A Real-Time Transactive Energy System for Nanogrids

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A Dissertation

Presented to the University of Dublin, Trinity College

in partial fulfilment of the requirements for the degree of

Master of Science in Computer Science

(Future Network Systems)

Supervisor: Prof. Donal O'Mahony

September 2020

Trinity College Dublin
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The University of Dublin

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A Real-Time Transactive Energy System for Nanogrids

Rohan Gupta, M.Sc. in Computer Science
University of Dublin, Trinity College, 2020

Supervisor: Dr. Donal O'Mahony

Abstract: The grid is witnessing an increasing emergence of small distributed energy resources (DERs), along with a greater prevalence of storage systems. These participants have highly dynamic properties and thus introduce several transactional challenges. We propose a rapidly convergent, privacy preserving, real-time transactive energy (TE) system which uses a dynamic pay-as-bid double auction. We describe a prototype which simulates the behaviour of the auction system and its participants who negotiate prices with individual bidding strategies. The proposed system allows the participants to transact without seeking numerous quantity-price trading pairs, thereby protecting confidentiality of cost curves of each competing participant. A less information-rich input does introduce some element of higher price volatility as an outcome, which, in this context, can be tolerated as parties perform small-ticket transactions. Such a TE system can be a step forward in preparing for a future where large generating firms and smaller complementary DERs participate in the market on an equal footing.

Acknowledgements

I would like to express a deep gratitude for my supervisor Dr.Donal O'Mahony for his kind patience, constructive critique as well as consistent motivation and guidance, while allowing me creative freedom, all throughout the dissertation.

I also humbly acknowledge my sponsors, Government of Ireland (Higher Education Authority, in association with Department of Education and Skills), as well as Trinity College Dublin, for a generous support with an International Education Scholarship.

Rohan Gupta

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6 Sept 2020

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Chapter 1

Introduction

1.1 Background

Households and enterprises have traditionally met their energy requirements by drawing power from the grid and paying to their respective distribution company. The pricing either is constant throughout the day or can vary depending on the time of use. These prices are usually controlled in compliance with the regulations. The distribution companies play the role of power re-sellers since they buy power from generating companies and pass it to the end-users. They estimate their end-user power demand and accordingly plan the purchase of power from the generating sources. The generation of energy has been dominated by large generation facilities like thermal, hydro and nuclear power plants.

The distribution companies enter long-term (10 or 15 yearlong) contracts, called Power Purchase Agreements (PPAs), with the generating firms. Closer to the power delivery period, these companies improve the forecast of end-user demand and meet any visible shortcoming by participating in the 'day-ahead' markets. Day-ahead markets are mediated by a central coordinator, like an energy exchange, and enable buying and selling of power for delivery on the next day. As we can see, there are a limited number of participants which engage in self-arranged bilateral contracts, or in a mediated day-ahead market for meeting their long-term and short-term needs respectively.

The mediator in day-ahead markets aggregates the individual power needs and preferences from each buyer and seller. As a central coordinator, it needs a complete view of market supply and demand to allocate power amongst the participants. The electricity grid has a centralized structure with limited points of power dispatch and multiple points of consumption. It can be observed that the grid as well as energy markets have centralized structures and are designed for a limited number of participants.

However, over the last few decades, the resources of energy have become more distributed. The advent of renewables and cheaper batteries has led to the deployment of massive renewable energy facilities and storage farms. Such large-scale DERs (distributed energy resources) have also been successfully integrated with the grid, along with the traditional participants, with established stable day-ahead trading processes transacting energy in the tune of MwH (Megawatt hours).

More importantly and recently, the growing use of electric vehicles and household-based solar, battery or combined systems introduces much smaller and pervasive DERs. Additionally, electric vehicles may move around plugging and unplugging from different locations – providing highly changeable demand as well as supply potential. These participants can act as prosumers (producers or consumers) depending on their local as well as well overall grid conditions.

A large number of such small-sized distributed and dynamic DER participants encourages a decentralized design of the grid. The concept of nano-grid was introduced as an independent building block to build such decentralized grid. The structure of DERs, a specific form of nanogrids, enables them to operate in isolation from or integrated with the grid, and they can plug and play into the grid on an ad-hoc basis.

Moreover, these participants can alter their power demand in response to changing power prices. For instance, in a high price scenario, local storage can be used as a source of power, or alternatively, the use of certain flexible loads can be postponed (or preponed). Thus, these prosumer DERs need to regularly make micro-choices like i) mode of operation (isolated or integrated), ii) managing excess (sell to grid or store locally) and deficit (buy from grid or consume from local store), iii) scheduling of flexible loads. Additionally, these participants can have embedded intelligence, in the form of agents, which can exchange information with the grid to guide these decisions.

On the market side, a transactive energy (TE) system was conceptualized as a highly interactive system which can facilitate information exchange and trading of power between such a large number of participants on short-time scales (15-min or closer to real-time).

1.2 Research objectives

Objective 1*: Identify the structural and functional attributes of the newer grid participants and any transaction challenges that these attributes introduce*

Here, we report the characteristics of these participants which make them highly dynamic in nature. This dissertation asserts that the intrinsic composition of these participants attaches a commodity-like character to power.

Objective 2*: Establish a set of design objectives for a TE system which can encourage participation of such smaller and pervasive DERs*

We state that a simple and effective TE mechanism must enable these participants to perform highly dynamic, opportunistic transactions with small amounts of energy (of the order of KwH and below), while preserving their privacy.

Objective 3: *Examine existing TE systems against these design objectives and identify any shortcomings*

Our literary investigations inform us that existing mechanisms either require the participants to submit portfolio bids (offer functions over a range of prices) or make the order book visible. The need for an access to complete market information to determine energy price has driven the use of centrally controlled uniform price auctions

Objective 4*: Design a new TE system to address these limitations and implement a prototype to demonstrate its behaviour*

We propose initial steps in the design of a TE system which can operate with partial information. This work introduces a rapidly convergent, privacy preserving, real-time TE system which uses a dynamic pay-as-bid double auction. Further, I describe a prototype which simulates the behaviour of the auction system and its participants who negotiate prices with individual bidding strategies. Our proposed system allows the participants to transact without seeking numerous quantity-price trading pairs, thereby protecting confidentiality of cost curves of each competing participant.

Objective 5*: Identify the performance metrics of TE systems and compare the proposed system against the existing system in terms of one of the metrics*

We observe that the proposed TE system, operating with partial information, does introduce some element of higher price volatility, as an outcome, in comparison with auctions with complete information. Price volatility can be tolerated in this context as parties perform small-ticket transactions.

1.3 Structure of dissertation

Chapter 2 identifies the state of the art in single-sided and double-sided power auctions as well as auction bidding strategies. It presents the evolution of nanogrids and outlines the progress made in real-time TE mechanisms.

Chapter 3 elaborates on the design of proposed TE mechanism and the construct of nanogrids used for the design. It discusses the behavioural modelling of participating agents as well as the auctioneer and the formulation of an energy marketplace.

Chapter 4 describes a software implementation of the proposed TE mechanism. It lists the structure and functions of a working prototype deployed on the cloud. It also elucidates the implementation of an existing TE system used for comparative evaluation.

Chapter 5 evaluates the proposed TE system in comparison with the existing TE system under the same scenario. It investigates the advantages introduced by the proposed TE system and proposes future directions to minimize the impact of observed shortcomings. It further identifies the promise of such a TE system.

Chapter 2

State of the art

2.1 Nanogrids

M. M. He et al [1] introduce the concept of an internet-like architecture for distribution and sharing of energy. The internet emerged as a group of networks with standardized protocols of data exchange between them. The paper envisages a similar formation of grid with smaller grid-like structures coming together to yield a large grid.

Nordman, Christensen and Meier [2] provide a rationale for a newer structure of grids. It should serve varying cost and reliability expectations from different sources of power. As the edges of the grid are becoming more complex, it must be able to communicate prices of energy at scale to influence usage and storage behaviour.

Nanogrids can be understood as an independent building block in a grid. In their simplest form, they are composed of at least one load (energy consuming) or supply source (energy producing) component, as well as a gateway (interfacing unit) which can help the nanogrid interact with the external world [2]. The gateway must enable exchange of data and flow of power (Fig 2.1). This allows the nanogrid to operate both in integration with the grid, as well as in an isolated mode. A notebook PC is a nanogrid as it can operate independently as well as in connection with the grid. Other examples include households, electric vehicles and even utilities can be modelled as nanogrids. It can also have a controller for an internal mediation between its components.

A nanogrid is a class-like abstraction and several instances of this class, in various shapes and forms can be connected to yield a grid-like structure. The traditional grid has had a centralized and radial structure. The emergence of newer and distributed energy resources solicits the need for a decentralized structure. The modular construct of a nanogrid class instigates a bottom up perspective to construction of grids.

