Gas pipeline vandalism is a huge threat factor to steady electricity generation and energy materials flow in the power sector of Nigeria. It imposes huge cost of risk to that sector. Due to incessant pipeline vandalism, power availability is subject to elements of chance and with undesired out comes that adversely impact on power generation value chain. To this end, this study seeks to develop a model for estimating the cost of risk for a power generation company (Genco) and calculating plant unavailability indices by applying the dispersion technique. Applying the dispersion technique is innovative and differentiates the current methodology from other works on the subject area concerned. The probability and impact of failure alongside the variances and standard deviations of the parameters were derived. Cost to the Genco was obtained by multiplying fuel utilization ratio by unsupplied power and associated differential between price of electricity (output) and price of its primary fuel. Results showed that the lost megawatt hours (MWh) standard deviation, $\delta$, of the case study plant is 48,176.776 MWh. During the 2010 to 2012 periods, the resultant risk to the Genco was estimated to be ₦45,399 per MWh, ₦42,022 per MWh and ₦42,832 per MWh with the exchange rate as ₦150/$, ₦155/$ and ₦159/$ respectively. To bridge a research gap based on literature, total cost index and model have been developed for measurement of impact or loss suffered as a result of vandalism. Inclusion of reliability index in the algorithm is a novelty as it allows measurement of level of system performance and its vulnerability to
vandalization. The information will be of immense benefit to private investors in the power sector who have to make decisions over management of electricity generation in Nigeria based on imperfect information, following the privatization exercise.

Keyword: Energy

1. Introduction

In Nigeria, the transformative strategies being undertaken to increase electricity availability is facing a worrisome challenge by the recent upsurge in the events of gas pipeline vandalism. The unbundling of the power sector into generation, transmission, distribution and marketing was a leading transformative strategy in the sector. The other strategies include commissioning of independent power projects (IPPs) to generate electricity and to sell to bulk buyers. They will also see to the construction of four thermal power plants namely: Geregu 1&2, Alaoji, Papalanto and Omotosho with a combined capacity of 1234 MW and lastly, see to the implementation of the National Integrated Power Projects (NIPP). The generation companies (Gencos), transmission, distribution and marketing companies form the operators of the power sector network. This unbundling is intended to lead to a competitive business structure that encourages several companies with similar corporate objectives to operate in the same business arena. The arrangement disallows vertical monopoly and improves product quality. However, for the arrangement to be successful, the risks involved must be assessed and the costs of the attendant risks evaluated.

Useful insights to the definition of risk, techniques of its assessment and management could be obtained from these literatures [1, 2, 3, 4, 5, 6, 7, 8, 9]. According to Haimes [4], “universally agreed definition of risk has been difficult to develop”. He presented that “the risk modelling and analysis process cannot be performed correctly and effectively without relying on the states of the system being studied”. However, Aven [5, 10] challenged the perspectives of Haimes [4] on risk, vulnerability and resilience. He considered a system based approach to them as had been described by Haimes [4]. He noted that risk, vulnerability and resilience all incorporate the (probability) uncertainty dimension and then came up with an alternative approach which provides a logically defined structure for risk, vulnerability and resilience. But for this study, we simply refer to risk as an event that keeps electric power industry off-normal mode. It can be categorized as operational, external and strategic with different factors being responsible for them.

1.1. Sources of the risks

Despite the reform processes earlier mentioned, there are still issues that impact on the power value chain. These issues are sources of risk to the power system.
Reviewing statistics on Nigeria’s energy production, transmission and distribution chain, the following issues or events can easily be observed:

- Hybrid/hegemonic ownership structure-partly private generation (Gencos) and distribution companies (Discos) and partly government transmission companies (TCN)
- Obsolete power infrastructure with inadequate capacity
- Poor energy metering [11]
- Skewed power infrastructure location pattern leading to high power loss factor
- Lack of synergy between market operators (Gencos and Discos)
- Poor feasibility study of electricity utility (leading to preponderance of illegally connected or unaccounted users)
- Poor tariff system (arising from poor feasibility study)
- Gas supply disruption through pipeline vandalism.

Of all these issues, the gas supply disruption is the most devastating to the system.

Faced with these problems, electrical power generation in Nigeria is unreliable with many uncertainties and hazards that occur every day resulting in poor service to consumers. “Most of these problems also affect both government and private institutions” leading to their low performance [11]. The uncertain power situation poses risks to social, economic and technological development of the country. “The uncertainty is epistemic as it can be reduced” if more reliable information become available [12]. Recent studies have articulated these risks as burdens on the ecosystem linking them to climate change [13], poverty [14], national insecurity [15] and resource wastage. To the best of our knowledge, to date, none of the studies have provided a practical strategy for evaluating impact of pipeline vandalism on Gencos. It has been presented that reducing the frequency of vandalism can also lead to a reduction of anthropogenic emissions [16]. On account of the consequences of the highlighted risks, the power production chain deserves full investigation for the purpose of exposing the many risks that all stakeholders face. These risks deter access to benefits of unbundled electricity supply. In doing that investigation in this study, the expected opportunity losses (monetary, time, materials, power and manpower requirements) arising from uncertainties will be implied by total cost concept.

