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# Blockchain-Based Gas Auctioning Coupled with a Novel Economic Dispatch Formulation for Gas-Deficient Thermal Plants

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**Abstract:** Inadequate gas supply is partly responsible for the energy shortfall experienced in some energy-poor nations. Favorable market conditions would boost investment in the gas supply sector; hence, we propose a blockchain-based fair, transparent, and secure gas trading scheme that facilitates peer-to-peer trading of gas. The scheme is developed using an Ethereum-based smart contract that receives offers from gas suppliers and bid(s) from the thermal plant operator. Giving priority to the cheapest offers, the smart contract determines the winning suppliers. This paper also proposes an economic dispatch model for gas-deficient plants. Conventional economic dispatch seeks to satisfy electric load demand whilst minimizing the total gas cost of generating units. Implicit in its formulation is the assumption that gas supply to generating units is sufficient to satisfy available demand. In energy poor nations, this is hardly the case as there is often inadequate gas supply and conventional economic dispatch is of little practical value. The proposed economic dispatch model's objective function maximizes the quantity of available gas and determines the optimal power output of each generating unit. The mathematical formulation is verified using data from the Egbin thermal station which is the largest thermal station in Nigeria and is solved using the General Algebraic Modeling System (GAMS). Obtained results indicate the viability of the novel approach as it results in a net power gain of 35 MW. On the other hand, the smart contract proved effective in accurately selecting winning suppliers and making payment.

**Keywords:** economic dispatch; GAMS; blockchain; Ethereum; smart contract

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## 1. Introduction

Despite the global drive to curb emissions, some energy-poor nations will need many years to make the shift from fossil gas-based energy sources to cleaner sources. A country like Nigeria, for instance, will likely remain heavily dependent on thermal units for a while, making research focused on such units worthwhile. Unlike nuclear and hydro plants, the operating cost of thermal units varies significantly with power output, and gas cost constitutes a major portion of this operating cost. The input/output (I/O) characteristic of a thermal unit relates its gas consumption to its power output, and this may vary among thermal units as a result of differing operating temperature, age of equipment [1], manufacturer's design etc. This disparity in I/O characteristics gives rise to the need to economically dispatch thermal units. Economic dispatch (ED) distributes demand among all online generating units, whilst minimizing operation cost [2]. Many ED formulations and solution methodologies have been reported in literature [3–7], but most assume the availability of sufficient gas supply. This is not the case with some major power stations in Nigeria. For a station experiencing gas supply shortfall, tradition ED formulations and algorithms fail. The lamentable state of electricity supply in Nigeria is partly due to inadequate gas supply to thermal plants. Aside from the fact that the total installed generating capacity is incommensurate to the country's total demand, inadequate gas supply makes it impracticable to get the most out of the available generating capacity. To salvage the situation, we propose an ED model aimed at maximizing the available quantity of gas. Whereas the input/output (I/O) characteristics of thermal units are used to perform conventional ED, the proposed model requires the O/I characteristics of the units. An unconstrained optimization problem is first formulated to estimate the coefficients of the O/I characteristic curves which are then used to build the model. The model seeks to maximize available gas. Furthermore, we propose a blockchain-based transparent, secure gas market. This creates a fair market for gas suppliers which would encourage an influx of suppliers, thereby boosting gas availability. The advent of smart contracts underpinned by blockchain technology has resulted in significant advancement in peer-to-peer (P2P) transactions. Without third-party involvement, credible P2P transactions can be made with the aid of blockchain-based smart contracts [8]. Consequently, researchers from various fields are investigating possible applications of blockchain in their respective domains. The energy sector is also being disrupted by blockchain technology. For instance, P2P energy trading can be facilitated by the technology. Blockchain-based smart contracts can be employed to execute energy trading and payment rules [8]. The Brooklyn microgrid is a New York City-based mini-energy market which uses blockchain to facilitate surplus solar energy trading between prosumers and neighbors. The Pebbles project is another blockchain-based digital platform for P2P energy trading [9]. Similarly, Power Ledger has a platform that facilitates P2P energy trading and traceability [10]. In [11], a blockchain-based energy trading scheme that ensures demand/supply balance whilst protecting consumers' information is proposed. In blockchain-based P2P networks, consumer privacy can be preserved despite transactions being public [12]. The authors of [13] developed a framework for P2P energy transaction that suitable for Industrial Internet of Things (IIOT) transaction scenarios. Smart contracts can improve security and fairness in energy trading [8]. Another energy trading framework that employs blockchain is also proposed in [14], and a double layered energy trading platform based on blockchain is developed in [15]. In addition to energy trading, the authors of [16] have incorporated carbon allowance trading using blockchain. The technology is also being explored for use in energy management [17,18]. Some other research articles in blockchain-based energy transactions are reported in Table 1.

Storage sharing is another emerging area of application of blockchains. The work presented in [23] explores blockchain-based storage sharing. In the paper, a smart contract-based scheme is proposed to enable storage sharing among power grid entities. Of particular interest in this study is the employment of smart contracts to automate auction procedures. In [8,16,24], auction procedures were performed by smart contracts. Their transparency and auditability make them appropriate to handle such procedures.

Among the benefits of incorporating blockchain technology in different energy-related fields, some of which have been highlighted in the foregoing research works, the decentralized nature of blockchains is one of its key strengths. However, most real-world blockchain applications involve the use of off-chain data that are sourced from traditionally centralized entities, which undermines the advantages of decentralization. The lack of trust from such sources inhibits the full realization of many potential blockchain use cases [25]. These sources of off-chain data have been termed "oracles". Oracles provide blockchains with real-world data [26]. To decentralize oracle-based systems, data from multiple oracles are validated using a consensus mechanism [27]. In the energy industry, Power Ledger employs decentralized oracles to obtain real world power meter readings.

