data test

Table 5 shows the results of the unit root without structural break test based on the Phillip-Perron unit root test. The result shows that, except for variability in hydro production, the rest of the variables become stationary after first difference. Perron [46] argues that failure to account for structural breaks introduces a bias, which reduces the ability to reject a false null hypothesis. Table 6 shows the results of the Perron unit root test with structural break. The test also confirms the mix integration of I(0) and I(1).

Table 7 shows the results of the Bounds cointegrating test for the baseline linear (BLR) and non-linear (NLR) models. For both models, it is evident that the calculated F-statistic exceeds the upper critical F-statistic. Thus, it can be concluded that price, income, investment, variability in hydro generation, and system losses can be treated as the 'long-run' forcing variables explaining electricity generation in Ghana.

4.2. Drivers of electricity supply – baseline model

This section shows the baseline result, where it is assumed that the relationship that characterizes electricity supply and system losses is linear. Specifically, the short- and long-run effects of distortions in the water-energy equilibrium and system losses are discussed.

[2] This was, largely, as a result of the decrease in electricity production from the hydro plants and the increase in generation from the thermal plants.

[3] This does not suggest that there was no progress in other renewables since the current generation mix seems to be shifting more to thermal energy.

Table 5
Phillip-Perron Unit root test.

Variables	Constant and no Trend		Constant & Trend	
	Level	First Difference	Level	First Difference
lnES	−1.199	−9.596***	−2.778	−10.120***
lnP_E	0.452	−12.578***	−4.055**	–
lnP_O	−1.649	−6.367***	−2.134	−6.381***
lnY	0.683	−4.288***	−1.745	−5.537***
lnSL	−1.329	−8.012***	−2.693	−7.978***
lnIV	−1.156	−7.106***	−2.646	−6.991***
lnH_V	−4.217***	–	−4.492**	–

*,**,*** denote 5% and 1% significance levels, respectively.

Table 6
Perron unit root test with structural breaks.

Variables	Perron Test Statistics		
	Crash model[a]	Changing growth model[b]	Combined model[c]
lnES	−5.658**(1982)	−4.714*(1983)	−5.582*(1982)
lnP_E	−8.963***(1983)	−4.463 (1994)	−9.480***(1983)
$dlnP_E$	–	−5.968***(1985)	–
lnP_O	−3.563 (2003)	−2.940 (1996)	−3.035 (2003)
$dlnP_O$	−7.286***(1998)	−7.261***(1983)	−7.354***(1986)
lnY	−3030 (1980)	−2.947 (1991)	−3.445 (1980)
dlnY	−5.584**(1985)	−5.747***(1986)	−5.709**(1986)
lnSL	−7.989***(1999)	−3.031 (1995)	−7.305***(1999)
dlnSL	–	−8.498***(2002)	−7.305***(1999)
lnIV	−3.542 (1988)	−3.068 (2003)	−4.273 (1983)
dlnIV	−8.364***(1984)	−7.443***(1987)	−8.355***(1984)
lnH_V	−4.187 (2000)	−2.722 (2002)	−4.594 (1999)
$dlnH_V$	−20.221***(2000)	−10.157***(2008)	−23.893***(2000)

[a] Null Hypothesis: the series has a unit root with a structural break in the intercept.
[b] Null Hypothesis: the series has a unit root with a structural break in trend.
[c] Null Hypothesis: the series has a unit root with a structural break in both intercept and trend. Note: the figures in the parentheses denote the chosen breakpoint location. *,**,*** denote 5% and 1% significance levels, respectively.

4.2.1. Short −run results

The second column of Table 8 shows the estimated baseline short-run electricity supply. The results show an evidence of a significant inertia in electricity supply. The existence of inertia in electricity supply implies that recorded inefficiencies in electricity production in previous years are likely to persist into the future. The price of electricity has a significant positive effect on electricity supply. According to the estimate, electricity supply, in the short-run, will increase by 1.49% for every 10% increase in electricity price. This confirms the claim that raising the price of electricity will boost electricity supply. Electricity revenue is a positive function of the price of electricity. Therefore, increasing the price of electricity, all things being equal, raises the revenue profile of electricity providers, and this positively affects the electricity supply. By implication, government interference in the electricity price determination that deviates from the marginal cost pricing rule might distort the revenue flows of electricity providers and hence electricity supply, especially when the government fails to redeem the subsidy expenditure on electricity.

Table 8
ARDL estimate of Short-run supply model.

Variables	ARDL (2,0,0,0,0,1,0)	ARDL (1, 1, 0, 0, 1, 1,1,1)[a]
	Baseline model	Non-linear model
dlnES_1	0.468*** (0.1387)	–
$dlnP_E$	0.149*** (0.0538)	0.236*** (0.0463)
$dlnP_O$	0.118 (0.0707)	0.202*** (0.643)
dlnY	0.396 (0.4542)	0.322 (0.4039)
dlnSL	−0.098* (0.0509)	−0.021 (0.2235)
dlnSLSQ	–	0.006 (0.0639)
dlnIV	0.082 (0.0986)	0.160* (0.0887)
lnH_V	−0.047 (0.0368)	−0.111*** (0.0312)
ECT_1	−0.881*** (0.1454)	−0.745*** (0.0991)
R^2	0.915	0.933
Adj. R^2	0.892	0.908
SER	0.139	0.130
SSR	0.660	0.5421
AIC	−0.9080	−1.0034
Log-likelihood	29.978	35.576
F-statistics	40.652***	37.152***

*,**,*** denote 10%, 5%, and 1% significance levels, respectively.
[a] The sum of hydro, thermal and other renewables.