1.2. Current power production chain and level of risk

Electricity generation in Nigeria is dominated by hydropower and thermal supply systems. However, it is skewed to thermal based plants (oil and gas fueled) which make up over 81% of installed generating capacity and these are dependent on the availability of natural gas supply [17]. Steady gas supply is therefore central to achieving the goals of unbundled electric system in Nigeria. Natural gas
consumption growth is the fastest of the energy carriers [18]. It is inextricably linked to a reliable pipeline network as the safe mode of its distribution over long delivery distances. The oil and gas fuels for the thermal based plants are transported through a pipeline network, a situation that exposes generation to risks from changes in pipeline integrity particularly gas pipeline vandalism. Oil and gas pipeline vandalism is an illegal act of destroying or puncturing the pipelines [19]. From these statements, it can be said that the integrity of the gas pipeline occupies the first position in ensuring electricity availability. However, the major setback with the pipeline network is the high susceptibility to attribute failures either by deterioration or deliberate sabotage. It is subject to more risk than that of crude oil.

Pipeline vandalism, just like gas flaring, has insidious environmental, maintenance cost and energy implications for Nigeria [14, 20, 21]. Due to incessant pipeline vandalism, power availability is subject to elements of chance and with undesired outcome. It is difficult for power generation systems to meet customers’ expectation of power availability. Unfortunately, physical attacks on those pipeline facilities have continued to increase in the past decade and high foreign exchange rate has made replacement of damaged components difficult. A recent report [22] shows that in 2014 alone, “a total of 3,732 line breaks was reported on NNPC pipelines out of which 3,700 was as a result of vandalism, while 32 cases were due to system deterioration”. To put the consequence of the problem into perspective, Nigeria’s installed capacity is put at 8866 MW with calculated available capacity of 6149 MW (without considering pipeline vandalization). Based on the capability of the vandalization to bring power generation to zero output, it implies that for each vandalization, 1.66 MW of power is lost. For the Nigerian population size of 150 million, this translates to 41 W per capita power requirements being lost on account of gas pipeline vandalism.

Gas pipeline vandalism is generally more serious than breaks involving oil pipelines. It is classified to be external risk and ranked as high risk (factor) because its end effect is catastrophic. Unlike the liquid petroleum products, there is no import substitution option for lost gases. The resulting gas outage poses risks and real hazard to sustainable development as it has implications beyond power disruptions. The total cost, including the unsupplied energy wasted due to the damages, the costs of substituted equipment and also the idle time spent by the workers, culminate to losses due to the downtime of the electricity generation systems. Outage costs can be divided into three categories as: cost to a generation company, consumer and environment [23].

1.3. Literature survey

Studies about risk analysis of power generation in Nigeria are not easy to come by. Most of the studies have been about the rate of growth of power generation and
A study in 2016 [11] indicates Nigeria has 16 existing generating plants, with 13 as thermal and three as hydropower stations. This number if compared to the number of plants established by Act of Parliament in 1951 as cited in [24] shows that the Nigerian power sector has undergone some transformation. According to Adegbulugbe et al [25] as cited in [26], “total generation from installed capacity showed vigorous double-digit annual growth over the 1970s, with an average of 15.3% for the years 1973–1980. The growth slowed down in each of the next two decades to averages of 6.6% over 1981–1990 and 1.3% over 1991–2000”. Over the period 2001–2015, the rate of power generation growth was very insignificant compared to the growing demand as shown in Table 1. There was no significant investment in capacity expansion and equipment maintenance in the country’s electricity generating sector in the decade 1991–2000, resulting in low generation of electricity and low growth of installed capacity. This was traced principally to the monopoly owners’ (Government’s) inability to raise the required on-shore and off-shore funding. Another reason for the problem was their inability to “develop a clear and functional energy supply mix and the infrastructure for power delivery” [27]. As implied by [27], there was a mismatch between the ambitious policy initiatives to facilitate energy infrastructure development and cash flow in the power sector.