**Table 1.** Objective, blockchain platform, and findings of selected articles.

| Ref. | Objective | Blockchain Platform | Findings |
| --- | --- | --- | --- |
| [8] | With a focus on retail electricity markets, a generic blockchain framework that enables P2P trading | Ethereum private chain | Transactions between multiple players using the platform was observed to be potentially efficient and effective. |
| [16] | Energy and carbon allowance trading framework facilitated by a P2P blockchain-based framework | Ethereum | With regards to carbon emissions and energy management, the proposed scheme outperforms centralised as well as aggregator-based trading. |
| [19] | Comparison of auction mechanisms. A blockchain-based trading network | Hyperledger Fabric | The results of the price-only game-theoretical bidding strategy were almost ideal in economic efficiency irrespective of the auction mechanism. |
| [20] | Novel approaches to ascertaining the trading preferences of participants within a P2P energy market | Hyperledger Fabric | With the proposed novel strategies, P2P trading peers spent less in procuring energy, compared to a baseline case. |
| [21] | Blokchain-based P2P trading platform design | Ethereum | Customers who are distant apart could employ the proposed platform to carry out successful P2P transactions. |
| [22] | Blockchain-based hybrid P2P energy market implementation | Ethereum | A reduction in consumers' electricity cost was achieved. |

In this paper, we employ blockchain via a smart contract to facilitate P2P gas trading. Gas suppliers submit their offers to the smart contract. Similarly, the thermal plant operator makes a bid for gas to the smart contract. The winning suppliers are determined by the smart contract, which also receives payment from the plant operator and pays the suppliers after gas delivery is ascertained. Since the transactions via the smart contract are stored and executed on a public blockchain, they can be easily viewed and therefore audited.

In summary, we propose: (1) an economic power dispatch model aimed at maximizing the available quantity of gas. This entails the computation of O/I characteristic coefficients for thermal units for use in the proposed economic dispatch formulation. Optimal power generation schedules are then obtained by solving the proposed formulation (an optimization problem) and compared to actual power schedules. (2) A blockchain-based P2P transparent gas marketplace. The paper focuses only on the smart contract development; the complete architecture needed for the actualization of the entire scheme is out of the scope of this study. The smart contract is programmed on a browser-based application (Remix IDE) and its various functions are manually triggered.

## 2. Smart Contract-Based P2P Gas Trading

Subsequent to the remarkable success recorded by Bitcoin, blockchain technology has garnered public attention. A blockchain is made up of blocks of P2P transaction records that are cryptographically merged in a chronological manner. The ledger is distributed among key peers on a blockchain network, and sophisticated mechanisms are used to reach consensus. The technology relies heavily on cryptography for its operation and security. Following the Bitcoin invention which was particularly intended to serve a cryptocurrency, smart contract technology emerged. The advent of smart contracts has paved the way for a wide range of industries to harness blockchain. Based on arbitrary pre-defined rules, smart contracts can move digital assets between peers within a blockchain network [28]. A smart contract is a piece of code that can be used to represent rules or conditions on a blockchain. It is stored and executed on the blockchain in a decentralized manner, without involving third parties. Smart contracts are written using specific programming languages depending on the blockchain they intended for. The Ethereum blockchain, for instance, houses smart contracts written in either Solidity or Vyper.

Figure 1 shows the proposed system architecture for the smart contract-based P2P gas trading scheme including decentralized oracles. However, the paper focuses on the smart contract development alone. The scheme entails gas suppliers sending their offers (in terms of amount and price) to a smart contract (represented by the space enclosed by the bold line) and the thermal plant operator sending their demand to the contract. The smart contract selects suppliers to fill the order of the operator, giving priority to the cheapest offers. As a result, the operator is assured of getting gas supply at the best prices. The contract also receives payment from the plant operator. To tackle the problem of oracle centralization, a decentralized oracle mechanism is proposed [27]. The gas supplier facility, power plant gas inlet, and outgoing power feeder are each equipped with smart meters. It is supposed that, for the smart power meter which records energy at the outgoing feeder, the amount of gas required to generate the recorded energy can be deduced. Hence, similar gas readings are expected from the three meters. In this context, the smart meters are the oracles, the use of which emulates the decentralization of blockchains off-chain. The readings are validated via a consensus mechanism to confirm gas delivery, after which they are sent to the smart contract, then payment to the suppliers is initiated. This decentralized oracle system makes it difficult for a bad actor to tamper with gas supply/offtake data.