The real oil price, income and investment show positive but insignificant effects on electricity supply in the short-run. System losses significantly cause a reduction in electricity supply. The elasticity suggests a decrease in electricity supply of 0.98% for every 10% rise in system losses. Rising system losses is an indication of reduced operational efficiency, and this increases the leakages in the system and hence lowers electricity supply. Rising variability in hydropower generation negatively impacts electricity supply, albeit statistically, it is not significant in the short-run. A higher variability in hydropower generation distorts the water-energy equilibrium, reduces electricity generation, and consequently limits electricity availability. The error correction term is significantly negative, which confirms the existence of cointegration. The speed of adjustment to equilibrium is also higher. For every 1% initial error, about 88% of the error is expected to be corrected in the first year. The higher adjustment factor implies that negative shocks that distort the efficiency of electricity generation have a temporal and not a permanent effect.

4.2.2. Long-run results

The associated long-run model is shown in the second column of Table 9. The price of electricity significantly causes the supply of electricity to increase. By increasing the electricity price by 10%, electricity supply will increase by 1.21% in the long-run. This confirms the claim that higher electricity price improves the revenue profile of electricity providers, and this facilitates investment in new technology and capital consumption, which subsequently enhances electricity supply. The price of oil has a significant positive effect on electricity supply. An increase in the price of oil by 10% will cause the supply of electricity to increase by 12.3% in the long-run. The positive effect of the price of oil suggests two things. First, it signals the degree of substitution, where the rise in the price of fossil fuel may cause the switch from thermal power generation to

Table 7
Bounds Cointegrating Test. Null Hypothesis: No long-run relationship exist.

Model F-statistics	10% Critical Values		5% Critical Values		1% Critical Values	
	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound
	I (0)	I (1)	I (0)	I (1)	I (0)	I (1)
$F_{BLR} = 3.592$	1.99	2.94	2.27	3.28	2.88	3.99
$F_{NLR} = 3.597$	1.92	2.89	2.17	3.21	2.73	3.9

Table 9
Long-run supply model.

Variables	ARDL (2,0,0,0,0,1,0)	ARDL (1, 1, 0, 0, 1, 1,1,1)[a]
	Baseline model	Non-linear model
lnP_E	0.121*** (0.0307)	0.169*** (0.0345)
lnP_O	0.123* (0.0706)	0.277*** (0.0838)
lnY	0.512** (0.2125)	0.380 (0.2258)
$lnSL$	−0.098** (0.0451)	1.592*** (0.5051)
$lnSLSQ$	–	−0.420*** (0.1262)
$lnIV$	0.261** (0.1040)	0.555*** (0.1376)
lnH_V	−0.055 (0.0513)	−0.165** (0.0718)
Constant	18.485*** (1.3238)	16.845*** (1.4901)
R^2	0.915	0.933
Adj. R^2	0.892	0.908
SER	0.139	0.130
SSR	0.660	0.542
AIC	−0.908	−1.003
Log-likelihood	29.976	35.576
F-statistics	40.652***	37.152***

*,**,*** denote 10%, 5%, and 1% significance levels, respectively.
[a] The sum of hydro, thermal and other renewables.

renewable energy sources. For instance, in the case of Ghana, this can increase the dependence on hydropower generation and other renewables (i.e. solar energy). In the case of the overdependence on hydropower, there is likely to be a decrease in water for other uses like residential and agricultural irrigation. An alternative explanation for the positive effect of the price of oil on electricity supply is the hedging policy for imported fuels which protects the country against the rising cost of oil.

Income significantly impacts electricity supply positively in the long-run. The elasticity is very elastic, which implies that electricity supply will increase more than proportionately for every 1% increase in income. Based on the estimated long-run income elasticity of supply, electricity supply will increase by 5.12% for every 10% increase in income. The positive effect of income on electricity supply suggests that economic growth or prosperity will boost electricity availability in Ghana. This further implies that the goal of economic growth is compatible with the SE4ALL and energy security goals. Investment significantly drives electricity supply upwards in the long-run. According to the estimate, electricity supply will increase by 2.61% for a 10% increase in investment. Significant investment in technology improves the technical processes in electricity generation, and this helps reduce leakages and improve operational efficiency, hence electricity availability. The effect of distortions in the water-energy equilibrium measured here by the variability in hydropower production is negative but statistically not significant in the long-term.