### Table 1. Installed and available Power Generation Capacity in Nigeria (2017).

| S/N | Plant              | Age (Years) | Type  | Installed Capacity (MW) | Available Capacity(MW) |
|-----|--------------------|-------------|-------|-------------------------|------------------------|
| 1   | Kainji             | 49          | Hydro | 760                     | 440                    |
| 2   | Sapele             | 38          | Gas   | 1020                    | 451                    |
| 3   | Afam IV-(V)        | 35-(15)     | Gas   | 726                     | 300                    |
| 4   | Jebba              | 32          | Hydro | 540                     | 540                    |
| 5   | Shiroro            | 27          | Hydro | 600                     | 600                    |
| 6   | Egbin              | 32          | Gas   | 1320                    | 994                    |
| 7   | Transcorp (Ughelli-Delta) | 25      | Gas   | 840                     | 650                    |
| 8   | Egbin ABS          | 17          | Gas   | 270                     | 270                    |
| 9   | Okpai              | 12          | Gas   | 480                     | 480                    |
| 10  | Omoku (I)          | 12          | Gas   | 150                     | 100                    |
| 11  | Geregu (I)         | 10          | Gas   | 414                     | 435                    |
| 12  | Geregu (II)        | 4           | Gas   | 434                     | 414                    |
| 13  | Omotosho           | 12          | Gas   | 336                     | 80                     |
| 14  | Ibom Power         | 8           | Gas   | 190                     | 90                     |
| 15  | Olorunsogo (I)     | 4           | Gas   | 336                     | 80                     |
| 16  | Alaoji             | 5           | Gas   | 450                     | 225                    |

Total 8866 6149

Compiled 2017. Source: Authors Survey adapted and modified from the National Bureau of Statistics’ data (http://www.nigerianstat.gov.ng/).
sector. As a way forward, the power sector unbundling, privatization and deregulation strategy was introduced. The unbundling entailed a change in the power infrastructure ownership and management structure from being public sector to private-sector driven. The unbundling strategy is not entirely free of hazards, it is susceptible to a high proportion of risks.

Quite some researches have been done in the area of risk analysis but more of the risk analyses carried out so far in the study area are qualitative. But, quantitative approach is more objective and accurate [3, 28] and is adapted in this study. This quantification constitutes a fundamental point when designing risk management strategies [29]. Mullet et al. [30] studied risk perceptions accessed for health and environmental bases relating to specific energy domains (fossil, nuclear, hydraulic and natural wood). Sun et al. [31] quantified the impact of electric power outages on GDP by using Cobb-Douglas production function. Wallnerstrom et al. [32] studied risk and reliability assessment for electrical distribution systems focusing on outages to the customer. Findings from the literature so far show that inadequate power generation predisposes people to burn fuels in inefficient devices. For this reason Smith et al. [33] maintain that lack of access to clean fuels and electricity in the world’s poor households is a particularly source of serious health risk. In contrast, there was not a very high degree of concern regarding the electrical energy transportation domain [34]. We are not aware of any work in the literature that quantitatively evaluated the cost imposed on unbundled electric power generation chain by risk of pipeline vandalism. The degree of diversity and indices of vulnerability of the Gencos to these outlined risks have not been determined and quantitatively addressed in studied research work. This study hopes to close the gap by quantifying the vulnerability, risk and costs involved in order to assist possible investors in making quick decisions.

As power generation companies seek certainty of costs and revenues and such activities, according to [35], they will require the quantifying, monitoring and controlling of trade risks in the wholesale and retail power markets. The main purpose of this study is to determine the total cost of risk on generation of electricity in Nigeria due to vandalism. The specific objectives include estimating total cost index and developing a model to quantitatively measure impact or loss to a power generation company (Genco), calculating plant unavailability index and determining appropriate risk mitigation measures to enhance sustainable steady power delivery. The development of a set of algorithm that accounts for impact of vandalism on Gencos is a novelty of this work from the perspective of the research area concerned. On the basis of information obtained, the reliability of the power generation system can be predicted. Successful implementation of the strategy would ensure sound management decisions without disproportionate spending on power production chain. This study will benefit any country with similar situations in her power sector in reducing cost of production, improving productivity and enabling economic growth.
in the long run. This is because the model will be useful in determination of expected value of economic loss coefficient involved in analyzing likelihood and consequence of plant failure events. Lastly, this study, to the knowledge of the authors, is the first quantitative study on pipeline vandalization in Nigeria and will provide background information to future researchers.

2. Methodology

In order to carry out this research work, plant-walk through and survey covering Sapele Power Generating Station Plc (in Delta State of Nigeria) as a case study were employed. Data collection, collation and analysis were carried out. Data collection for this research work was done using well-structured questionnaires and personnel interviews. Primary data for this research work were collected, which included power generation performance (installed capacity, available capacity, total expected power generation, delivered energy, total gas consumption), pipeline vandalization records, nominal hours of gas unavailability, generation reliability data, employee statistics, income/cost structure, plant maintenance records. Hence, the data for gas supply during 2010—2012 to the plant were obtained and information regarding frequency and duration of pipeline vandalization events were extracted.