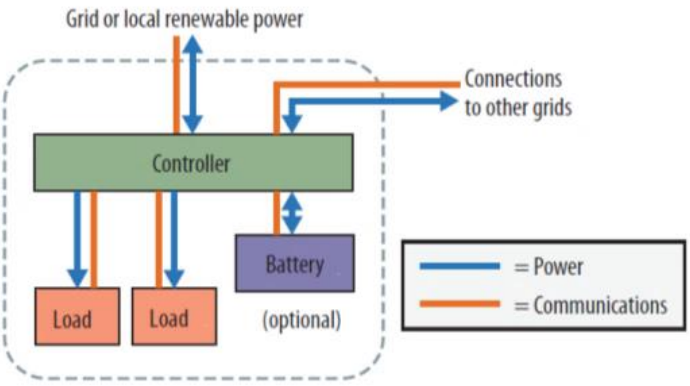

Figure 2.1: Components of a nanogrid

In a nanogrid context, a village can be envisaged as a composite of multiple nanogrids with different units like households, schools, windmills etc (Fig 2.2). The power sources in this scenario could be storage, renewables, and grid supply.

The traditional model of a grid necessitates a centralized control of communication which exerts a burden of administration and is also a single point of failure. The distributed model allows isolated nanogrids as well as a network of inter-operable nanogrids.

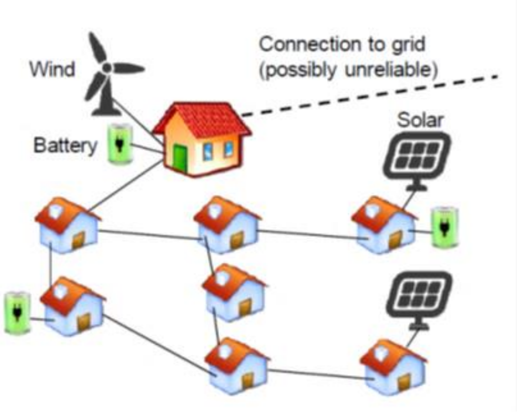

Figure 2.2: A network of nanogrids in a village

Nordman and Christensen [3] articulate the need for nanogrids, amidst the presence of micrögrids and mega grids. It also distinguishes nanogrids from the initial concept in reference [1] that nanogrids only need communication and connection with adjacent grids, while the initial concept needed a standard stack for end-to-end delivery (Fig 2.3). It also elaborates on the operation of nanogrid, possible ways of implementation and need for standardization. An architecture that supports local power distribution with proximate participants must be i) universally applicable, ii) scalable, iii) inexpensive, iv) flexible, and v) simple for use [4].

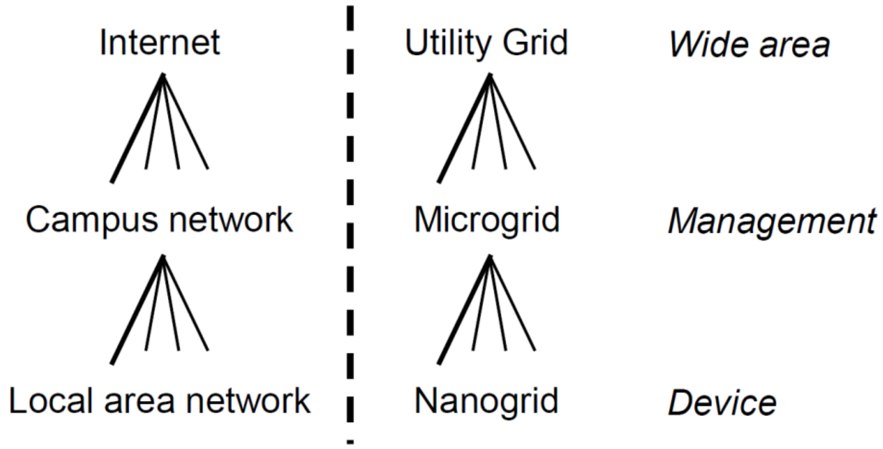

Figure 2.3: An analogous comparison of nanogrids with data networks

El-Shahat [5] identifies the benefits, characteristics and challenges of nanogrids. The next stage in evolution of nanogrids was hardware demonstrations. Burgio et al [6] introduce a laboratory-based hardware prototype of a 1kW nanogrid for home applications and uses a behaviour tree approach for control. A student paper at Trinity College Dublin [7] also demonstrates a hardware-based deployment of nanogrid using Raspberry Pi. Further, some very recent works have proposed applications of nanogrids. Jie and Naayagi [8] propose a 10kW simulation of energy aware buildings as nanogrids. Yoomak and Ngaopitakkul [9] investigate the feasibility of nanogrid in road lighting systems. Somma et al [10] proposes a design of cost-effective residential applications using nanogrids.

2.2 Types of auction

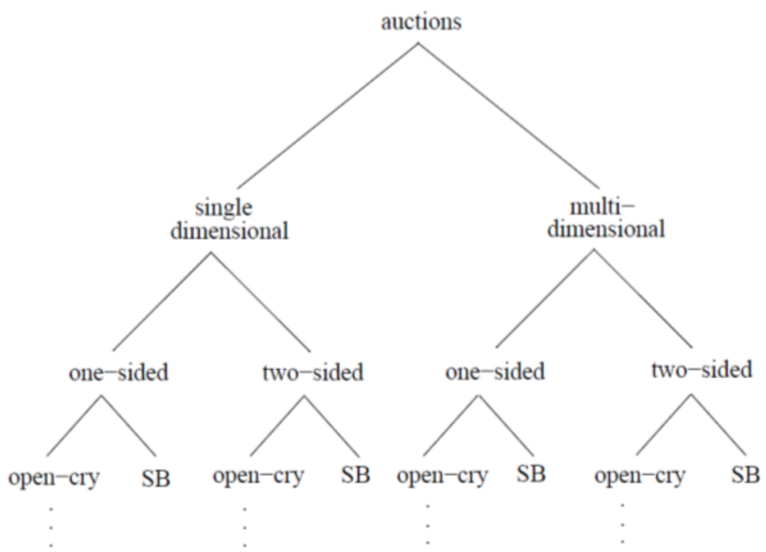

Figure 2.4: A brief classification-tree of auctions [11]

Auctions have been in use since ancient times. The most common form of auction is the English auction. For instance, an auctioneer announces the sale of an antique item and participants need to physically visit the auction house to declare their bids. The auctioneer begins with a reserve price (a lowest price) and participants shout out their bids in an increasing order. This form of auction is a one-sided, open-cry, first price ascending bid auction. A brief classification of auctions is presented in Fig 2.4 [11]. Table 2.1 lists and summarizes the various elements of an auction and associated types of auction.

Table 2.1: Various kinds of auctions

Sr. No.		**Type of auction**	**Description**
1	1a	Single-dimensional	Auctions which are decided based on a single dimension (usually price)
	1b	Multi-dimensional	Auctions with multiple dimensions like price, quality, age etc
2	2a	One-sided	Seller-only auctions (A single seller auctioning the item to multiple buyers) or buyer-only auctions (a single buyer auctioning the purchase amongst multiple sellers)
	2b	Two-sided	Auctions where multiple sellers and multiple buyers come together
3	3a	Open cry	Auctions in which participants publicly reveal their bids or make it visible (and other participants can use that information to influence their bids)
	3b	Sealed bid	Auctions in which the bids are submitted privately to the auctioneer (and the participants trust the auctioneer to protect this information from other participants)
4	4a	First price	Auctions in which the highest or the lowest price is used to determine the winning bid
	4b	Kth price	Auctions in which kth highest or kth lowest price is used to determine the winning bid
5	5a	Single unit	Auctions in which a single unit of quantity is being auctioned
	5b	Multi-unit	Auctions in which multiple units of an item are being auctioned
6	6a	Single item	A single item is being auctioned
	6b	Multi item	A bunch of items is being auctioned (for instance, software being sold along with requisite hardware)

7	7a	Uniform price	Auctions in which a constant single price point is used for all the participants
	7b	Discriminatory price	Auctions in which the prices are determined uniquely for each participant
8	8a	Portfolio bid	A bidding format which requires participants to share various pairs of quantity and price
	8b	Custom bid	A custom bidding format in which participants must submit their bids to the auctioneer
9	9a	Static auction	Auctions in which bids are submitted in a single round
	9b	Dynamic auction	Auctions which allow participants to submit bids in various rounds
10	10a	English auction	A one-sided open-cry ascending-bid auction
	10b	Dutch auction	The auctioneer keeps dropping the price and the participant which first accepts the price wins the bid.
	10c	First-price sealed-bid auction	Participants submit their bids to the auctioneer in a sealed format. The auctioneer opens the bids and determines the winner.
	10d	Vickrey auction	These are second-price sealed bid auctions where the winner pays the second highest price amongst the submitted bids.
	10e	Double auction	Auctions in which there are multiple sellers and multiple buyers on both sides

Fig 2.5 depicts the broad process specifications for commonly used auctions. Stock exchanges (or equity markets) as well as cryptocurrency exchanges are usually operated in the form of continuous double auctions. Sellers who own the stock (or any other item like currency, metal etc) submit ‘asks’. An ‘ask’ is a combination of quantity and price at which the seller is willing to sell that quantity. Similarly, buyers submit their ‘bids’, which is a

representation of their demand quantity and price at which they are willing to pay to buy that quantity.