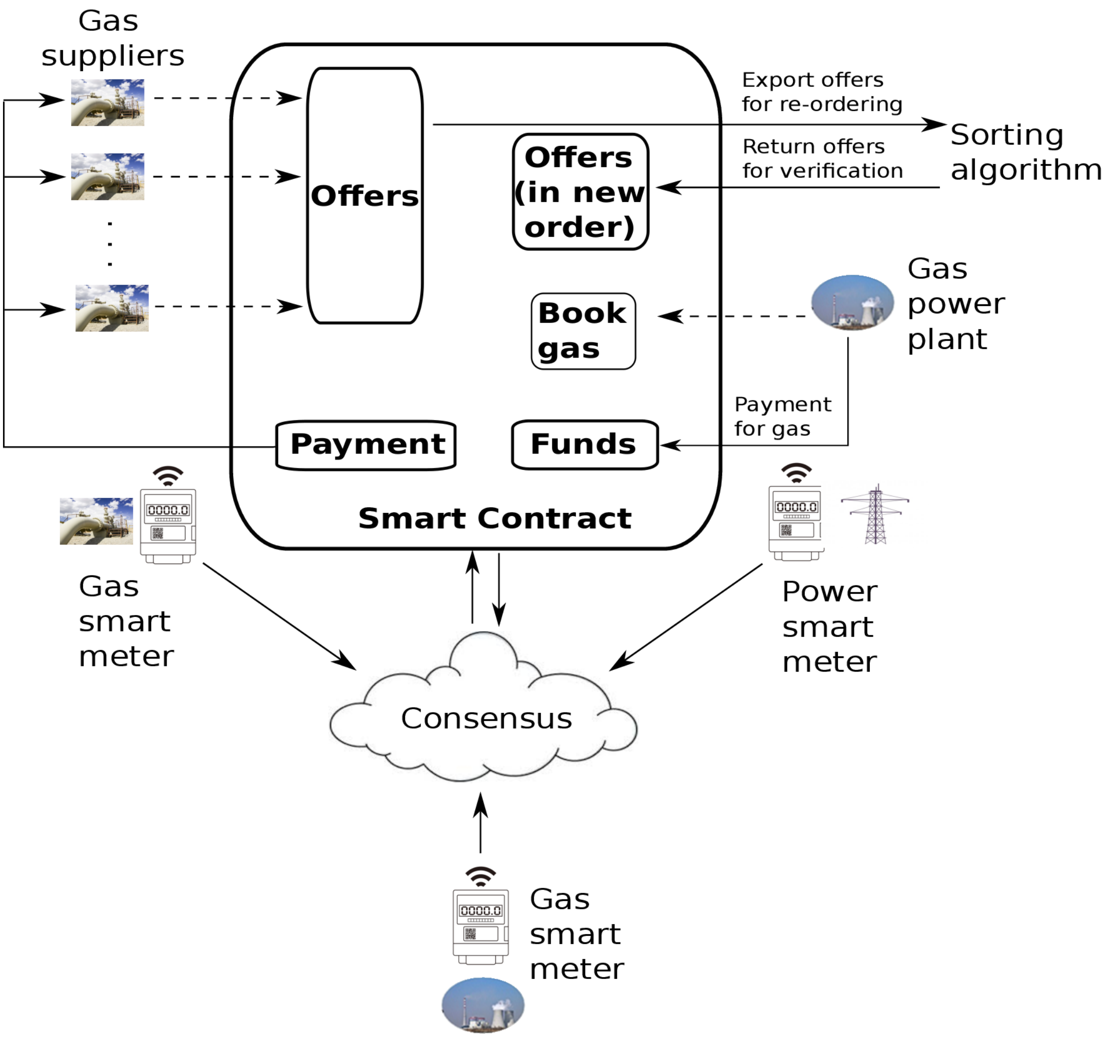


**Figure 1.** Blockchain-based P2P gas trading scheme with decentralized oracles.

## 3. Problem Formulation

### 3.1. O/I Characteristic Parameter Estimation

An unconstrained optimization problem is first formulated to estimate the coefficients of the O/I characteristic curves. It is based on the principle of the least squares error approach to polynomial approximation. The O/I characteristic estimation problem can be formulated as:

$$Min \sum_{j=1}^{n} (P_{actualj} - P_{estimatedj})^2 \quad (1)$$

where

$$P_{estimatedj} = \gamma_i + \beta_i f_j + \alpha_i f_j^2 \quad (2)$$

The coefficients $\gamma, \beta, \alpha$ are obtained from the O/I characteristic estimation problem and used in the adapted economic dispatch formulation.

### 3.2. Adapted Economic Dispatch Formulation

The proposed ED model aims to maximize power output; hence, the sum of O/I characteristics of thermal units serves as objective function. The constraints include gas consumption limits and gas balance constraints.

The O/I characteristic of each generating unit is given by:

$$P_i(f_i) = \gamma_i + \beta_i f_i + \alpha_i f_i^2 i = 1, 2, \ldots, n \quad (3)$$

The proposed economic dispatch formulation is given as:

$$MaxP(f) = \sum_{i=1}^{n} (\gamma_i + \beta_i f_i + \alpha_i f_i^2)$$

Subject to:

$$f_{imin} \leq f_i \leq f_{imax} i = 1, 2, \ldots, n \quad (4)$$

$$\sum_{i=1}^{n} f_i = f_a \quad (5)$$

## 4. Simulation Setup and Solution Methodology

The proposed ED model is specified and solved with GAMS. It is a mathematical specification language specially dedicated for the solution of optimization problems [29]. Large and complex problems can be represented in GAMS in a concise manner and can easily be altered for testing and research purposes [30]. It has been effectively employed by researchers to solve typical economic dispatch problems [29–31]. Typically, GAMS formulation follows the basic format in [30].

The P2P gas trading scheme is implemented on the Remix IDE. The environment simulates a blockchain network having participants who can transact in a P2P manner. It provides nodes or network accounts that each represent a participant. To enable the initiation on network transactions, nodes are supplied with test Ethers. In the present study, a node is reserved as the administrator node and used to perform tasks like initiating payments, while another node is assumed to represent the thermal station. The gas suppliers are represented by other nodes in the network. The foregoing therefore represents a blockchain network of gas suppliers and the thermal station. The proposed smart contract is also developed within Remix and can therefore interact with the various nodes in the environment. For the simulation in this study, gas supply offers are manually submitted to the proposed smart contract using each supplier's node, and the thermal station's bid is manually submitted using its node. The administrative node is then used to initiate the selection of winning supplier(s) by the smart contract, and subsequently make payments. The proposed smart contract is coded with Solidity within the Remix IDE, using an i5-6200U processor (7.7 GiB memory) and the Ubuntu 20.04.1 LTS operating system. Figure 2 is a flowchart that depicts the logic programmed into the proposed smart contract. Further details regarding the smart contract functions are given in Algorithm 1.

**Algorithm 1** Smart Contract-Based Gas Trading Scheme.

The proposed smart contract for P2P gas trading is composed of functions some of which the peers need to call. For instance, gas suppliers call the 'gasOffers' function to submit their offers.

Function 1: Constructor
This is a self-executing function that is automatically executed at the point of deploying the smart contract.

Function 2: setValue
This function is used to set the dollar equivalent of 1 Ether—the native cryptocurrency of the Ethereum blockchain.

Function 3: gasOffers
The gas suppliers call this function to submit their gas offers in terms of amount and price.

Function 4: vergasOffers
The offers received by the previous function—gasOffers—are re-arranged from the least price offer to the highest and returned to the current function for verification and on-chain storage.

Function 5: marketPrice
The plant operator calls this function to view the cost of his gas demand based on the available market offers.