4.2.3. Evaluation of the baseline model

This section evaluates the baseline model. The baseline model passed the serial correlation and heteroscedasticity tests but failed the normality test (see Appendix A1 for the result). Further, the model also passed the functional misspecification test (Appendix A1 for the result). The predictive power or fitness of the estimated model is also examined. The plot of the fitted values versus the actual values indicates that the model predicts actual electricity supply well. There is no evidence of an outlier in the dataset (see Appendix A2 for the graph). The model also passed the parameter stability test based on the Cumulative Sum (CUSUM) and the Cumulative Sum of Squares (CUSUMSQ) plots (See Appendix A3 for the results). Finally, the study tests for multicollinearity using the coefficient variance decomposition. No two or more regressors have eigenvalues of greater than 0.5. Therefore, based on the recommendation of Belsely et al. [47], the study concludes that there is no multicollinearity. In other words, the regressors are strictly independent of each other. In conclusion, the baseline model did not pass all the residual-based tests. Other diagnostics like the Sum Square Residual (SSR), the Sum of Error of Regression (SER), the Log Likelihood, and the Akaike Information Criterion (AIC) can further be examined but they need to be compared to another model before a decision can be reached. The next section discusses these issues.

4.3. Drivers of electricity supply - nonlinear model

This section of the paper presents the results when the study imposes a non-linear relationship between electricity supply and system losses. Before discussing the results, a particular mention of the model diagnostics and how the non-linear model performed is important. First, the model now passes all three residual-based diagnostic tests: normality, serial correlation, and heteroscedasticity (see Appendix B1 for the result). Further, the predictability/fitness of the model is good. There is no evidence of an outlier (see Appendix B2 for the result). The parameters are also stable (see Appendix B4 for the result), and there is no problem of multicollinearity (see Appendix B3 for the results). The adjusted r-square is relatively higher when compared to the baseline model, as well as the Log Likelihood value. Also, the values for SER and SSR have reduced when compared to the baseline model. Finally, the value of the AIC for the non-linear model is lower than that of the baseline model. All these suggest that the non-linear model provides a better fit of the data. Therefore, this paper uses the non-linear model as the acceptable model. Consequently, discussions and further inferences are derived based on this model.

4.3.1. Short-run results

The last column of Table 8 shows the estimated short-run supply. The price of electricity has a significant positive effect on electricity supply. This confirms the baseline result that a higher electricity price incentivises electricity supply in the country. The estimated coefficient indicates an increase in electricity supply by 2.36% if the price of electricity increases by 10% in the short-run. Recently, the government of Ghana reduced the price of electricity by GH₵ 0.5/kWh in the fulfilment of a manifesto promise to make electricity affordable. The simulated impact of this price decline on electricity supply is negative. It is expected that such a policy will reduce electricity supply in the short-run by 18%[4]; this is based on the assumption that the government fails to provide the revenue shortfall to the utility providers. Thus, if the government can fulfil her financial commitment, then such an intervention by the government in the pricing of electricity might not affect electricity supply negatively. Previous experiences, however, have revealed that the government always has a challenge in redeeming such subsidy expenditures, and this, in recent times, has plunged the electricity generator (i.e. the Volta River Authority) into serious debt. Therefore, in the case of Ghana, government interference in electricity price determination that deviates from the marginal cost pricing rule will decrease electricity availability.

The price of oil has a significant positive effect on electricity supply in the short-run, which confirms the baseline result. An increase in the price of oil by 10% will cause the supply of electricity to increase by 2.02%. As indicated earlier, the positive effect of oil price could indicate substitution possibilities in the electricity sector, as well as the significance of the government's hedging policy for imported fuel. In the case of the former, the substitution

[4] $P_{es}*\left(\frac{PE\uparrow}{WAEP}\right)*100$; P_{es} is the own-price elasticity of supply; $PE\uparrow$ is the change in electricity price, and $WAEP$ is the weighted average electricity price.

is likely to be towards other electricity generating sources, such as hydropower, gas, and other renewables. Currently, there are about eleven (11) thermal plants installed in the country in addition to the three other hydro plants. Out of this, about six (6) of the installed thermal plants use dual fuel [31]. The diversity in electricity generation source implies that rising cost of oil will increase the dependence on renewables and gas-fired plants to compensate for the losses that might occur as a result of reducing the production from oil-fired thermal plants.

Investment has a significant positive effect on electricity supply in the short-run. Increasing total investment in the economy by 10% will increase electricity supply by 1.6%. Investment can be in the form of new energy sources, new technology and consumption capital. Investment in new energy sources, such as renewables and non-renewable sources will increase the supply portfolio and hence improve electricity availability. On the other hand, investment in new technology and consumption capital minimizes the leakages in the system, and this helps to improve electricity supply.

The effect of income is positive but insignificant. System losses show a U-shaped but statistically insignificant effect in the short-run. The variability in hydropower energy sources significantly reduces electricity supply in the short-run. The estimates show that electricity supply will fall by 1.11% if the variability in hydropower energy sources increases by 10%. Climate change disturbs the equilibrium flow of the water in the dams, and this increases the variability in hydropower production. An increase in the variability in hydropower energy sources subsequently distorts the water-energy equilibrium, which impacts negatively on electricity supply. By implication, in the case of Ghana, where the electricity system heavily depends on hydropower, climate change can aggravate the variability in hydropower energy sources, cause serious distortions in the energy-water equilibrium and create serious energy scarcity in the electricity sector. The adjustment factor is significantly negative and high. Thus, there is an evidence of a high degree of equilibration in electricity production in the country.