Auction protocol	Process specification
Dutch	$Opening.((BidCall.BidCollection)^{+}.WinnerDetermination.TieBreaking.[InfoRevelation])^{+}.Clearing.Closing$
English	$Opening.(BidCall.BidCollection.[BidRetraction].WinnerDetermination.InfoRevelation)^{+}.Closing$
Japanese	$Opening.(BidCall.BidCollection.[BidRetraction].WinnerDetermination.TieBreaking.InfoRevelation)^{+}.Closing$
Continuous Double	$Opening.((BidCall\|\|AskCall).(BidCollection\|\|AskCollection).[BidRetraction\|\|AskRetraction]).[Clearing])^{+}.Closing$

Figure 2.5: Process specification for common auctions [11]

$x.y$	x followed by y	$x\|y$	x or y occurs
$x*$	x occurs 0 or more times	x^{+}	x occurs 1 or more times
$x\|\|y$	x and y interleaved	$[x]$	x is optional

Figure 2.6: Operators used in Figure 2.5

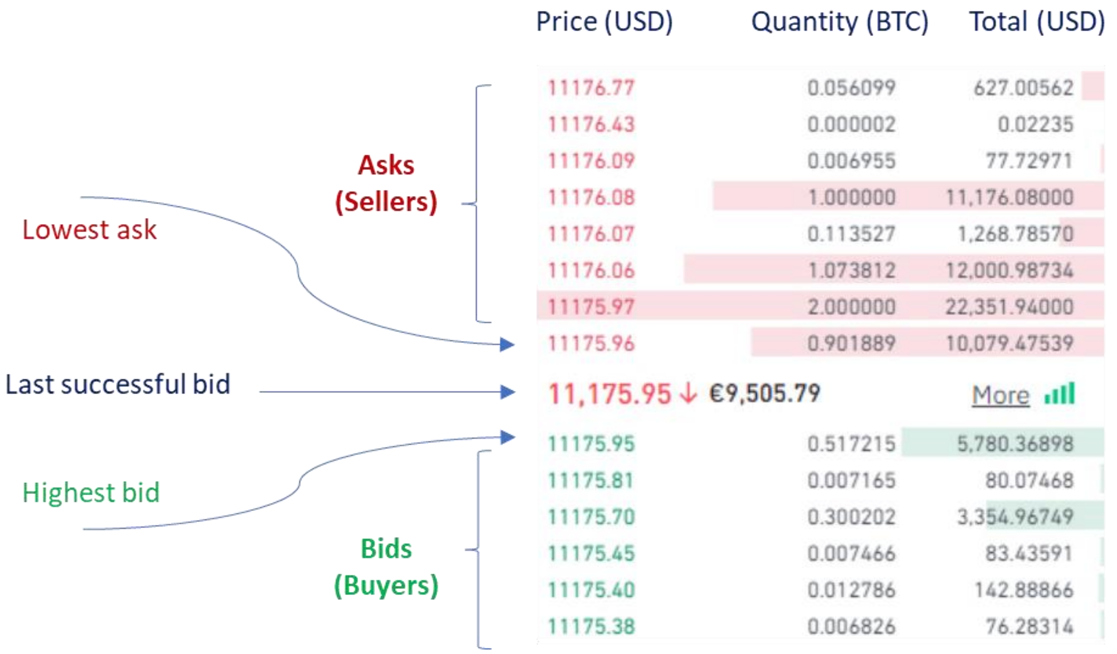

Figure 2.7: Order book in a continuous double auction

The auctioneer sorts the various bids and asks in a descending order and makes an anonymized list available to the participants, called the order book as shown in Fig 2.7. In most cases, the submitted orders can be retracted by the participants before it becomes completely successful. In case, a submitted bid equals or exceeds the ask, a trade is considered successful and subsequently executed. The price at which the item was last traded indicates the most recent monetary value of the item. Thus, the auctioneer chooses to reveal some part of information (anonymized or/and aggregated) which can act as market signals to the participants to inform their bidding behaviour in the near future (Fig 2.8).

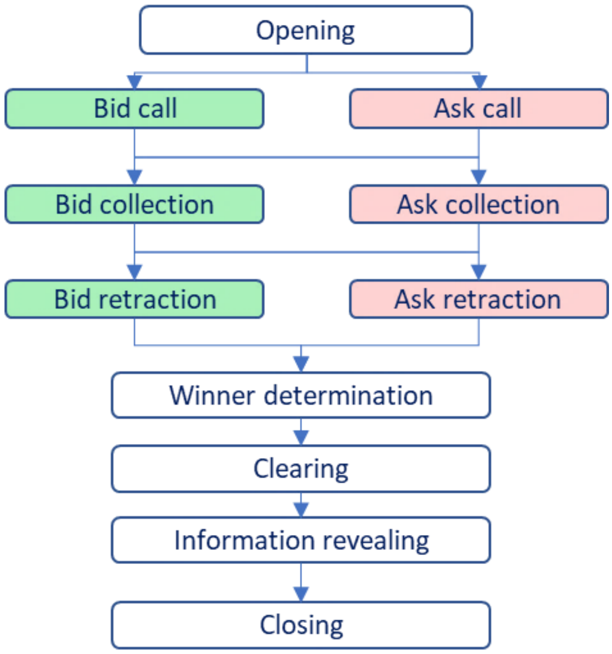

Figure 2.8: Abstract process model for continuous double auction [11]

2.3 Power auctions in industry

As seen in Fig 2.9, the grid is conventionally composed of three sets of participants i) medium to large generating firms ii) transmission companies iii) distribution entities. The generating firms sell energy to distribution entities which further sell it to end users under different tariff arrangements. Fig. 2.10 shows the several types of trading arrangements between generators and distributors across different time scales [12]. Long term power purchase agreements (10 or 15 yearlong) are arranged and executed on a bilateral basis. The various other time scales at which electricity markets operate include : i) day-ahead market (trading for power a day in advance), ii) intraday market (trading for same day) iii) real time or balancing market (trading for small hourly or 15 minute slots on same day). The energy exchange conducts an auction between several participants to allocate power.

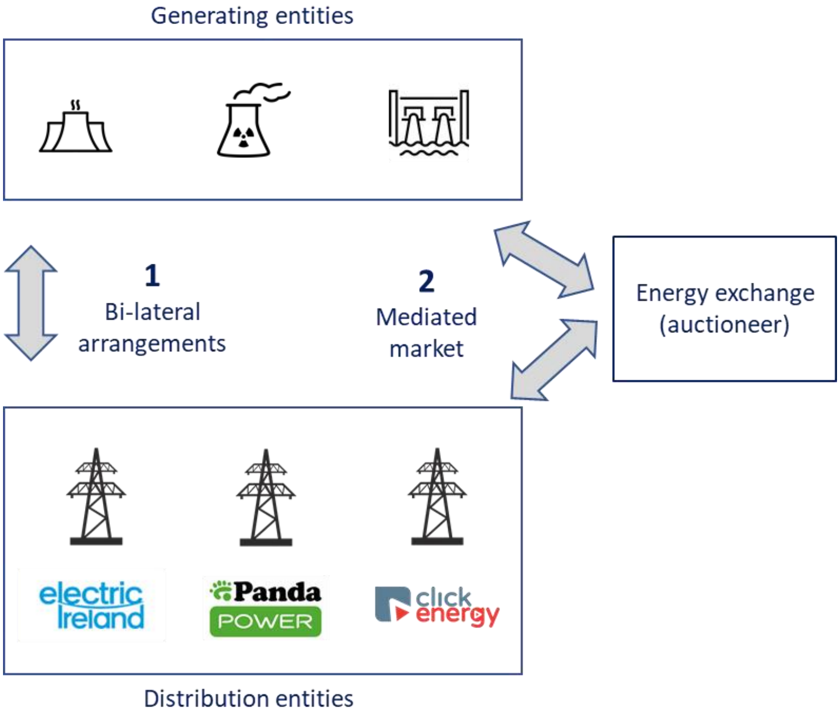

Figure 2.9: Conventional electricity trading arrangements

Thus, electricity is traded in several wholesale markets, each with a different time scale ranging from 20-year long arrangements, to shorter day-ahead, intra-day and real time trading. Each market at a particular time scale plays a unique role [12]. The real time or balancing market is critical in handling last minute variations in the system. Morey [13] mentions that at shorter time scales, it becomes increasingly difficult to find participants to trade electricity in smaller quantities, and therefore, the opportunity cost of discovering a suitable trading counterparty (either a seller or a buyer) is high. Thus, grid participants prefer a mediated market, with availability of supply and demand from many other pre-registered participants, over traditional self-arranged bilateral markets. The mediation can be performed by an auctioneer (or an energy exchange) with auctions at frequent regular intervals ahead of the physical delivery.