Occurrence of pipeline vandalism event is unpredictable. Estimating the likelihood or probability of its occurrence and thus time were undertaken on the basis of data from questionnaires, while the rating of risk factors was based on personnel interviews (ranged from low, medium and high rating), which reduces subjectivity by non-operators or experts. According to the interviewees’ opinions, gas pipeline vandalism was the highest threat factor to steady power generation and energy material flows. The experts deduced their decisions on risk factors from assessment of the severity (catastrophic, critical, minor, etc.) of events. In this study, probability is expressed as a quotient of number of monthly outcomes of events over total number of outcomes of vandalization in the periods. So given the daily pipeline vandalism events, this study summed them according to month and annual records. Then, monthly probabilities of occurrence as fraction of the total sum was worked out within the time span under consideration. Also, in order to understand the relations between energy units, gram of oil equivalent conversion factor for natural gas (1 kWh is equal to 77 gram of oil equivalent) is applied. A probabilistic risk assessment model was used to look at the frequency and consequences of not achieving a normal mode working condition for the plant which differed in value each time vandalization event occurred. With lack of uniformity observed in the magnitude of outcomes of the vandalization, the dispersion approach was found suitable for studying this problem in order to measure the diversity. Inclusion of dispersion approach is innovative and differentiates the current methodology from other works on the subject area concerned. This is the area under discussion in subsection 2.1.
2.1. Dispersion outcome approach

Dispersion represents the extent of the variability in individual events. There are two main types, namely absolute and relative dispersion. The absolute type of dispersion was determined by methods of variance and standard deviation about the mean value. The absolute was preferred to relative type because it is better and is usually “expressed in the same unit as the original data of the series” [36]. However, relative dispersion is expressed as a ratio or percentage such as coefficient of variation. Being dimensionless, it offers the researcher an opportunity to compare other probability distributions with different means. The next stage in using dispersion is to assign scale to the events. Following those procedures, we applied the probability distribution function to evaluate the hazards of pipeline vandalization. In this study, the probability distribution is considered discrete and random, so a particular probability of occurrence is associated with each outcome. For a given outcome, information is needed concerning the payoff: loss or profit associated with it. The determination of risk requires the knowledge of the probability of a natural hazard event and its associated intensity, as well as the damage potential (vulnerability) which is site and object specific [12]. Having identified the risk factors, the risk mitigation strategies were suggested. The basis used for suggesting risk mitigation strategies include the effects of a strategy on energy price (tariff) and its ability to encourage investment in low carbon technology options. The latter point will create an incentive for Gencos to invest in new generation capacity instead of relying on old installations.

2.2. Calculations

Having identified and categorized risks, we proceeded to quantitatively assess the probability and consequence. Economic losses associated with gas pipeline disruption can be estimated by quantifying the monetary value of lost gases and the cost of energy lost or unsupplied by a generating company as expressed in this study. The quantity of gas not supplied is obtained as a product of the rate of supply of gas and the nominal hours of gas unavailability. Some risk indices of importance include:

(i) The labour requirement per unit of energy output, given in Eq. (1). It measures the occupational hazards to which the workers would have been exposed had they been doing something else including being unemployed [37].

\[
\text{labour intensity} = \frac{\text{labour requirement}}{\text{energy output}}
\]  

(ii) Fuel utilization ratio. This is expressed as in Eq. (2)
\[ F_{ur} = \frac{G_{con} \times j}{E_{igen}} \]  

(2)

where \( F_{ur} \) is the fuel utilization ratio, \( G_{con} \) is the volume of gas consumed (MM\(^3\)), \( E_{igen} \) is the total energy generated (MWh), \( j \) is a conversion factor (MWh/scf), scf is standard cubic feet, and MWh means megawatt hour.

Note, in the natural gas industry, one standard cubic foot of natural gas (at 14.73 psi and 60 °F) equals 0.0283058557 standard cubic meters (at 101.325 kPa and 15 °C).

(iii) Reliability of the power generation value chain

The major concern is about the reliability of the power generation value chain evaluated through relevant indices as expressed in Eqs. (1), (2), (3), (4), (5), (6), (7), and (8).

\[ \text{collapse per hour} = \frac{\text{number of collapses}}{\text{operating hours}} \]  

(3)

The amount of lost or unsupplied power during pipeline damage can be calculated as expressed in Eq. (4). Also some key performance parameters for the plant, which can influence decisions, have been calculated and are presented in Table 2.

\[ \pi_i = \frac{G_{fr} \times V_{di} \times 1kWh}{\text{kgoe}} \]  