4.3.2. Long-run results

The last column in Table 9 shows the estimated long-run electricity supply. The price of electricity has a significant positive impact on electricity supply. For every 10% increase in the electricity price, the supply of electricity will increase by 1.69%. Thus, higher electricity price will boost the production of power in the country. The estimated own-price elasticity suggests that the government policy to reduce electricity prices in the country by GH₵ 0.5/kWh will reduce electricity supply in the long-run by 13%. As indicated above, this is conditioned on the fact that the government fails to redeem the subsidy expenditure. Compared to the short-run, the long-run own-price elasticity is smaller. This could possibly be explained by the existence of large generation capacity in the electricity sector. Ghana has enough capacity installed but the problem has been the lack of funds[5] to buy the fuel to power these plants. The already existing installed capacity makes it possible for the power generators to become more responsive to price changes in the short-run. In general, the positive effect of the own-price elasticity suggests that interferences in the determination of the price of electricity that deviates from the marginal cost pricing rule may disturb energy security in the electricity sector.

The price of oil has a significant positive effect on electricity supply. The long-run price elasticity suggests an increase in electricity supply of 2.77% for every 10% increase in the price of oil. Compared to the short-run, the effect of oil price on electricity supply is larger in the long-run. This indicates that the tendency to substitute towards other generating sources like renewables is higher in the long-run. This is expected since the long-run provides enough time to experiment with and develop other energy sources that will compensate for any potential loss in output recorded due to the surge in oil prices.

Income has a positive but insignificant effect on electricity supply in the long-run. Investment has a significant positive effect on electricity supply in the long-run. Increasing investment by 10% will boost electricity supply in the long-run by 5.55%. Compared to the short-run, the positive effect of investment on electricity supply is larger in the long-run. The possible explanation is that the adjustment cost might be higher and prohibitive in the short-run. However, in the long-run, the benefits of information and knowledge sharing and learning-by-doing might improve the rate of new technology integration and hence boost electricity supply.

System losses have a concave effect on electricity supply. Thus, beyond a certain level, further increases in system losses will decrease electricity generation in the country. According to the estimate, this threshold is estimated at 6.65%. Given that the current system losses are more than 20%, this implies cutting down on losses in the electricity sector by 13.35%. Thus, Ghana has already crossed the red line in system losses in the electricity sector by 13.35%. Distribution losses constitute the largest share of total system losses in the electricity sector. Therefore, investing massively in the distribution sector would prove useful in terms of promoting operation efficiency in the electricity sector. In this regard, some initiatives have been taken. The Electricity Company of Ghana (ECG) on September 29, 2016, signed a memorandum of understanding with the Korean Electricity Company [48]. The partnership is expected to help ECG tap into the experiences of the Korean company to help it reduce distribution losses to about 3%. Unfortunately, this partnership did not see the light of day.

The long-run effect of variability in hydro energy sources on electricity supply is significantly negative. Electricity supply is expected to decrease by 1.65% for every 10% increase in hydro energy sources. Compared to the short-run effect, the long-run effect of variability in hydropower energy sources is higher. Thus, climate change is likely to create more distortions in the water-energy equilibrium in the long-run than in the short-run and hence create serious energy security problems.

4.4. Further robustness checks

Table 10 contains the long-run estimates based on the approaches by Phillip and Hansen [29] and Stock and Watson [30]. The first part of the table shows the regression that imposes linearity on the system losses-electricity supply relationship. The last two columns relax this assumption. The diagnostic statistics, such as r-square, SER, and SSR favour the model that imposes non-linearity on the system losses-electricity supply relationship. This confirms the previous results. Focusing the discussion on the last two columns, variability in hydropower energy sources impact negatively on electricity supply, albeit not statistically significant. The negative effect confirms the previous result that climate-induced variability in hydropower energy sources, which increases the distortions in the energy-water equilibrium, reduces electricity availability. The relationship between electricity supply and system losses is concave in nature; this confirms the earlier result that there is a threshold beyond which further increases in system losses will negatively affect electricity supply.

The own-price elasticity is significantly positive and compares well with the result obtained in Table 9. The price of oil impacts positively on electricity supply in the long-run. The estimated

[5] One of the reasons for the financial problems is the determination of electricity price which defies the marginal cost pricing rule.

Table 10
Long-run estimates.

	Linear regression		Non-linear regression	
	FM-OLS	DOLS	FM-OLS	DOLS
lnP_E	0.143*** (0.0246)	0.148*** (0.0193)	0.177*** (0.0237)	0.181*** (0.0270)
lnP_O	0.082 (0.0629)	0.088 (0.0642)	0.125** (0.0537)	0.159** (0.0606)
lnY	0.478** (0.1941)	0.591*** (0.1383)	0.439** (0.1637)	0.477*** (0.1437)
$lnIV$	0.184** (0.0821)	0.153** (0.0611)	0.248*** (0.0724)	0.262*** (0.0890)
lnH_V	−0.014 (0.0529)	−0.086 (0.0749)	−0.027 (0.0449)	−0.087 (0.0628)
$lnSL$	−0.115** (0.0429)	−0.130** (0.0524)	0.571** (0.2544)	0.594 (0.4925)
$lnSLSQ$	–	–	−0.177** (0.0656)	−0.184 (0.1150)
constant	19.179*** (0.9756)	18.503*** (0.9756)	18.744*** (1.0537)	18.278*** (0.8621)
R^2	0.825	0.942	0.844	0.953
Adj. R^2	0.797	0.901	0.814	0.908
SER	0.193	0.132	0.185	0.127
SSR	1.418	0.436	1.264	0.355