Function 6: pay4Order
Upon viewing the cost of gas, the plant operator calls the current function to make payment to the smart contract.

Function 7: paySuppliers
This function is called to initiate payment to the gas suppliers for their supplies

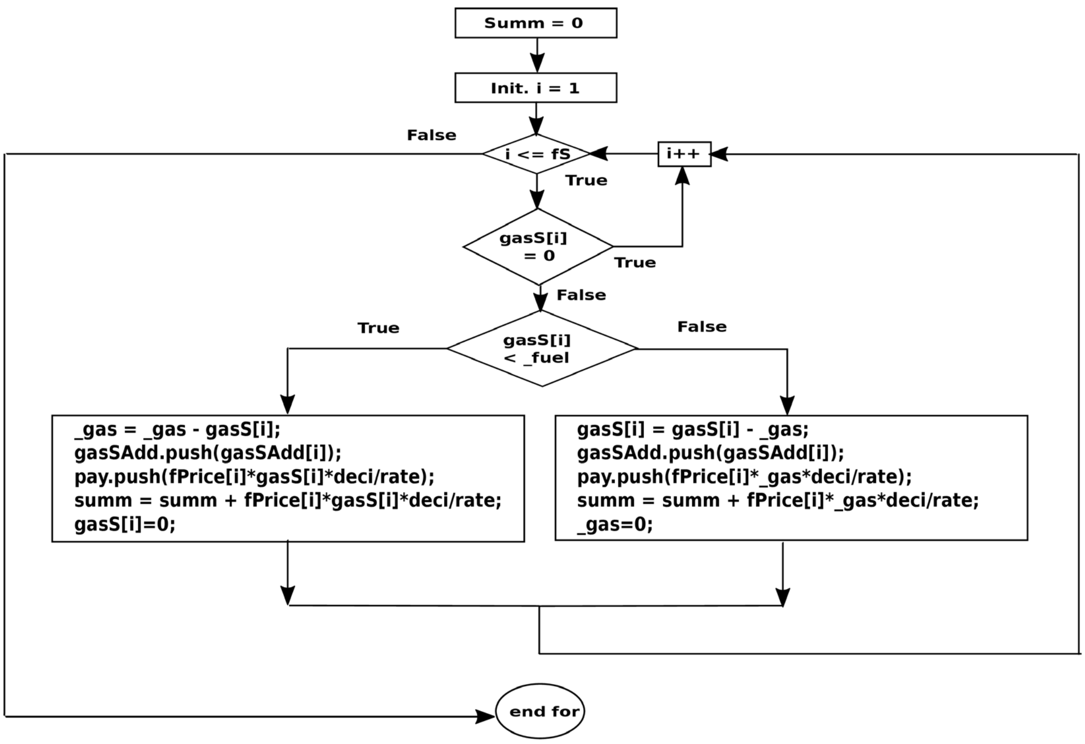


**Figure 2.** Flowchart for P2P gas trading scheme.

## 5. Case Study

A major thermal power plant in Nigeria is taken as case study in this paper. Egbin power plant is the largest installed single electricity generation plant in Nigeria having an installed capacity of 1320 MW. It is located in Ijede area of Ikorodu, Lagos State. The plant was commissioned in 1985 and consists of 6 units each having a generating capacity of 220 MW. It receives its natural gas supply directly from the Nigerian Gas Company (NGC). As at the time of this research work, only five of the units were functional and data showing monthly energy generated, gas consumed, and operating hours for each of the units were obtained from January to September 2014. These were the months for which data were available and could thus be utilized for research. The average power output and average gas consumed are computed and shown in Table 2. $f_{imin}$ and $f_{imax}$ are the average gas consumed when Unit 1 is generating at minimum and maximum average power level observed from historical records. $f_a$ is the sum of average gas consumed by all units taken from the historical data. These data were used to generate the O/I characteristics of the thermal units according to the mathematical expressions in (1) and (2), after which (3)–(5) were used to perform the economic dispatch.

**Table 2.** Historical power generation data for Units 1–5.

| | UNIT 1 | | UNIT 2 | | UNIT 3 | | UNIT 4 | | UNIT 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Month** | **Average Power Output (MW)** | **Average Gas Consumed (kg/h)** | **Average Power Output (MW)** | **Average Gas Consumed (kg/h)** | **Average Power Output (MW)** | **Average Gas Consumed (kg/h)** | **Average Power Output (MW)** | **Average Gas Consumed (kg/h)** | **Average Power Output (MW)** | **Average Gas Consumed (kg/h)** |
| January | 77.7741 | 18,450.35 | 145.505 | 30,778.11 | 123.455 | 27,763.99 | 142.914 | 31,180.47 | 102.071 | 22,044.17 |
| February | 137.088 | 29,384.65 | 147.475 | 31,542.15 | 112.898 | 25,573.33 | 150.961 | 33,000.24 | 127.274 | 26,742.18 |
| March | 116.578 | 25,196.22 | 113.232 | 24,949.88 | 119.953 | 26,906.76 | 128.134 | 28,447.52 | 130.711 | 27,074.93 |
| April | 102.697 | 22,889.51 | 145.330 | 31,148.13 | 118.899 | 26,604.08 | 103.358 | 23,700.90 | 104.425 | 22,625.98 |
| May | 111.552 | 24,245.33 | 165.760 | 35,494.70 | 133.559 | 29,191.30 | 114.479 | 25,720.00 | 107.809 | 23,777.06 |
| June | 150.622 | 31,041.21 | 146.658 | 31,146.30 | 96.2589 | 21,413.01 | 112.890 | 23,749.31 | 119.221 | 24,764.57 |
| July | 112.188 | 23,819.35 | 133.734 | 28,538.02 | 127.040 | 27,253.19 | 131.790 | 27,974.23 | 106.337 | 21,951.83 |
| August | 79.4093 | 17,503.18 | 158.402 | 33,008.63 | 74.3212 | 17,235.02 | 153.076 | 32,307.98 | 83.6560 | 17,756.14 |
| September | 88.9975 | 19,299.56 | 156.622 | 32,863.68 | 91.0932 | 20,378.03 | 152.394 | 32,478.26 | 93.6379 | 17,480.47 |

While the data collected are more suitable for investigating the proposed economic dispatch formulation, they provide details about the amount of gas utilized by the thermal plant. This guided the development of the hypothetical gas marketplace presented in Table 3. To test the effectiveness of the proposed smart contract, data from the month of June were utilized. The average amount of gas used in the month was approximately 132,114 kg/h and the gas supply offers are shown in Table 3. The dollar equivalent of an ether token is taken to be 4000 USD. The smart contract is developed and tested in the Remix IDE. The environment offers a simulated blockchain network of peers/nodes, each equipped with 100 ethers.