(4)

where \( \pi_i \) is the level of lost or unsupplied power per month associated with \( i^{th} \) outcome or \( V_{di}, G_{fr} \) is gas flow rate for the power plant (MSCFD). MSCFD

| Table 2. Some calculated parameters used for 2010 total cost calculations. |
|-----------------------------|-----------------|-----------------|-----------------|
| Month (2010) | \( \beta \) (MM\(^3\)) | \( \text{\$/Elect} \) | \( \Phi \) (MW/MM\(^3\)) | Fuel Ut. ratio |
|-----------------------------|-----------------|-----------------|-----------------|
| Jan. | .0149 | 3687.04 | 0.0771 | 3.604\( \times 10^{-4} \) |
| Mar. | .0061 | 1532.14 | 0.0813 | 3.416\( \times 10^{-4} \) |
| Apr. | .0167 | 4612.55 | 0.0892 | 3.416\( \times 10^{-4} \) |
| May | .0142 | 3807.00 | 0.0870 | 3.114\( \times 10^{-4} \) |
| Jun. | .0208 | 6535.73 | 0.1018 | 3.194\( \times 10^{-4} \) |
| Jul. | .0208 | 6535.73 | 0.1018 | 2.73\( \times 10^{-4} \) |
| Aug. | .0220 | 6535.73 | 0.0966 | 2.73\( \times 10^{-4} \) |
| Sept. | .0112 | 2961.79 | 0.0950 | 2.878\( \times 10^{-4} \) |
| Oct. | .0226 | 4133.01 | 0.0591 | 2.927\( \times 10^{-4} \) |
| Nov. | .045 | 15328.7 | 0.1105 | 4.70\( \times 10^{-4} \) |
| Dec. | .045 | 15648.7 | 0.0878 | 2.516\( \times 10^{-4} \) |

MM\(^3\) = million cubic meter, \( \text{\$} = \) Nigerian currency, the naira.
means million standard cubic feet per day, $V_{di}$ is duration of vandalism hours in each month, kgoe is kilogram of oil equivalent, kWh is kilowatt hour and MW is megawatt. Note the $G_{fe}$ for the plant is 43 tons per hour.

Regarding the scale of the risk, the likelihood score was interpreted using probability of failure. In this study, two dimensions of risks are: likelihood and impact. The likelihood, $P$, is derived from uncertainty of risk occurrence. Impact, $I$, is the effect of the contingency. Thus, “Likelihood of an event refers to a quantitative measurement of occurrence, which is expressed either as frequency (i.e., rate of event occurrence in unit time) or probability (i.e., the chance of event to occur in defined conditions) of occurrences” [38]. Therefore, risk, $R$, is given as the product of the size of the impact and likelihood.

$$R = I \times P$$ \hspace{1cm} (5)

It is also given by Benjamin et al [8] as

$$R = P(A) \times C$$ \hspace{1cm} (6)

$P(A)$ is the probability of an event $A$ to occur and $C$ is the corresponding consequence of an event. $P(A)$ is further defined from theoretical background thus: if a situation occurs a large number of times say, $S$, and if an outcome, $A$, occurs $w$ times, the probability of the event $A$ is expressed as follows:

$$P(A) = \frac{w}{S}$$ \hspace{1cm} (7)

Where $w(A)$ is the quantity of resource in the $i$th outcome. A probabilistic property of Eq. (7) is that $P(A)$ will always be a value greater than or equal to 0 and less than or equal to 1, mathematically expressed by [39] as

$$0 \leq P(A) \leq 1$$ \hspace{1cm} (8)

This understanding can be extended to pipeline vandalism, where $P(A)$ represents simple probability percentage loss accountable to vandalism. For $N$ independent events, the probability $P(A_N)$ is the probability of occurrence of event $A$ for $N$ times. If those events are mutually exclusive, their probabilities are additive. In line with the above for a discrete variable, we calculate an expected value as weighted average of the variable outcomes. The product of the probabilities and expected impact or opportunity loss of the outcomes can be summed over all the events in order to express the mean unsupplied power as in Eq. (9):

$$E(\pi) = \sum_{i=1}^{N} \pi_i P(\pi_i)$$ \hspace{1cm} (9)

where $E(\pi)$ is the mean value of unsupplied power (MWh).
The occurrences of vandalization events are independent because occurrence of one event has no impact on another event. Since each outcome is being weighted by its probability of occurrence, probability value in Eq. (9) says the same thing as Eq. (7). The relationship of the power system unavailability with reliability is expressed in Eq. (10) [39]. It measures the ability of the system to incur or avoid failure.

\[ R(t) = e^{- \sum_{j=1}^{K} FOR_j t_j} \]  

(10)

where \( K \) denotes the total number of months for the period, \( R(t) \) is the reliability function and \( t \) represents the disruption time of pipeline.

The generating plant unit unavailability is estimated after calculating the ratio of expected failure rate (frequency of failure), \( \lambda \), to expected repair rate, \( \mu \) (related to pipeline downtime duration). This is the probability of the unit being on forced outage rate (FOR) or unavailability at some time in the future [40] expressed in Eq. (11):

\[ FOR = \frac{\lambda}{\lambda + \mu} \]  

(11)

(iv) The net electrical energy output (in MWh)

The net electrical energy output (production), \( E_{net} \), given each amount per number of pipeline breakdown is calculated as in Eq. (12)

\[ E_{net} = \sum_{i=1}^{N} E_T - w(A_i)P(A_i) \]  

(12)

where \( E_T \) is level of electricity output (MWh) and \( P(A_i) \) is the probability of \( i \)th outcome.