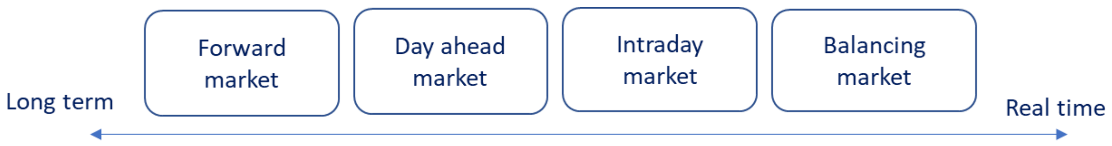

Figure 2.10: Types of electricity markets at different time scales

A conventional energy exchange uses a uniform price double auction mechanism to determine prices for a given time slot. In a uniform price double auction, the auctioneer collects detailed information from each participant about its bidding preferences. The participants share their individual cost curves (price vs quantity) with the auctioneer as shown in Fig 2.11. Upon completion of bid collection process, the auctioneer further aggregates these curves to draw consolidated supply and demand curves. The intersection of these curves is used to determine the Market Clearing Price (MCP) and Market Clearing Volume (MCV). The MCP is then uniformly used for sale and purchase of power by all participants.

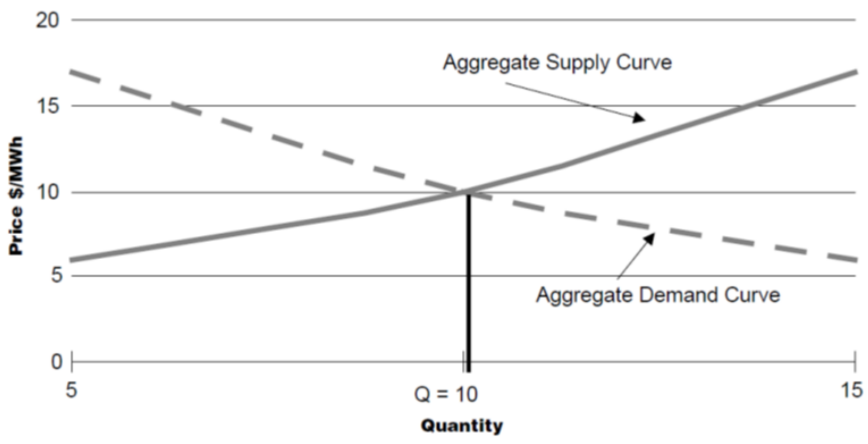

Figure 2.11: Uniform price determination in a double auction

Energy exchanges across the world, including Columbia in United States [13][14], Guangdong in China [15] and all regions in India [16] use a uniform Market Clearing Price (MCP) and Market Clearing Volume (MCV), in association with Locational Marginal Pricing (LMP).

Price Tick	0	1	1.1	2	2.1	2.5	3	3.1	3.5	3.8	4	4.1	5	7	9	12	14	17	19	20
Portfolio A	20	20	20	20	20	20	20	10	7	4	0	0	0	0	0	0	0	0	0	0
Portfolio B	60	60	60	60	50	40	40	40	40	40	40	40	20	20	20	20	20	20	20	20
Portfolio C	70	70	70	70	70	60	50	50	50	50	50	50	50	10	10	10	10	10	10	10
Portfolio D	40	20	0	0	-40	-60	-80	-81	-85	-100	-120	-120	-120	-120	-120	-120	-120	-120	-120	-120
Portfolio E	0	0	0	0	0	-40	-50	-50	-50	-50	-60	-60	-90	-90	-90	-90	-90	-90	-90	-90
Portfolio F	0	0	0	0	0	-20	-20	-20	-20	-20	-20	-30	-40	-40	-40	-40	-40	-40	-40	-40
Total Buy, MW	190	170	150	150	140	120	110	100	97	94	90	90	70	30	30	30	30	30	30	30
Total Sell, MW	0	0	0	0	-40	-120	150	-151	-155	-170	-200	-210	-250	-250	-250	-250	-250	-250	-250	-250
Net Transaction, MW	190	170	150	150	100	0	-40	-51	-58	-76	-110	-120	-180	-220	-220	-220	-220	-220	-220	-220

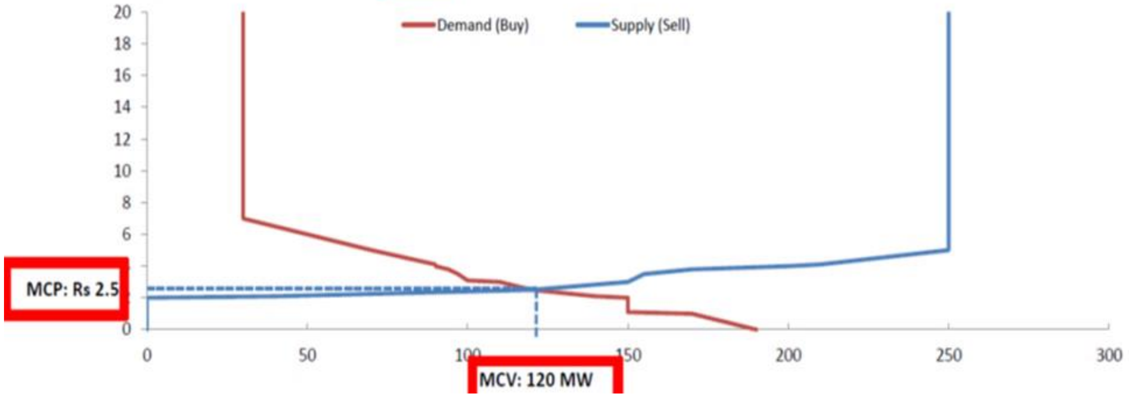

Figure 2.12: Bidding format in Indian Energy Exchange [16]

As seen in Fig 2.12, 6 participants submit their entire portfolio preferences across a range of prices, INR 0 to INR 20 in this case. In the figure, the exchange identifies INR 2.5 as the market clearing price and 120 MW as the market clearing volume.

2.4 Power auctions in literature

This section identifies prior literary works in electricity auctions. Auctions used in TE systems which can mediate transactions between smaller DERs, apart from the larger participants, must be simple and inexpensive to use [4]. Thus, it must reduce bidding participatory cost and limit complexity to encourage participation [13]. However, many prior works indicate that it is complex to design and operate such a system. The ability to communicate prices and market information is a critical challenge and further contributes to asymmetry in information [3]. Dynamic auctions, which use multiple rounds to enable participants observe price movements, can be more difficult to implement than static auctions and complex to participate in [17]. Thus, simplification is a key objective of an effective TE system.

The notion of multiple sellers and buyers in an electricity market have encouraged the study and use of double auctions in the past [18][11]. Double auctions have attracted renewed interest with the advent of DERs and evolution of electricity buyers from traditional consumers into prosumers.

A market simulation study compares double-sided auctions and supplier-only auctions to observe that double-sided auctions are more efficient as they limit the generating firms in exerting market power and yield a stable market clearing price as an outcome of elastic demand [19]. Flikkema [20] introduces a uniform clearing price based multi-round double auction at different time scales. This requires bid participants to submit offer functions and utilizes average bid and ask prices as market signals. A smart contract based Continuous Double Auction (CDA) which allows trading of energy in designated time intervals, before the delivery period, uses a visible order book enabling participants to evaluate others' preferences [21].

These mechanisms either require the participants to submit portfolio bids (offer functions over a range of prices) or make the order book visible. The need for a complete view of market information to determine energy price has driven the use of centrally controlled uniform price auctions. Such auctions usually need participants to share their preferences over blocks of time [13], thus making the allocation of power a feasible exercise amongst limited participants.

This work addresses these limitations and aims to propose initial steps in the design of a TE mechanism which can operate in an environment of limited information. Such a mechanism might need iterations, each involving an exchange of partial information, to determine the value of power and make subsequent allocations.

2.5 Negotiations for price discovery

In some of the dynamic auctions, participants can engage in negotiations, where they increase or decrease their bid prices in an attempt to win the bid. Both sellers and buyers negotiate at different prices and quantities according to their own requirements and propensity. In such protocols, participants send in bids across multiple rounds to find a counterparty which is willing to trade at that price and this determines the price for that individual pair of buyer and seller in that round. Negotiation protocols have been proposed earlier in the form of iterative pricing using constrained tatonnement [22] and continuous double auction [21]. The convergence in constrained tatonnement was investigated for single-sided auctions. However, it may not be possible to apply overall capacity constraints in the presence of multiple prosumers and smaller DERs who plug into the TE system on an ad-hoc basis. Mezquita et al [23] leverage the notion of transaction fees to minimize the number of transactions performed as part of the negotiation process.