*, **, *** denote 10%, 5% and 1% statistical significance levels. Optimal leads and lags for DOL based on the AIC. The heteroskedastic consistent standard error is used.

elasticity is between 0.125 and 0.159 compared to the previous estimate of 0.277.

Income has a significant positive effect on electricity supply. The elasticity is estimated to be between 0.439 and 0.477 compared to 0.380 in Table 9. The positive effect of income confirms the previous claim that the economic growth goal is consistent with the SE4ALL and energy security goals. Investment also positively impact electricity supply, and the estimated elasticity is inelastic as obtained in Table 9.

4.5. Comparison of results with the literature

The negative effect of hydropower generation variability induced by climate change on electricity generation is not comparable to other studies, such as Van Rheenan et al. [9], Enete and Alaba [14], and Kwakwa [16] that also examined the effect of climate change on electricity supply. This is because climate change is captured differently in these studies. In contrast to the findings of Opeyemi et al. [19], Ubi et al. [49], Sihombing [17], and Nababan [18] who all found a negative and linear relationship between electricity supply and system losses, this study found the relationship to be concave. By implication, the current study disputes the fact that zero system losses can be tolerated. The positive effect of the long-run own-price elasticity is consistent with the findings of Ubi et al. [49], Sihombing [17], and Nababan [18]. The positive income elasticity is also consistent with the findings of Peprah [50] and Opeyemi et al. [19]. Opeyemi et al. [19] found both the long-run and short-run elasticity to be inelastic while Peprah [50] also found the long-run income elasticity to be inelastic. The positive effect of oil price is in sharp contrast to the results of Nababan [18] and Sihombing [17] who all found the effect to be negative. This could be due to the difference in generation structures in these economies. It is important to note that, although this study compares the results with the above-mentioned studies, the authors do not seek to enter into the argument of establishing some sort of similarity or equality with these papers for the following reasons; different context, different model set-up, and method applied.

5. Conclusion and policy recommendation

This study investigated the supply-side of the electricity sector in Ghana. Specifically, this article examined the effect of system losses and distortions in the water-energy equilibrium (proxy by variability in hydropower energy sources) on electricity supply. The study applied the ARDL method since the supply of electricity involves irreversible investment decisions, which introduces dynamism into the sector. Preliminary analyses of the data revealed evidence of a long-run relationship. The following results emerged.

Higher distortions in the water-energy equilibrium negatively impact electricity availability both in the short and long-run. The effect is, however, large in the long-run than in the short-run. In the case of Ghana, where hydropower energy source constitutes a significant renewable energy source in the electricity sector, the findings imply that climate change presents an important risk factor towards achieving the SE4ALL and energy security goals both in the short- and long-run. While the development of hydropower is encouraged in the sector to ensure energy security and make electricity affordable, the potential climate change effect on the sustainable supply from this renewable energy source suggests that future developments should rather focus on storage hydro energy to ensure operational flexibility and compensate for the variability in water flow. Moreover, there is an important synergy that could exist between storage renewable hydro energy and non-flexible renewable energies, such as wind turbines and solar. Storage hydropower can store more water in reservoirs when wind turbines and solar are injecting energy into the grid and then use it later when renewable energy from solar and the wind drops. Thus, the important synergy that exists between storage hydropower and non-flexible renewables (i.e. solar and wind) makes storage hydropower an essential asset even for the future development of other non-flexible renewable energies.

System losses have a significant concave effect on electricity generation in the country. The threshold level is estimated at 6.65%. Thus, for levels of system losses that exceed the threshold level, production of electricity will fall. Given the current total system losses of more than 20%, the threshold implies reducing system losses in the electricity sector by 13.35%. This requires that the government makes a substantial investment in distribution lines, meters, and accounting frameworks. In this regard, it might be necessary for the government to partner with the private sector, especially given the tight budget the government is currently running.

Higher electricity price boosts the supply of electricity both in the short- and long-run. The positive effect of the own-price elasticity suggests that interferences in the determination of electricity price by the government that deviates from the marginal cost pricing rule could be counter-productive in the electricity sector. Adopting the marginal cost pricing rule would help boost the financial position of utility companies and hence electricity supply [34]. Such a pricing rule would have some welfare implications especially on the vulnerable in the country. In order to protect the vulnerable, the government should have alternative compensatory relief programs as in the case of the Free Senior High School program in the education sector and the National Health Insurance

Scheme in the health sector.

Economic-wide investment significantly boosts electricity supply in the short- and long-run. This implies that factors, such as high-interest charges and high tax regimes that limit investment levels in the country should be addressed. In this sense, ensuring low-interest rate and business-friendly tax regimes may prove valuable in the electricity sector.