To obtain variance of the expected impact or opportunity loss for a discrete outcome, we recall Eq. (9). Next step is to subtract this expected value from each possible outcome in Eq. (4) and the resulting squared deviations multiplied by associated probabilities. The products are then summed as expressed in Eq. (13) and is the variance of the deviations, \( \delta^2 \).

\[ \delta^2 = \sum_{i=1}^{N} [\pi_i - E(\pi)]^2 P(\pi) \]  

(13)

To obtain the standard deviation, we simply take the square root of Eq. (13). The standard deviation, \( \delta \), is determined as a useful measure of risk to the Genco in Eq. (14).
\[ \delta = \sqrt{\sum_{i=1}^{N} \left[ \pi_i - E(\pi) \right]^2 P(\pi)_i} \]  

(14)

(v) Capacity utilization

\[ C_u = \frac{C_a}{C_i} \]  

(15)

Where \( C_u \) is the capacity utilization, \( C_a \) is the available capacity and \( C_i \) denotes installed capacity.

2.3. The cost to the power generation company (Genco) due to gas pipeline vandalism

The total cost model was formulated and economic losses associated with the events were estimated by quantifying the monetary value of lost gases and the cost of energy lost or unsupplied by a generating company.

For data availability, this study calculates the cost to the Genco, \( C_{genco} \), which is mainly: lost sales less cost of gas not supplied plus cost of salaries and overhead, \( C_{so} \), incurred in spite of no electricity generation. It does not include cost of alternative fuel used (if any). The fuel costs are based upon market worth of the wasted natural gas and idle labour. Although, a survey [41] indicates that the current Nigerian’s gas-to-power pricing benchmark is 2.8 times lower than the Henry Hub United States’ standard of $7.00 per million cubic feet (MCF), yet the total cost of lost gases due to vandalism maintains a high proportion. Cost of repair of pipelines is borne by Nigerian Gas Company (NGC). NGC is responsible for the supply of gas to all generation companies.

To obtain the amount of natural gas lost, fuel utilization ratio is multiplied by unsupplied power due to vandalism. The ratio method approximates the volume of natural gas for generating 1 MWh in the plant utilizing natural gas and heat rate (efficiency) of power plant. The significance of this method is that it captures in reality weather effects on the plant and heat rate, which are site specific. The drawback of the ratio method is that historical data should be available for its applicability. Therefore, the \( C_{genco} \) can be obtained as the product of differential between price of electricity (output) and price of its primary fuel and the lost volume of gas as expressed in Eq. (16).

\[ C_{genco} = \beta((\theta \phi + C_{so}) - \rho) \]  

(16)

where \( \beta \) represents gas not supplied (Mscf), \( \theta \) is the energy output (kWh/Mscf), \( \rho \) is naira cost of gas (₦/Mscf), \( \phi \) denotes sale of 1 kWh (₦/kWh) and Mscf is million standard cubic feet.
We can express the cost of salaries/overhead and man-hour goal as in Eqs. (17) and (18) respectively.

\[
C_{so} = M_h \times V_d
\]  

(17)

\[
M_h = \frac{M_{goal}}{P_{man}}
\]  

(18)

where \(M_h\) is naira per man-hour goal, \(M_{goal}\) is month-end goal, \(V_d\) is lost man-hours of no generation and \(P_{man}\) is production man hours per month.

3. Results and discussion

The estimation of the cost of risks was based on computed relevant performance indicators. The calculated results of key performance measures for the power plant, which can influence decisions, have been presented in Table 2. In 2010, a total of 0.2452\(\times 10^3\) natural gas was lost because of vandalization of pipeline for 61 lost hours for this plant. This implies that \(4.01967 \times 10^{-3}\) \(\times 10^3\) MM\(^3\) was lost per hour. Using three regimes of gas-to-power pricing of \$1.00 per MCF, \$1.50 per MCF and \$1.80 per MCF for 2010, 2011 and 2012, respectively [42] alongside Eqs. (16), (17), and (18), the total cost of lost gases for the period 2010, 2011 and 2012 is estimated as shown in Table 3. To show the trend of the losses, the data of the cost of lost gases due to vandalism is plotted for the year 2010 (Fig. 1). The increase in vandalism experienced in the fourth quarter of the year could be linked to a social problem. Periods of festivities have been linked to increased vandalization of oil and gas

Table 3. Total cost of lost gases due to vandalism.