The mechanism we develop in this dissertation uses discriminatory pricing since a lack of total information hinders the ability to determine a uniform price. Discriminatory price auctions also bring other advantages. Nicolaisen, Petrov and Tesfatsion [18] argue that the practice of implicit collusion is difficult in discriminatory price auctions. There might be large gaps in the value that each participant attaches to power in such a scenario, and techniques like mid-point pricing can be used to mitigate the impact of a possibly high bid-ask spread. Midpoint pricing is the use of the average of ask and bid prices in matched orders as a reference price.

2.6 Storage systems

Storage systems enable participants to respond to changes in supply and demand in the grid. For instance, a household with a storage can choose to use a local battery to power its needs when the demand and price for power in the grid is high. Alternatively, if it has excess storage, it can be offloaded to the grid to at a high price to earn profits. Similarly, in a situation of excess supply, the agent might want to purchase excess power and recharge its battery systems to a hundred percent level. This helps the larger distributing entities in minimizing their generations costs as they set out to achieve a flatter demand across the day. One of the important objectives of utilities is to minimize the PAR (Peak to Average) ratio. So, periods with a peak demand can witness consumers using some of the local storage and respond to the peak by shaving it off totally or partially.

Further, the use of storage systems introduces a shift from 'time-of-use' pricing to 'time-of-sale' pricing as it enables the users to exploit the storage as a buffer during low or high prices. A shift in the time of use must also be coordinated amongst the participants [22]. A non-coordinated use of storage amongst participants might just shift the peaks, thus leading to creation of new peaks. This further motivates the need for such a design as it must allow participants to make and dynamically improvise their offers. The TE system must enable sharing of market signals for participants to react and influence their bidding behaviour accordingly. Nunna, Sesetti, Rathore and Doolla [24] present an example of an energy trading platform which integrates storage systems and uses continuous double auctions.

2.7 Agent bidding strategies

Each participant can have embedded intelligence with the use of automated agents. These agents can exchange information with the grid and make decisions on behalf of the participant. Amin and Ballard [25] identify various bidding strategies which can be used by the buyer and seller agents. A bidding strategy used by an agent must capture the intended behaviour of the participant under different market conditions. Fig 2.13 depicts some of these strategies depending on the local state of the agent and the surrounding grid conditions. For instance, if the power demand is low and the supply is high, a buyer agent would be very “reluctant” to increase prices with time. Similarly, a seller agent must be act “urgently” if the supply levels are high and demand is low. These bidding strategies can thus observe linear or non-linear changes in price with time. A TE system must allow participants to practice the bidding strategies of their choice and thus enable such revision of prices by participants as they receive more information and visibility over a period of time.

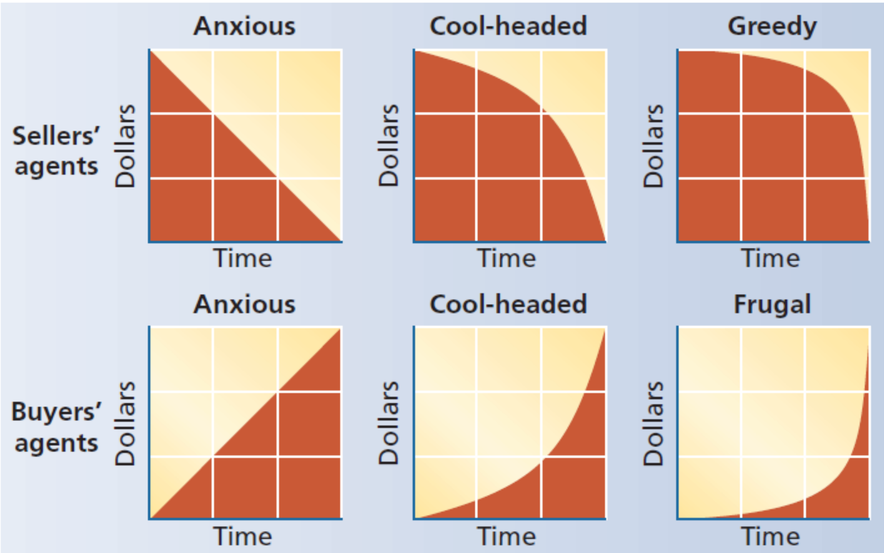

Figure 2.13: Various bidding strategies used by sellers and buyers

2.8 Transactive energy systems

The Gridwise Architecture Council defines Transactive Energy systems as “A system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter”. It identifies the role of a transactive energy system as a highly intelligent and interactive electric system that enable participants to exchange information, create, identify and exploit marked based opportunities and facilitate decision making. These decisions could be of various forms like the choice to be a seller or a buyer, the choice to act independently or interact with the grid and the choice of bidding strategy.

The performance of transactive energy systems can be evaluated using several quantitative metrics: i) social welfare, ii) violation level, iii) algorithmic complexity iv) price volatility index; and quantitative metrics like scalability and robustness [26].

Social welfare is defined as “the difference between the total utility of energy consumption of individual customers and the total cost due to energy generation of individual suppliers. Violation level reflects the severity of deviation from multiple constraints in the grid. The algorithmic complexity measures the complexity of computation and indicates the amount of resources that might be needed by the TE mechanism to determine prices and allocate power. As shown in equation (1), the Price volatility Index (PVI) measures the degree of change in market clearing prices (MCP) across different cycles (or time slots). It is defined as “the root mean square (RMS) of the differences between two consecutive market clearing prices over a period of time”.

$$PVI = \sqrt{\frac{\sum_{k=2}^{T}[\tau_{clear}(k) - \tau_{clear}(k-1)]^2}{T-1}} \quad (1)$$

τ_{clear} represents the market clearing price in a single time slot. The scalability of a TE system measures the feasibility of a large-scale implementation of the TE system. This implies that scale in terms of number of participants, smaller time slots, or any other form must not directly impact the amount of resources used to execute the TE system. This implies that auction algorithms must have a lower computational complexity in terms of time and space and the message payload necessary to exchange information must also be minimal. The robustness of the TE system represents its capability to meet its intended objectives in a set of external conditions which were not originally considered during the design. A TE system can be called robust if performance deterioration is negligible in this set of additional conditions.

2.9 Blockchains for payment settlement

A TE system must also be attached to a payment system which can process transactions and maintain a history of transaction records. The use of blockchains as payment systems has gathered widespread interest. The idea first appeared in a whitepaper on Bitcoin which surfaced in an online cryptographic forum [27]. The concept of blockchain has been primarily used as a distributed ledger. While the idea of distributed systems is not new, blockchains allow the ability to operate distributed systems in a trust-less environment.

Some recent prior works in the electricity trading domain have explored blockchains for settlement mechanisms and smart contracts. Smart contracts are a set of business rules encoded into programs which can automatically process transactions depending on the conditions. The idea of automated transaction processing is further encouraged with the underlying use of intelligent agents as decision makers. Thus, the use of blockchains can assist in automating the transactional part of the entire trading process.

Mezquita et al [23] propose a smart contract-based peer to peer electricity trading mechanism between multiple agents. This mechanism is designed for a microgrid use case and does not require any human intervention. The paper introduces three different layers i) a device layer, ii) an agent layer, and iii) a blockchain layer. Each time slot is 1 hour long, and the negotiation process can run for 50 minutes. Each participant in the negotiation process is encouraged to perform a small number of transactions since the blockchain network imposes an associated fee with each transaction. The authors also share a hardware demonstration using microcontrollers (ESP-32 platform) and a private library is developed for the devices to interact with the blockchain network. The Ethereum's Rinkeby test network is used as a blockchain network for performing the transactions and each node is initialized with some cryptographic (ERC-20) tokens.

Luo et al [28] introduce a coalition-based mechanism to support prosumer-type multiple agents on the network. The first layer enables them to build coalitions and negotiate for electricity. The second layer, built on top of the first layer, is a blockchain based transaction mechanism to settle financial transactions. This work conducts a P2P (peer-to-peer) energy simulation on 300 households using randomized values of PV (photovoltaic) solar and wind generation within a stipulated range. There are three algorithms proposed i) agent coalition formation ii) negotiation and iii) final contract determination. The agents calculate a forecast of their requirements and perform a local need analysis. Further, a social analysis is done to form coalitions and engage in negotiations. The negotiations lead to formation of temporary contracts. The analysis is extended over a period of time to finalize the contracts.

Chapter 3

Design

Power distribution has been traditionally looked at as a resource allocation problem: X amount of power (variable quantity), available exactly at time t, needs to be distributed across N buyers (with varying needs). The introduction of energy exchange is a recent introduction that came with deregulation in the electricity distribution sector. Here, the auctioneer aggregates individual cost curves and identifies an equilibrium price and clearing quantity to match supply and demand. However, the utilization of storage systems introduces the idea of an 'inventory' of power and reduces the significance of 'time' in its availability. This change in the intrinsic composition of grid participants endows them with the ability to hold and store and thus, also attaches a commodity-like character to power. Therefore, an effective TE mechanism that satisfies these emergent needs must resolve resource allocation at the said time as well as enable a physical commodity trade.