**Table 3.** Gas supply offers.

| Gas Supplier | Offer ($10^{-3}$ $/kg) | Quantity (kg) |
|---|---|---|
| A | 92 | 20,000 |
| B | 95 | 30,000 |
| C | 100 | 50,000 |
| D | 90 | 40,000 |
| E | 93 | 50,000 |

## 6. Results and Discussion

Using the data collected, the expressions in (1) and (2) were used to generate the O/I coefficients of the units, the results of which are presented in Table 4.

**Table 4.** Estimated parameters for O/I characteristics of generators.

| **Unit** | **1** | | | **2** | | | **3** | | | **4** | | | **5** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coefficients | $\gamma$ | $\beta$ | $\alpha$ | $\gamma$ | $\beta$ | $\alpha$ | $\gamma$ | $\beta$ | $\alpha$ | $\gamma$ | $\beta$ | $\alpha$ | $\gamma$ | $\beta$ | $\alpha$ |
| Coefficient Estimate | 4.434 | 0.004 | $3.51 \times 10^{-8}$ | −91.07 | 0.01 | $-8.68 \times 10^{-8}$ | −3.668 | 0.004 | $7.25 \times 10^{-9}$ | 14.643 | 0.003 | $3.24 \times 10^{-8}$ | 125.64 | −0.006 | $2.39 \times 10^{-7}$ |

The economic dispatch problem described by the expressions in (3)–(5) was solved to obtain the optimal generation schedule shown in Table 5. In the table, power gain is the monthly difference between the actual and optimal power generation schedules.

**Table 5.** Simulation results for a period of nine months.

| Month | Generator Index | Actual Generation Schedule | Optimal Generation Schedule | Power Gain (MW) |
|---|---|---|---|---|
| January | 1 | 77.77408 | 162.439 | 17.37982 |
| | 2 | 145.5045 | 139.504 | |
| | 3 | 123.4546 | 67.426 | |
| | 4 | 142.9139 | 145.395 | |
| | 5 | 102.0711 | 94.335 | |
| **Total output (MW)** | | **591.71818** | **609.098** | |
| February | 1 | 137.0878 | 162.439 | 1.441 |
| | 2 | 147.4748 | 154.528 | |
| | 3 | 112.8984 | 119.276 | |
| | 4 | 150.9613 | 145.395 | |
| | 5 | 127.2737 | 95.500 | |
| **Total output (MW)** | | **675.696** | **677.137** | |
| March | 1 | 116.578 | 162.439 | 10.6577 |
| | 2 | 113.2316 | 144.511 | |
| | 3 | 119.953 | 72.587 | |
| | 4 | 128.1337 | 145.395 | |
| | 5 | 130.711 | 94.335 | |
| **Total output (MW)** | | **608.6073** | **619.265** | |

**Table 5.** *Cont.*

| Month | Generator Index | Actual Generation Schedule | Optimal Generation Schedule | Power Gain (MW) |
|---|---|---|---|---|
| April | 1 | 102.6972 | 162.439 | 18.9634 |
| | 2 | 145.3304 | 124.078 | |
| | 3 | 118.8991 | 67.426 | |
| | 4 | 103.3578 | 145.395 | |
| | 5 | 104.4251 | 94.335 | |
| **Total output (MW)** | | **574.7096** | **593.673** | |
| May | 1 | 111.5517 | 162.439 | 11.3557 |
| | 2 | 165.7601 | 142.208 | |
| | 3 | 133.5591 | 100.139 | |
| | 4 | 114.4793 | 145.395 | |
| | 5 | 107.8091 | 94.335 | |
| **Total output (MW)** | | **633.1593** | **644.515** | |
| June | 1 | 150.6223 | 162.439 | −8.34962 |
| | 2 | 146.6581 | 144.689 | |
| | 3 | 96.25892 | 70.442 | |
| | 4 | 112.8897 | 145.395 | |
| | 5 | 119.2206 | 94.335 | |
| **Total output (MW)** | | **625.64962** | **617.300** | |
| July | 1 | 112.1879 | 162.439 | −5.0694 |
| | 2 | 133.7335 | 136.424 | |
| | 3 | 127.0399 | 67.426 | |
| | 4 | 131.7904 | 145.395 | |
| | 5 | 106.3367 | 94.335 | |
| **Total output (MW)** | | **611.0884** | **606.019** | |
| August | 1 | 79.4093 | 162.439 | 0.56758 |
| | 2 | 158.4022 | 121.282 | |
| | 3 | 74.32116 | 67.426 | |
| | 4 | 153.0758 | 103.950 | |
| | 5 | 83.65596 | 94.335 | |
| **Total output (MW)** | | **548.86442** | **549.432** | |
| September | 1 | 88.99751 | 162.439 | −10.953 |
| | 2 | 156.6217 | 134.159 | |
| | 3 | 91.09318 | 67.426 | |
| | 4 | 152.3937 | 113.433 | |
| | 5 | 93.63793 | 94.335 | |
| **Total output (MW)** | | **582.74402** | **571.791** | |
| **9 Months Output (MW)** | | **5452.2368** | **5488.236** | **35.99916** |

Figures 3 and 4 depict results of the smart contract-based gas trading marketplace. The offers made by the gas suppliers, as well as the demand made by the thermal station to the smart contract can be seen in Figure 3. Giving priority to the cheapest offers, the gas demand is distributed among gas suppliers by the smart contract, as shown. The thermal station makes appropriate payment to the smart contract which also pays gas suppliers.