| Month | 2010 \(\times 10^6\) | 2011 \(\times 10^6\) | 2012 \(\times 10^6\) |
|-------|---------------------|---------------------|---------------------|
| Jan.  | 52.700              | 51.47               | 50.69               |
| Mar.  | 8.4310              | 7.920               | 7.610               |
| Apr.  | 74.524              | 73.14               | 72.28               |
| May   | 51.929              | 50.75               | 50.02               |
| Jun.  | 132.823             | 131.10              | 130.02              |
| Jul.  | 132.823             | 131.10              | 130.02              |
| Aug.  | 140.486             | 138.67              | 137.52              |
| Sept. | 31.492              | 30.56               | 29.98               |
| Oct.  | 90.016              | 88.15               | 86.97               |
| Nov.  | 683.041             | 679.32              | 676.99              |
| Dec.  | 788.894             | 693.73              | 691.40              |
| Total | 2,187.156           | 2,024.44            | 2,063.5             |
| Naira (₦)/$ rate | 150/1$           | 155/1 $            | 158/1 $             |

https://doi.org/10.1016/j.heliyon.2018.e00702
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pipelines. Towards the end of each year, the urge to make money for the unattended needs drives oil and gas theft.

Examination of recent incidences of vandalism and impact on gas supply and power generation records for the case study electric power plant, Sapele Power Generating Station Plc, revealed a rise in the frequency of pipeline breakdown from yearly records of 20, 33 to 45 in 2010, 2011 and 2012 respectively.

The disruption of gas supply affects operating capacity and ultimately, the revenue yield from sale of electricity, as well as increases cost of maintenance. High profile revenue loss has implications on payback period for power projects and thus discourages further investments in gas infrastructure. In analyzing the risks, two annual probability distributions, failure and expected repair rates due vandalization were estimated using the frequency of occurrence and duration of pipeline downtime data respectively.

For the period under consideration (2010), the actual average capacity utilization index was 14.30% compared to targeted capacity of 50% as shown in Fig. 2. Two inferences can be drawn from Fig. 2: first is the inconsistent energy use effectiveness and second is that the generation performances over the period were abysmally low. These observations therefore, indicate that continued ability of the electric power industry to satisfy electricity requirements is in jeopardy. Correlating this capacity utilization index with staff productivity, it was observed that productivity index decreased by 43.4 % from targeted value of 174.32 MW per head. The current low human capital coefficient of 98.61 MW per head is advantageous from the perspective of employment for a country with high unemployment rate. In another perspective, the two performance indicators have revealed that the impact of gas pipeline vandalism can lead to low productivity and huge overhead cost on the unbundled electric power systems. It is generally agreed that the riskiness of a given decision is directly related to the extent of the dispersion of the probability distribution of losses resulting from a decision [43].
The lost MWh standard deviation, \( \sigma \), of the case study plant as calculated from Eq. (14) is 48,176.776 MWh. The realized value of standard deviation indicates how off-centered the series of lost MWh power is from the mean value [44]. This resultant risk value is large and amounts to unserved electricity. From Table 3, total cost of gas lost to vandalism stood at ₦2,187,161,000.00; ₦2,024,440,000.00 and ₦2,063,500,000.00 respectively. Applying the above mentioned unserved electricity (output), the total cost of risk per output for the Genco was estimated to be ₦45,399 per MWh, ₦42,022 per MWh and ₦42,832 per MWh for the periods. The total cost of risk is affected by the exchange rate. The criticality of the effect can be seen on inspection of Table 3. Thus, for countries relying heavily on imported power machinery such as Nigeria, the lack of foreign exchange adversely affects support for such investments that generate economic growth.

The result of FOR calculations revealed that the plant has an average value of 0.72 due to vandalism, implying that vandalization of gas pipeline is a major risk factor. As outage rate is one of the main factors for ranking power plants, high FOR value impacts on the reliability of the power production chain. If the pipeline vandalism incident rate is reduced, power generation has good prospects since new power stations run on Open Cycle Gas Turbine Plants (OCGT). Old plants are being decommissioned and re-commissioned with OCGT, for example, Transcorp commissioned 110 MW OCGT in March 2017, thus raising its available capacity to 650 MW from previously 540 MW.

By examining Fig. 2, it could be seen that there is the risk of bankruptcy due to inadequate capacity utilization or production capacity below break-even point. The studied plant adopted a break-even point of 50% of installed capacity but the result above showed that the actual average capacity utilization index was 3.5 times below the benchmark. The foregoing statements suggest the possibility of the plant to have

![Fig. 2. Plant capacity utilization index.](https://doi.org/10.1016/j.heliyon.2018.e00702)
low reliability. This assertion, if corroborated with high unavailability as indicated in Fig. 3, then the total cost of pipeline vandalism on unbundled electric power system is enormous with potential for adverse consequences. This has implications for Nigeria, where recession induced by the fallen oil prices does not only reduce the capacity to import but also limits expansion of gas infrastructure. According to Eydeland and Wolyniec [45], forced outages have an impact on value of plant because it limits the total amount of energy available from a unit. Hence, it can have a substantial impact on the risk profile of the unit’s cash flow. For the period being considered, the systems reliability is 0.4867 and it means there is 48.67% chance that the power plant will not fail or be at service state if there is pipeline vandalization.