3.1 Rationale for proposed TE system

A single-dimensional auction was chosen over multi-dimensional auction for simplicity of design. The simpler instances of auctions like English and Dutch auctions use a single dimension. The current design uses 'price' as the only dimension in the auction. In the context of electricity trading, multiple dimensions like power quality, type of source (renewable or non-renewable) etc can also be introduced. Some of these dimensions are implemented alternatively, rather than being embedded directly into the auction. For instance, some energy markets use RECs (Renewable Energy Certificates) [29] to declare a legitimate renewable source, instead of directly influencing the power prices and choice of supplier, and these RECs can then be traded. The addition of other dimensions in the design can influence the auction system in other ways which fall out of scope of the current design and implementation.

The design uses a double-sided (or a two-sided) auction, over a single-sided (one-sided) auction. The choice of double auction is influenced by the presence of multiple selling and buying nanogrids. A single sided auction can be used when there is a single supplier of power (or a supplier monopoly). Double auctions can be more complex than single auctions as the need for quicker and deeper information exchange between participants grows with multiplicity of sellers.

The proposed auction design uses a sealed bid format to invite bids from the grid participants to protect the privacy of submitted bids. Since these auctions run in real-time and at very frequent intervals, an open-cry auction might allow unscrupulous participants to deduce the behaviour and preferences of other participants. As the auction design is intended to encourage participation from smaller DERs, preserving privacy is an important objective of the TE system.

This auction system is designed as a multi-unit auction, since multiple quantities of power need to be traded, as against a single-unit auction where a single quantity of the item is to be sold or bought. The design allows multiple trade transactions each with a unique quantity (say, 4 kWh in one transaction and 10 kWh in another).

The proposed auction is a single-item auction as the only item being traded is electricity. The discussed context may not foreseeably need a multi item auction.

The TE system design uses discriminatory price auctions over uniform price auctions. Uniform price auctions are usually used in scenarios where the auctioneer has access to complete market information which enables it to arrive at a uniform price which can be consistently used for all participants. Since, the proposed auction is designed for use in a limited information scenario, discriminatory prices are used which remain unique to each transaction and its participants.

The design uses a custom bid format for inviting bids from the participants. In the current design, the participants can submit single limit order for each trading round to extend participant comfort with a control on pricing. Table 3.1 highlights the differences between several types of orders used in double auctions. Portfolio bids, which are usually used by the uniform price double auctions, require the participants to submit offer functions over a large range of prices, thus completely revealing their preferences with the auctioneer.

Table 3.1: Types of orders used in double auctions

No.	Types of order	Description
1	Limit order	An order with a particular bid price. The auctioneer should make the transaction only when the bid price is met (or better)
2	Market order	An order which necessitates a successful transaction at the nearest available price.
3	Stop limit order	A buy or sell limit order which gets triggered (or activated) when the market price reaches (or crosses) a designated price threshold (i.e. the stop price)

The proposed TE system uses a dynamic auction as the prices need to be discovered over several rounds. The participants need to engage in a trial-and-error process over multiple rounds to find suitable prices and make trades. Static auctions, which use a single round, only the participants with only a single window of opportunity to make orders.

3.2 Construct of nanogrid abstraction

Each participant is modelled as a nanogrid. The extended nanogrid class shown in Fig 3.1 is composed of 2 components, a primary load or generating unit as well as a storage. The nano-grids are also connected to the auctioneer and have the capability to interact with it.

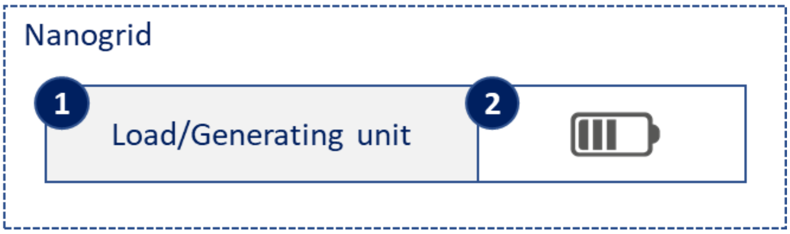

Figure 3.1: The construct of a nanogrid class

3.3 Formulation of auction process

The trading begins with the announcement of the opening of the first round for time slot t. Each time slot involves trading of energy across multiple rounds. Fig 3.2 and Fig 3.3 respectively present a conceptual and programmatic flow of the proposed auction system.

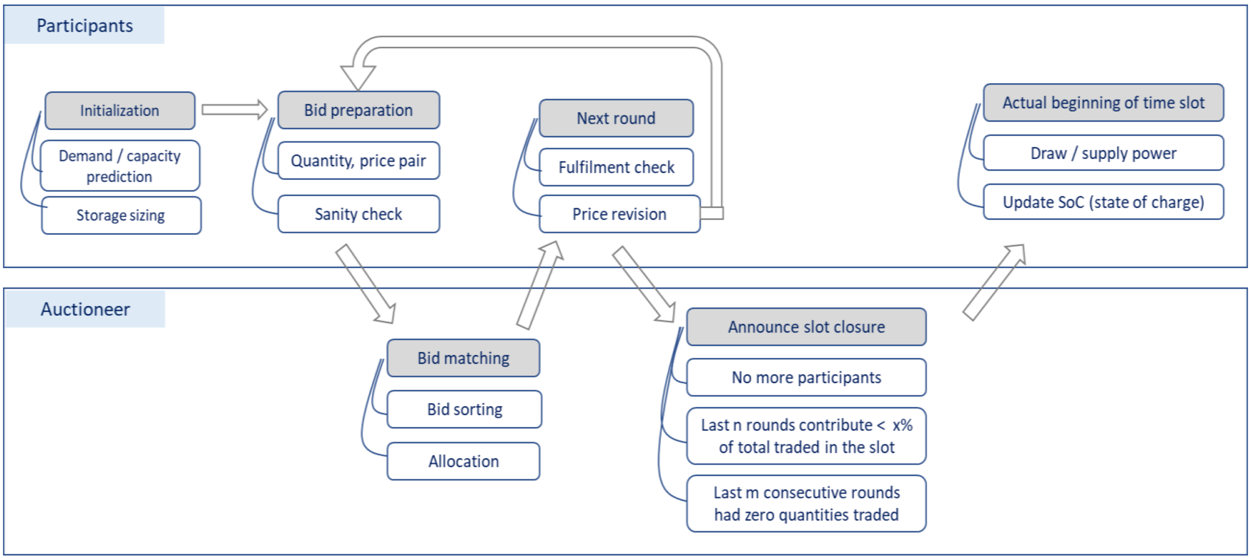

Figure 3.2: Conceptual flow of the proposed TE system

Auction process flow
Beginning of trading for time slot t
1. Repeat for each time slot
A. Repeat until rounds close
i) Bid preparation
ii) Bid collection
iii) Bid matching
I. Bid sorting
II. Allocation
iv) Bid result unicast
v) Fulfilment check
vi) Price revision
B. Trading for time slot t stops
C. Broadcast of slot average prices
D. Draw or supply power
E. Update State of Charge (SoC)

Figure 3.3: Programmatic flow of the proposed TE system

3.4 Agent modelling

Each TE participant is modeled as a combination of a primary component (fixed load or generating unit) and a storage system. The behaviour of each participant is modelled using i) a demand or supply curve of the form of Q = f(P) based on the principles of microeconomics, and ii) a dynamic bidding strategy which revises bid (or ask) prices depending on several factors including energy requirements in the current slot and the ability to self-fulfil the requirement with its current local storage.