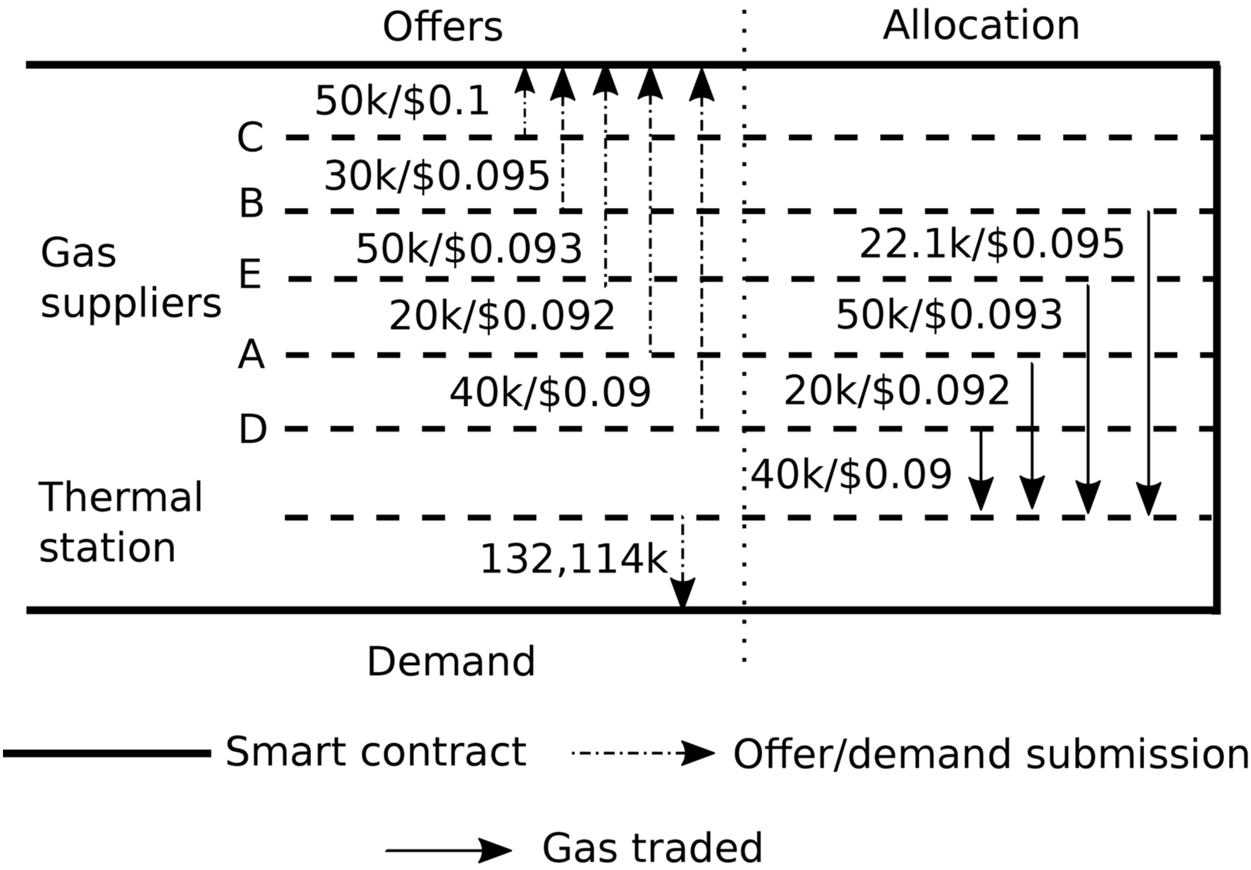


**Figure 3.** Smart contract execution of P2P gas trading.

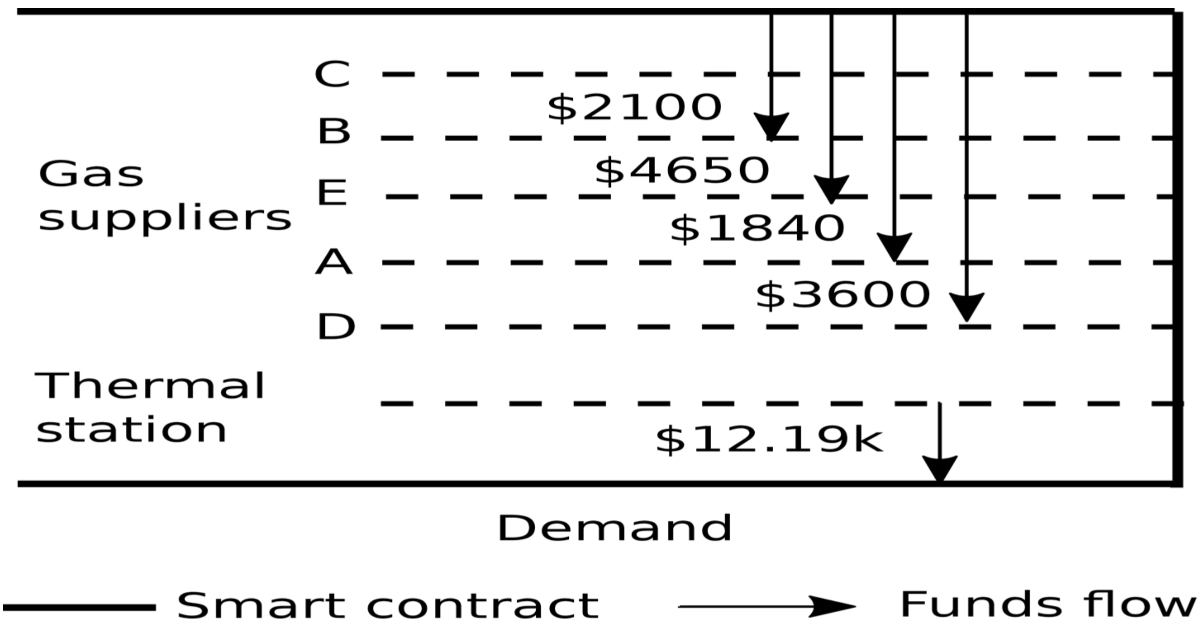


**Figure 4.** Smart contract execution of payments for the proposed P2P gas trading scheme.

The power gain displayed in Table 4 is the difference between the aggregate power output during normal operation and total output of the resulting generation schedule obtained from the proposed method. For six out of the nine months considered in this paper, the approach was successful as power gains were realized. It should be noted that the data obtained from Egbin power plant were records of energy generated and gas consumed monthly by each unit; hence, the estimated O/I characteristics curves are quite imprecise. Data recorded at shorter intervals would give more accurate results. This somewhat justifies the negative power gains recorded in the months of June, July, and September. However, an aggregate gain of 35 MW is recorded for the whole duration. The proposed formulation possesses gas-saving potentials in energy poor countries grappling with insufficient gas supply.

Figure 3 shows the submission of gas supply offers and demand to the smart contract. The selection of suppliers as well as the amount of gas to be supplied to meet demand is also shown. To meet the demand at the best possible price, received supply offers are re-ordered in ascending order of prices, thereby giving the lowest price offer topmost priority. This results in the supplier order—D, A, E, B, and C. It can be observed from the figure that Suppliers D, A, and E are selected to supply their entire offer amounts, while Supplier B is expected to supply the fraction of its offer amount needed to completely meet the demand.

Figure 4 shows the flow of funds to/from the smart contract. The thermal station makes payment to the smart contract upon confirming the cost of gas demanded, then the suppliers are paid via the smart contract. It can be seen that only suppliers A, B, D, and E were paid, as expected. By investigating the gas offers alongside the employed gas supplier selection mechanism, it can be seen that the accurate amounts were paid by the smart contract to individual suppliers. The accurate selection and payment of the suppliers by the smart contract proves its effectiveness in transparently selecting suppliers and making payments.