The theoretical implications of the gas pipeline vandalism to electric power production chain situation in Nigeria are significant to risk management and its costs appraisal. The above risk indices are indications of the level of vulnerability to which the plants are exposed. With higher scores representing indicators that pipeline vandalism is more influential in determining likelihood or consequence [46] of risks posed to power generation. For example, Fig. 3 indicates the degree of unavailability of the generation plant due to vandalism over the study period.

In Fig. 3, the spike between March and April 2011 was as a result of prolonged downtime of gas infrastructure. Since greater impact of vandalism depends on length of the interval of pipeline downtime, more spikes per year have the potential to stimulate request for tariff changes on account of power output in order for Gencos to realize marginal cost. The above statement is in agreement with the work of Tafreshi et al. [40] that the Genco maximizes its own profit based on generation level. Frequent and prolonged pipeline down time predisposes the production chain as a whole to behave as a stochastic unit. Stochastic units are those units whose production is variable and uncertain [47].

Similarities between the trends of Figs. 1, 2, and 3 show the link between the parameters: cost of lost gases, plant capacity utilization and forced outage rate. It has been

![Fig. 3. Forced outage rate per month.](image-url)
shown that the trends are all as a result of pipeline vandalism. The findings from this study have been discussed with a view to suggesting suitable mitigation measures.

4. Conclusions

The methods of plant walk-through and questionnaires for acquisition of data as well as likelihood and consequence based on dispersion approach for the cost estimation have been used for the study. The total cost of risks of gas pipeline vandalism imposed on electric power generation companies has been estimated and a model to quantitatively measure the impact of vandalism or loss to a power generation company (Genco) has also been developed. The cost index and the model have shown that the total cost of lost gases due to vandalism maintains a high proportion of the cost. The $C_{genco}$ has been obtained as the product of differential between price of electricity (output) and price of its primary fuel and the lost volume of gas. It has been shown that on the basis of information obtained from the model, the reliability of the power generation system can be predicted.

Based on the results and discussion in the text, the following deductions could be made:

- The dispersion approach is a suitable and practical strategy for evaluating the impact of pipeline vandalism on Gencos.
- The three tiers of the unbundled power production chains and delivery are seriously affected as the damage occurs and natural gas is released and wasted.
- The distortion of the integrity of gas pipeline imposes a huge cost on the Gencos and this has negative impact on their performance as well as on the cost competitiveness of power output.
- One of the consequences of these risks on the electric power value chain is the ability to trigger off quest for recalculation of electricity tariff by system operators.
- Another source of risk, i.e. the payments risk, which all the network operators are susceptible to, has been exposed.
- Following the severe lost opportunity costs (pay-off) on power generation, maintaining the integrity of gas pipeline is of utmost important for profitable unbundled electric power systems.

4.1. Recommendations

Having established the fact that pipeline vandalism maintains a high proportion of the cost of power generation in Nigeria and is a major risk factor, strong mitigation measures are required to help reduce both the probability and consequence of vandalism. Since unavailability of natural gas has been identified as a critical
impact from pipeline disruption on Nigeria’s unbundled electric power systems, there is need for interconnected links between the gas feeder lines as defensive measure for emergency situations. This cross area pipeline link will increase gas availability at the moment of a break or disruption on a major feeder line.

Vandalization is a human problem and hence a consideration to increase the level of awareness of the gravity of the effects of vandalism needs to be made to the public. Use of enlightenment campaigns on the effects of vandalism is recommended in this study. Maintaining effective security against vandalism through improved information gathering capability (unmanned aerial vehicles), good relationship with the local community and employment of security outfits can significantly decrease pipeline vandalism.

Beyond the policy level, further research work should be continued particularly in the tariff modelling and gas inventory for the generating companies. Finally, it is recommended that the payment risk, as it affects the whole power network operators, be further researched into.

Declarations

Author contribution statement

Stephen Nwanya: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Charles Ezeoke: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Chigbo Mgbeemene, Onwuamaez Iloeje: Analyzed and interpreted the data; Wrote the paper.

Competing interest statement

The authors declare no conflict of interest.

Funding statement

The authors received no funding from external an external source.

Additional information

No additional information is available for this paper.
Acknowledgements

We express our profound gratitude to the project students, who generated some of the data, and to the companies that provided some data and other information related to this study. We also gratefully acknowledge the anonymous reviewers for their comments which have improved quality of the work.

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