The findings of this paper are based on the econometric projections of the existing trends in electricity supply and the roles of renewable hydro energy and system losses and do not consider scenarios of greater utilization of renewable energy. This certainly is crucial for the sustainability of the energy system and ensuring lower cost of electricity in Ghana. Future research can capitalize on this weakness of the paper.

Acknowledgement

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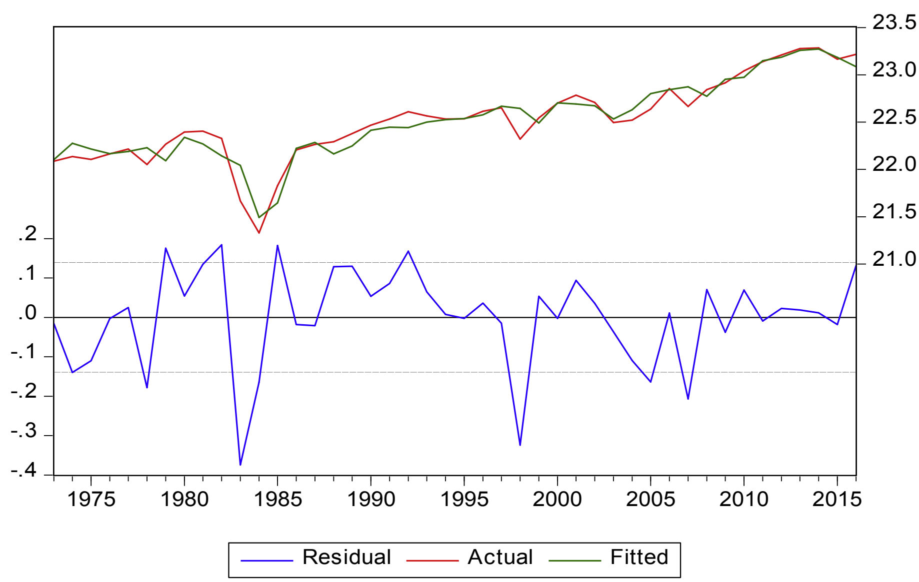
Appendix A

Diagnostic Test: Baseline Model

Appendix A1
Model Residual-based/functional misspecification tests

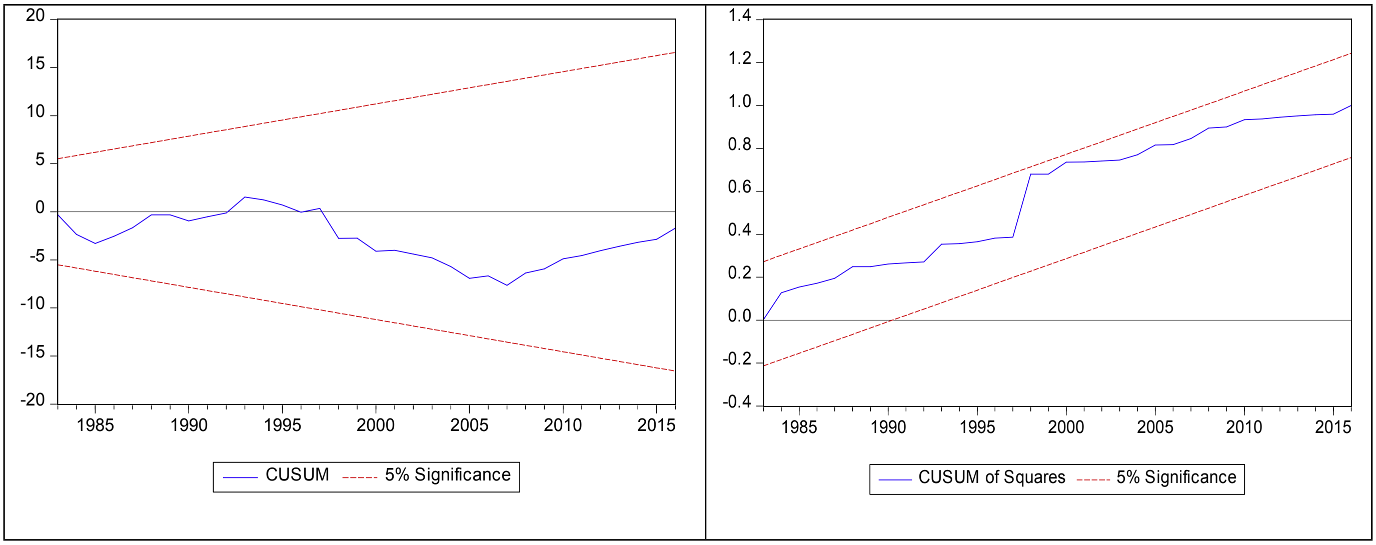
Residual diagnostic	Test	Statistic
Heteroscedasticity	ARCH	0.435 [0.5131]
Serial correlation	Breusch-Godfrey	0.085 [0.7726]
Normality	Jarque-Bera	9.739 [0.0077]
Functional misspecification	Ramsey RESET	0.052 [0.8208]



Appendix A2. Model fitness/Predictability test.