Identifiers	
i	Auction participant
j	Trading round within slot k
k	Time slot interval
z_a	Constant ($a \in N$ and $a < 5$)
Energy quantities	
$Q_{i,j,k}$	Demand or capacity on sale
$L_{i,k}$	Primary load demand
$B_{current,i,j,k}$	Current SoC (State of Charge)
$B_{max,i}$	Storage system capacity
$C_{i,k}$	Primary generation capacity
Fulfilment levels	
$L_{fulfil,i,j,k}$	% of load requirement
$B_{fulfil,i,j,k}$	% of storage-related demand
$C_{sold,i,j,k}$	% of generation capacity sold
$B_{sold,i,j,k}$	% of stored capacity committed
Prices	
$P_{i,j,k}$	Estimated price of power
$P_{min,i}$	Minimum selling price

Figure 3.4: Description of variables used

Equation (2) represents the demand quantity $Q_{i,j,k}$ of a potential buyer i in the jth round for kth time slot at price $P_{i,j,k}$. The bids and asks are submitted as single limit orders for each round in the format of {quantity, unit price}.

$$Q_{i,j,k} = \left\{L_{i,k} \times \left(1 - L_{fulfil,i,j,k}\right) - k_1 \times \left(\frac{B_{current,i,j,k}}{L_{i,k}}\right) \times P_{i,j,k}\right\} + \left\{\left(B_{max,i} - B_{current,i,k}\right) \times \left(1 - B_{fulfil,i,j,k}\right) - k_2 \times \frac{B_{current,i,j,k}}{B_{max,i}} \times P_{i,j,k}\right\} \quad (2)$$

Similarly, each seller determines a portion of its primary or/and storage capacity to be offered for sale in the j^{th} round at a given price as depicted in equation (3).

$$Q_{i,j,k} = \left\{C_{i,k} \times \left(1 - C_{sold,i,j,k}\right)\right\} + \left\{\left(1 - \frac{P_{min,i}}{P_{i,j,k}}\right) \times B_{current,i,j,k} \times \left(1 - B_{sold,\, i,j,k}\right)\right\}, \; when \;\; P_{i,j,k} > P_{min,i} \quad (3)$$

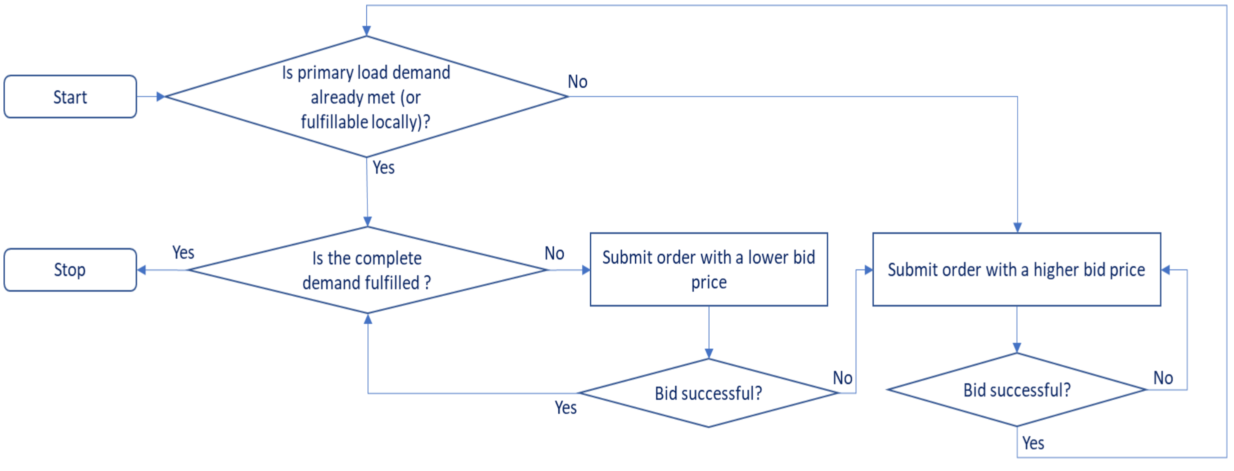

Figure 3.5: Price revision as per different bidding strategies for a buyer

Each buyer revises its price estimate at the end of each round as shown in Equation (4). Fig 3.5 represents the process for determining the revised bid prices by a buyer in the form of a flow chart. The price changes can be linear or non-linear with the number of rounds.

$$P_{i,j+1,k} = P_{i,j,k} \times \left[1 + \left\{ \left(k_3 \times \left(1 + \frac{j_k}{k_4} \right) \right) \times \left({L_{i,k} \times \left(1 - L_{fulfil,i,j,k} \right)} \Big/ {B_{current,i,j,k}} \right)^{1/2} \right\} \right] \tag{4}$$

Similarly, the sellers update their prices after each round as shown in Equation (5). Sellers decide to reduce prices if they are unable to sell off their un-storable primary capacity. Once it is sold off, sellers tend to increase their prices in order to earn profits.

$$P_{i,j+1,k} = \frac{P_{i,j,k}}{1 + \left\{ \left(k_3 \times \left(1 + \frac{j_k}{k_4} \right) \right) \times \left(\frac{C_{i,k} \times \left(1 - C_{sold,i,j,k} \right)}{B_{max,i} - B_{current,i,j,k}} \right)^{1/2} \right\}} \tag{5}$$

3.5 Role of auctioneer

The auctioneer arranges the bids in an increasing order (for asks) and a decreasing order (for bids) as shown in Fig 3.6. Once the bids are sorted, allocation is performed by fulfilling the highest paying bid with lowest ask. For instance, the bid priced at $10.03 per KWh is matched with asks of $3.02 kWh and partially with $5.15 kWh to fulfil its demand of 5.12 kWh. The price discovered is thus unique to each successful transaction.

Asks		Bids	
Quantity	Price	Quantity	Price
4.03 KWh	$ 3.02 per KWh	5.12 KWh	$10.03 per KWh
10.45 KWh	$5.15 per KWh	2.54 KWh	$8.27 per KWh
2.39 KWh	$12.23 per KWh	9.26 KWh	$4.52 per KWh

Figure 3.6: Ordered bids and asks after collection from different participants

The round is open for a pre-defined period and only accepts single limit orders. Each participant dynamically updates its bidding strategy for a round. For instance, the foremost objective of a buyer participant in the initial rounds is to fulfil its primary load requirement. Thus, it is willing to raise its bid prices in a play-safe mode to avoid any unmet demand scenario [25]. A buyer's demand is unmet when its primary load requirement cannot be fulfilled by purchased electricity and/or the local storage.

As the rounds progress and the key objective is achieved, the focus of the buyer shifts to buying additional power at opportunistically low prices. Here, the buyer is more price sensitive and the approach is to store incrementally purchased power for future needs. In this mode, the buyer begins to experiment with a lower bid price and adjusts it in the next rounds according to the success or failure of previous bid. The sellers act in a reciprocal manner.

At the end of the round, the result of each bid (partial success, complete success or complete failure) is unicast to the respective bid owners. Participants can update their set of local parameters on basis of the power quantity they could buy or sell in this round.

The auctioneer uses a set of rules to decide the last round and announce closure of trading for the time slot: i) there are no more bids in the round ii) last n rounds contribute to less than x% percent of the total trade, iii) last m consecutive rounds effectively saw zero quantity being traded. The average slot prices are broadcast to all the participants to inform their bids for the next time slot. The participants draw or supply the committed levels of power during the delivery period and update their SoC.

3.6 Energy marketplace

An energy marketplace was designed to demonstrate the behaviour of the participants in the presence of multiple sellers and buyers (Fig 3.7). Thus, the prototype is designed to depict such a marketplace with a central auctioneer and two sellers as well as two buyer nanogrids. The rationale behind choosing 'two' as the number of sellers or buyers includes i) need for multiplicity of each kind of participant in the demonstration, and ii) a minimum number of each type to ensure simplicity of design. Each participant is unaware of the number of other participants out there in the market. This implies that the behaviour of each participant is indifferent to the number of participants and thus, the proposed system should scale well and work for a higher number of participants as well.

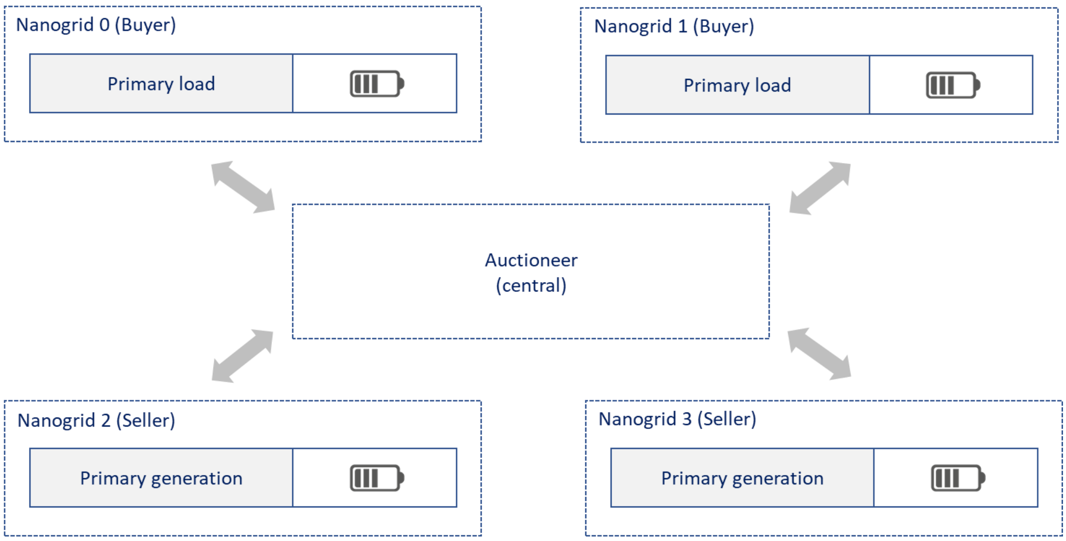

Figure 3.7: An energy marketplace

3.7 Design of benchmark for comparison

The evaluation of the proposed TE system is done by benchmarking its performance characteristics against the uniform price double auction. In a uniform price double auction, the participants submit portfolio bids and thus, essentially share their complete price-quantity curves.