The study develops a smart contract that facilitates P2P gas trading between power plant operators and gas supplies. The smart contract has been developed for the Ethereum Virtual Machine (EVM) and hence can also be used on other EVM-compatible blockchains. Although it already implements some key trading logics in the system, the smart contract needs to be modified to be integrated with a practical system. For instance, it needs to be enhanced for greater autonomy and ability to receive data from oracles.

## 7. Conclusions

The novel ED has been successfully applied to Egbin thermal plant. Egbin power plant is one of the plants faced with the challenge of insufficient gas to power generating units. O/I characteristics parameter estimation is first performed to determine the coefficients $\gamma$, $\beta$, and $\alpha$, after which these values are utilized in the adapted ED formulation. Simulation results showed that the proposed approach can achieve a greater output power than was realized during normal operation of the plant. It can therefore be concluded that the proposed ED approach can be effectively applied to gas-deficient thermal stations. Results from P2P gas trading simulations also prove the effectiveness of the proposed Ethereum smart contract in accurately selecting gas suppliers and making payments. With the proposed gas dispatch model, available gas can be optimally used for maximum power output. The proposed fair and transparent P2P gas trading attracts gas suppliers, thereby improving gas supply to the thermal plant.

Future work could involve modeling emissions into the novel formulation and including the ramp rate constraints. With regards to the P2P trading, further work could entail the development of an appropriate mechanism of distributing transaction costs incurred by the smart contract among the participants of the trading scheme. In addition, the communication architecture and security mechanism for secure transmission of data between users and the smart contract should be investigated.

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**Notation**

| | |
|---|---|
| $i$ | Index of thermal units |
| $j$ | Index of data points |
| $f_{imin}$ | Number of thermal units |
| $\gamma, \beta, \alpha$ | Coefficients of estimated O/I characteristic |
| $P_i(f_i)$ | O/I characteristic of Unit 1 (MW) |
| $f_i$ | Quantity of gas consumed by Unit 1 (kg/h) |
| $f_a$ | Quantity of gas available (kg/h) |
| $f_{imin}$ | Minimum quantity of gas consumable (kg/h) |
| $f_{imax}$ | Maximum quantity of gas consumable (kg/h) |
| $P_{Gi}$ | Power output of ith generator (MW) |
| $P_{Gj}$ | Power level at jth data point (MW) |
| $P_{actualj}$ | Actual power output (MW) |
| $P_{estimatedj}$ | Estimated power output (MW) |