Appendix A3
Multicollinearity Test- Coefficient variance decomposition

Sample: 1971 2016										
Included observations: 44										
Eigenvalues	14.50144	0.043671	0.035283	0.015222	0.004350	0.002178	0.001280	0.000784	7.68E-05	3.95E-07
Condition	2.73E-08	9.05E-06	1.12E-05	2.60E-05	9.09E-05	0.000182	0.000309	0.000504	0.005146	1.000000
Variance Decomposition Proportions										
Associated Eigenvalue										
Variable	1	2	3	4	5	6	7	8	9	10
LES(-1)	0.315639	0.014297	0.602675	0.064542	0.002466	0.000133	0.000114	0.000117	9.50E-06	7.45E-06
LES(-2)	0.313108	0.040415	0.568286	0.073414	0.002538	0.001622	0.000442	0.000159	8.63E-06	7.80E-06
LNP_E	0.760898	0.001064	0.017545	9.62E-07	0.007520	0.130782	0.046673	6.62E-06	0.035508	3.62E-06
LNP_O	0.071467	0.265447	0.004208	2.17E-05	0.552285	0.014106	0.007047	0.085134	0.000283	1.74E-06
LNY	0.015573	0.975916	0.005041	0.000962	0.002150	0.000267	8.90E-06	7.65E-05	4.05E-06	4.13E-07
LNSL	0.343865	0.042208	0.023118	6.58E-05	0.195766	0.039958	0.238754	0.113447	0.002818	6.34E-07
LNIV	0.004409	0.007195	0.297066	0.574179	0.075110	0.022940	0.011446	0.007416	0.000239	2.48E-07
LNIV(-1)	0.021067	0.085008	0.341258	0.466421	0.054165	0.021191	0.005205	0.005470	0.000215	2.00E-07
LNH_V	0.000260	0.044083	0.000313	0.029369	0.052356	0.635315	0.216468	0.021235	0.000601	4.33E-08
C	1.000000	3.50E-07	2.26E-08	1.87E-08	5.12E-08	8.11E-15	1.73E-09	6.88E-11	1.04E-10	2.45E-11



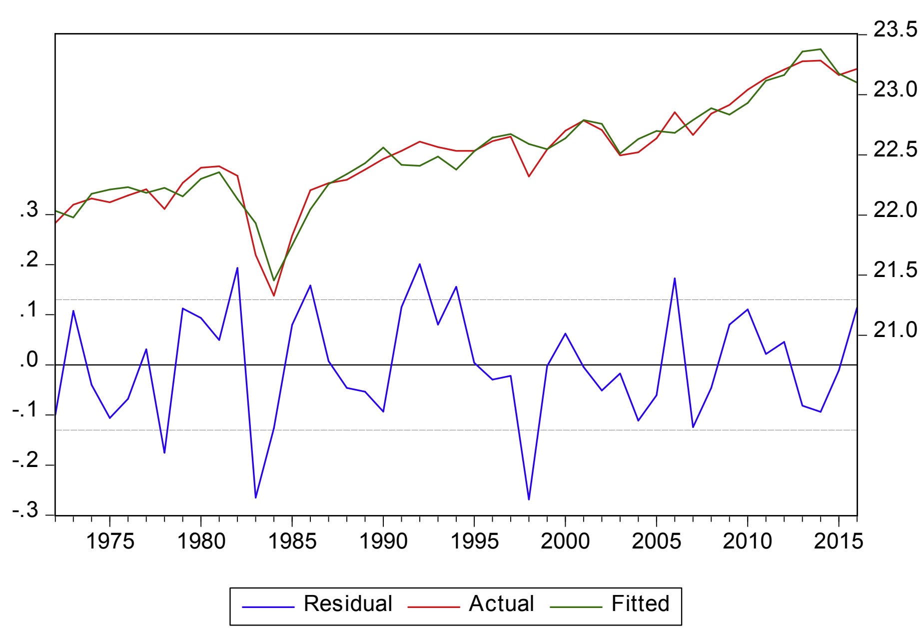
Appendix A4. Parameter stability test.

Appendix B

Diagnostic Test: Non-linear Model

Appendix B1
Model Residual-based/functional misspecification tests

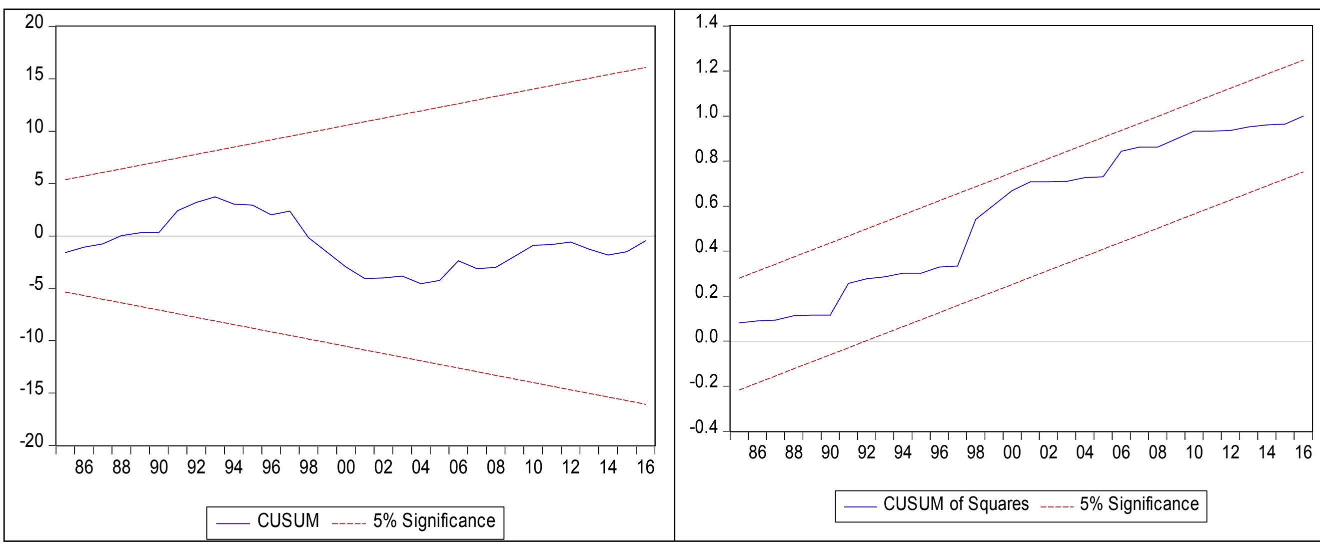
Residual diagnostic	Test	Statistic
Heteroscedasticity	ARCH	0.058 [0.8112]
Serial correlation	Breusch-Godfrey	0.2086 [0.6510]
Normality	Jarque-Bera	0.608 [0.738]
Functional misspecification	Ramsey RESET	2.259 [0.1430]



Appendix B2. Model fitness/Predictability test.

Appendix B3
Multicollinearity test-Coefficient Variance decomposition

Sample: 1971 2016													
Included observations: 45													
Eigenvalues	9.592911	0.157374	0.056705	0.034123	0.016252	0.004143	0.003457	0.002046	0.000884	0.000265	0.000122	1.06E-05	5.51E-07
Condition	5.75E-08	3.50E-06	9.72E-06	1.62E-05	3.39E-05	0.000133	0.000159	0.000269	0.000623	0.002076	0.004507	0.051853	1.000000
Variance Decomposition Proportions													
Associated Eigenvalue													
Variable	1	2	3	4	5	6	7	8	9	10	11	12	13
LES(-1)	0.893700	0.002597	4.61E-06	0.087937	0.003593	0.002483	0.008698	0.000280	8.92E-05	7.30E-08	0.000590	1.02E-05	1.87E-05
LNP_E	0.343253	0.068906	0.001596	0.079769	0.069743	0.292515	0.119719	0.011276	0.004305	9.99E-06	0.008605	0.000300	3.30E-06
$LNP_E(-1)$	0.026389	0.043039	0.108426	0.058648	0.123880	0.400174	0.142959	0.069408	0.012238	9.16E-10	0.014362	0.000471	5.80E-06
LNP_O	0.115707	0.092497	0.115369	0.098855	0.001314	0.218270	0.237800	0.009355	0.110145	5.60E-05	0.000621	8.01E-06	4.05E-06
LNY	0.000146	2.85E-05	0.083810	0.878679	0.035322	5.81E-06	0.001943	1.47E-05	2.34E-05	5.58E-07	2.59E-05	3.11E-07	1.25E-06
LNSL	0.043134	0.511748	0.429467	0.015127	1.60E-05	1.61E-05	0.000252	0.000121	6.54E-06	9.55E-05	1.40E-05	2.14E-06	4.17E-08
LNSL(-1)	0.074507	0.810642	0.110511	0.003831	1.83E-06	0.000254	0.000156	3.41E-07	4.22E-06	8.35E-05	8.43E-06	1.31E-06	2.63E-08
LNSLSQ	0.026503	0.556746	0.367442	0.019734	9.32E-05	0.002565	1.15E-05	0.005201	0.000179	0.019265	0.001642	0.000614	3.45E-06
LNSLSQ(-1)	0.077101	0.802503	0.094227	0.004496	0.000159	0.001136	4.70E-05	0.005732	0.001271	0.011849	0.001097	0.000379	2.08E-06
LNIV	0.012333	0.011957	0.010915	0.036593	0.799224	0.006712	0.101673	0.000516	0.019632	6.92E-05	0.000373	1.99E-06	6.35E-07
LNIV(-1)	0.094313	0.007008	0.063253	0.163498	0.582252	0.039348	0.029615	0.005709	0.014721	1.15E-05	0.000269	1.58E-06	4.78E-07
LNH_V	0.000380	0.076365	0.034738	0.040955	0.010699	0.126826	0.031319	0.652871	0.019553	0.006189	9.60E-05	8.62E-06	8.05E-08
C	0.999973	2.62E-05	2.44E-08	3.04E-07	2.06E-07	1.22E-07	3.00E-08	8.80E-09	7.11E-12	4.01E-11	9.21E-10	8.36E-11	8.42E-11



Appendix B4. Parameter stability test.

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