## References

1. Sönmez, Y. Estimation of gas cost curve parameters for thermal power plants using the ABC algorithm. *Turk. J. Electr. Eng. Comput. Sci.* **2013**, *21*, 1827–1841. [CrossRef]
2. Abdelaziz, A.; Ali, E.; Abd-Elazim, S. Implementation of flower pollination algorithm for solving economic load dispatch and combined economic emission dispatch problems in power systems. *Energy* **2016**, *101*, 506–518. [CrossRef]
3. Nwulu, N.I.; Xia, X. Implementing a Model Predictive Control Strategy on the Dynamic Economic Emission Dispatch Problem with Game Theory Based Demand Response Programs. *Energy* **2015**, *91*, 404–419. [CrossRef]
4. Damisa, U.; Nwulu, N.I.; Sun, Y. A robust optimization model for prosumer microgrids considering uncer-tainties in prosumer generation. *J. Renew. Sustain. Energy* **2019**, *11*, 066302. [CrossRef]
5. Nwulu, N.I.; Xia, X. A Combined Dynamic Economic Emission Dispatch and Time of Use Demand Response Mathematical Modelling Framework. *J. Renew. Sustain. Energy* **2015**, *7*, 043134. [CrossRef]
6. Damisa, U.; Nwulu, N.I.; Sun, Y. Microgrid energy and reserve management incorporating prosumer behind-the-meter resources. *IET Renew. Power Gener.* **2018**, *12*, 910–919. [CrossRef]
7. Nwulu, N.I.; Xia, X. Multi-Objective Dynamic Economic Emission Dispatch of Electric Power Generation Integrated with Game Theory Based Demand Response Programs. *Energy Convers. Manag.* **2015**, *89*, 963–974. [CrossRef]
8. Han, D.; Zhang, C.; Ping, J.; Yan, Z. Smart contract architecture for decentralized energy trading and management based on blockchains. *Energy* **2020**, *199*, 117417. [CrossRef]
9. Available online: https://pebbles-projekt.de/en/project/ (accessed on 15 May 2022).
10. Available online: https://www.powerledger.io/platform#energyTradingTraceability (accessed on 15 May 2022).
11. Guan, Z.; Lu, X.; Wang, N.; Wu, J.; Du, X.; Guizani, M. Towards secure and efficient energy trading in IIoT-enabled energy internet: A blockchain approach. *Future Gener. Comput. Syst.* **2020**, *110*, 686–695. [CrossRef]
12. Abdella, J.; Shuaib, K. Peer to Peer Distributed Energy Trading in Smart Grids: A Survey. *Energies* **2018**, *11*, 1560. [CrossRef]
13. Hu, W.; Li, H. A blockchain-based secure transaction model for distributed energy in Industrial Internet of Things. *Alex. Eng. J.* **2021**, *60*, 491–500. [CrossRef]
14. Khorasany, M.; Dorri, A.; Razzaghi, R.; Jurdak, R. Lightweight blockchain framework for location-aware peer-to-peer energy trading. *Int. J. Electr. Power Energy Syst.* **2020**, *127*, 106610. [CrossRef]
15. Esmat, A.; de Vos, M.; Ghiassi-Farrokhfal, Y.; Palensky, P.; Epema, D. A novel decentralized platform for peer-to-peer energy trading market with blockchain technology. *Appl. Energy* **2020**, *282*, 116123. [CrossRef]
16. Hua, W.; Jiang, J.; Sun, H.; Wu, J. A blockchain based peer-to-peer trading framework integrating energy and carbon markets. *Appl. Energy* **2020**, *279*, 115539. [CrossRef]
17. Van Leeuwen, G.; Al Skaif, T.; Gibescu, M.; van Sark, W. An integrated blockchain-based energy management platform with bilateral trading for microgrid communities. *Appl. Energy* **2020**, *263*, 114613. [CrossRef]
18. Li, Y.; Yang, W.; He, P.; Chen, C.; Wang, X. Design and management of a distributed hybrid energy system through smart contract and blockchain. *Appl. Energy* **2019**, *248*, 390–405. [CrossRef]
19. Lin, J. Analysis of Blockchain-Based Smart Contracts for Peer-to-Peer Solar Electricity Transactive Markets. Ph.D. Dissertation, Virginia Tech, Blacksburg, VA, USA, 2019.

20. Al Skaif, T.; Crespo-Vazquez, J.L.; Sekuloski, M.; van Leeuwen, G.; Catalao, J.P.S. Blockchain-Based Fully Peer-to-Peer Energy Trading Strategies for Residential Energy Systems. *IEEE Trans. Ind. Inform.* **2021**, *18*, 231–241. [CrossRef]
21. Kwak, S.; Lee, J. Implementation of blockchain based P2P energy trading platform. In Proceedings of the 2021 International Conference on Information Networking (ICOIN), Jeju Island, Korea, 13–16 January 2021.
22. Khalid, R.; Javaid, N.; Almogren, A.; Javed, M.U.; Javaid, S.; Zuair, M. A Blockchain-Based Load Balancing in Decentralized Hybrid P2P Energy Trading Market in Smart Grid. *IEEE Access* **2020**, *8*, 47047–47062. [CrossRef]
23. Luo, B.; Shen, X.; Ping, J. Energy Storage Sharing Mechanism Based on Blockchain. In Proceedings of the 2020 IEEE 3rd Student Conference on Electrical Machines and Systems (SCEMS), Jinan, China, 4–6 December 2020; pp. 913–917.
24. Khattak, H.A.; Tehreem, K.; Almogren, A.; Ameer, Z.; Din, I.U.; Adnan, M. Dynamic pricing in industrial internet of things: Blockchain application for energy management in smart cities. *J. Inf. Secur. Appl.* **2020**, *55*, 102615. [CrossRef]
25. Zeiselmair, A.; Steinkopf, B.; Gallersdörfer, U.; Bogensperger, A.; Matthes, F. Analysis and Application of Verifiable Computation Techniques in Blockchain Systems for the Energy Sector. *Front. Blockchain* **2021**, *4*, 725322. [CrossRef]
26. Caldarelli, G. Understanding the Blockchain Oracle Problem: A Call for Action. *Information* **2020**, *11*, 509. [CrossRef]
27. Poblet, M.; Allen, D.W.E.; Konashevych, O.; Lane, A.M.; Valdivia, C.A.D. From Athens to the Blockchain: Oracles for Digital Democracy. *Front. Blockchain* **2020**, *3*, 41. [CrossRef]
28. Buterin, V. A next-generation smart contract and decentralized application platform. *White Pap.* **2014**, *3*.
29. Benhamida, F.; Ziane, I.; Souag, S.; Salhi, Y. An effective GAMS optimization for Dynamic Economic Load Dispatch with Ramp Rate Limit. *Adv. Model. Optim.* **2013**, *2*, 477–485.
30. Bisen, D.; Dubey, H.M.; Pandit, M.; Panigrahi, B.K. Solution of Large Scale Economic Load Dispatch Problem using Quadratic Programming and GAMS: A Comparative Analysis. *J. Inf. Comput. Sci.* **2012**, *7*, 200–211.
31. Uchchkotiya, A.K.; Singh, R.; Trivedi, A.S. Evolutionary Techniques of GAMS used in Optimization of economic load dispatch in Power system. *Int. J. Eng. Res. Technol.* **2013**, *2*, 2359–2367.