The buyer agents are modelled in a similar manner for the uniform price auction. The demand quantity for a buyer agent participating in this auction is given by equation (6) and the capacity on sale for a seller agent is given by equation (7). The entire energy marketplace designed is also used for the uniform price double auction for comparative evaluation.

$$Q_{i,k} = \left\{L_{i,k} - k_5 \times \left(\frac{B_{current,i,k}}{L_{i,k}}\right) \times P_{i,k}\right\} + \left\{\left(B_{max,i} - B_{current,i,k}\right) - k_6 \times \frac{B_{current,i,k}}{B_{max,i}} \times P_{i,k}\right\} \quad (6)$$

$$Q_{i,j,k} = C_{i,k} + \left\{\left(1 - \frac{P_{min,i}}{P_{i,k}}\right) \times B_{current,i,k}\right\},\ when\ \ P_{i,k} > P_{min,i} \quad (7)$$

The uniform price double auction is a single round auction for a given time slot. The auctioneer announces the opening of auction for a pre-defined period and invites portfolio bids from each participant.

Chapter 4

Implementation

4.1 Description of the prototype

A software prototype was developed to simulate the proposed TE mechanism with two selling as well as two buying participants. Each participant is modelled as a combination of a fixed load (or energy source) and an appropriately sized storage system. Several parameters including a primary load forecast, capacity and SoC (State of Charge) can be configured to initialize the model. Table 4.1 lists the various features of the prototype. Empirical observations from the prototype are reported in the dissertation.

Table 4.1: Features of the proposed prototype

Prototype features			
1	Configuration and initialization		
2	Auction behaviour for single time slot		
	2a	Auction behaviour in a single round	
		2a.i)	Incoming bids (Price and quantity)
		2a.ii)	Quantity traded in the round
		2a.iii)	Demand fulfilment status of buying nanogrids
		2a.iv)	Capacity sale status for selling nanogrids

	2b	% distribution curve Round-wise quantity traded
	2c	History of individual price movements tracked against several parameters
	2d	Comparative history of price movements of all nanogrids
	2e	Updated State of Charge for each nanogrid
	2f	Number of rounds required for each time slot
	2g	Total quantity traded in each time slot
	2h	Weighted average price for each participant
	2i	Average price for buyers and sellers
3	Auction behaviour for multiple time slots	
	3a	Cumulative count of slots witnessing an outage or excess unsold capacity

4.2 Components of the prototype

An interactive input table, as shown in Fig 4.1, allows the user to simulate the TE system under different initial and future conditions. The primary load (or generating unit) and the storage size are rated and fed in kWh. The design assumes that storage sizes are appropriately sized with regards to the primary unit. The initial SoC can be configured in terms of percentage. The initial prices for each participant (at the beginning of simulation of TE system) can also be customized.

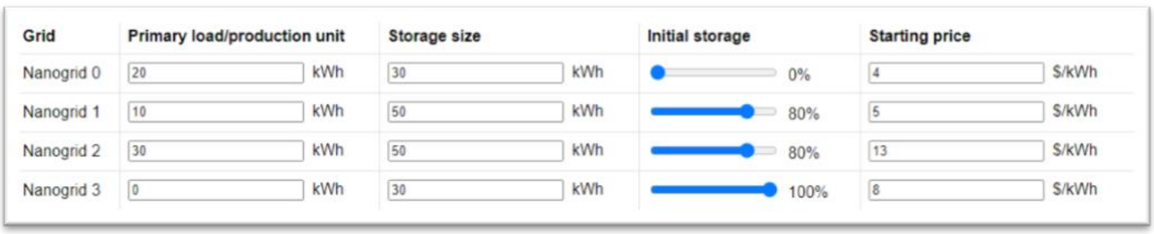

Figure 4.1: Ability to configure initial state

Fig 4.2 shows the second component which summarizes a single round. Various incoming bids from each participant (inputs) are listed and the amount of quantity traded (output) is displayed.

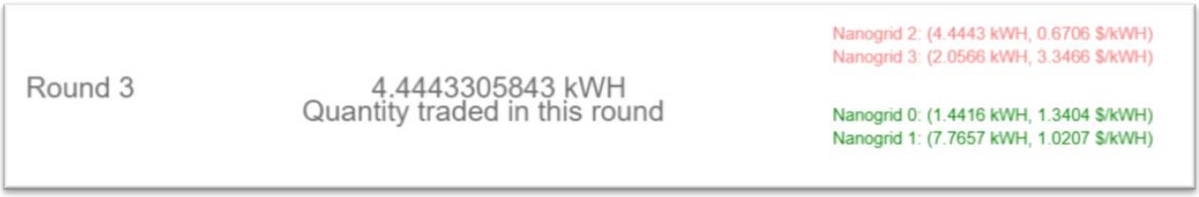

Figure 4.2: Listing of incoming bids and round-wise results

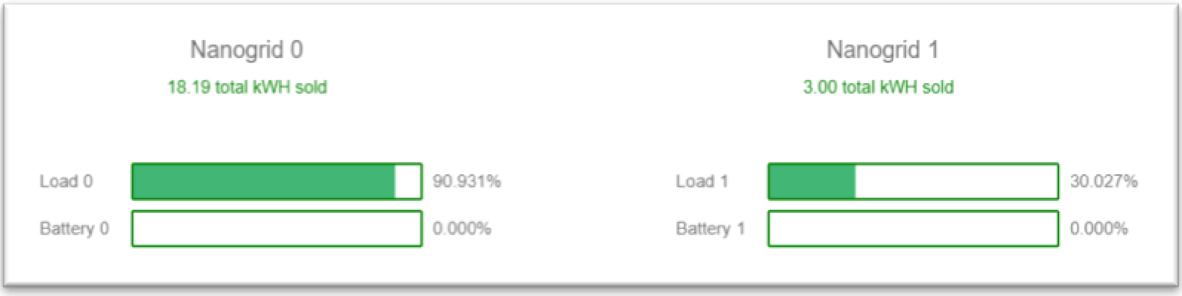

Figure 4.3: Fulfilment of buying and selling nanogrids

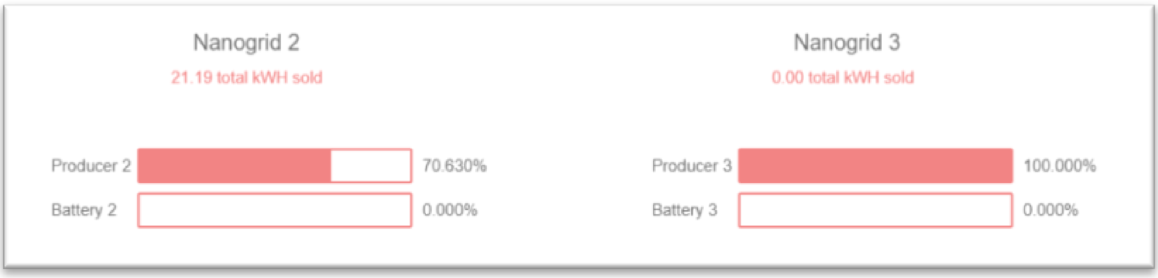

Figure 4.4: Fulfilment of buying and selling nanogrids

Fig 4.3 depicts the degree of demand fulfilment for each buyer participant at the end of each round. The upper horizontal bar reflects the percentage of primary load demand fulfilled. The lower bar indicates the percent of storage-related demand fulfilled. For sellers, Fig 4.4 represents the percent of primary generational capacity and percentage of available storage already committed for sale and delivery till the end of the current round. Fig 4.5 indicates the round-wise percentage distribution of quantity traded across several rounds in a single time slot. This component helps us examine the auction behaviour in terms of quantity traded.

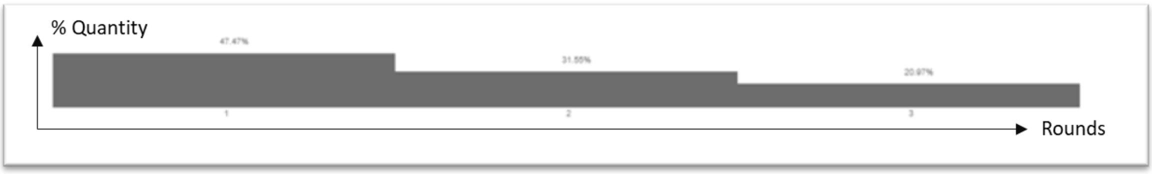

Figure 4.5: Round-wise % distribution of quantity traded

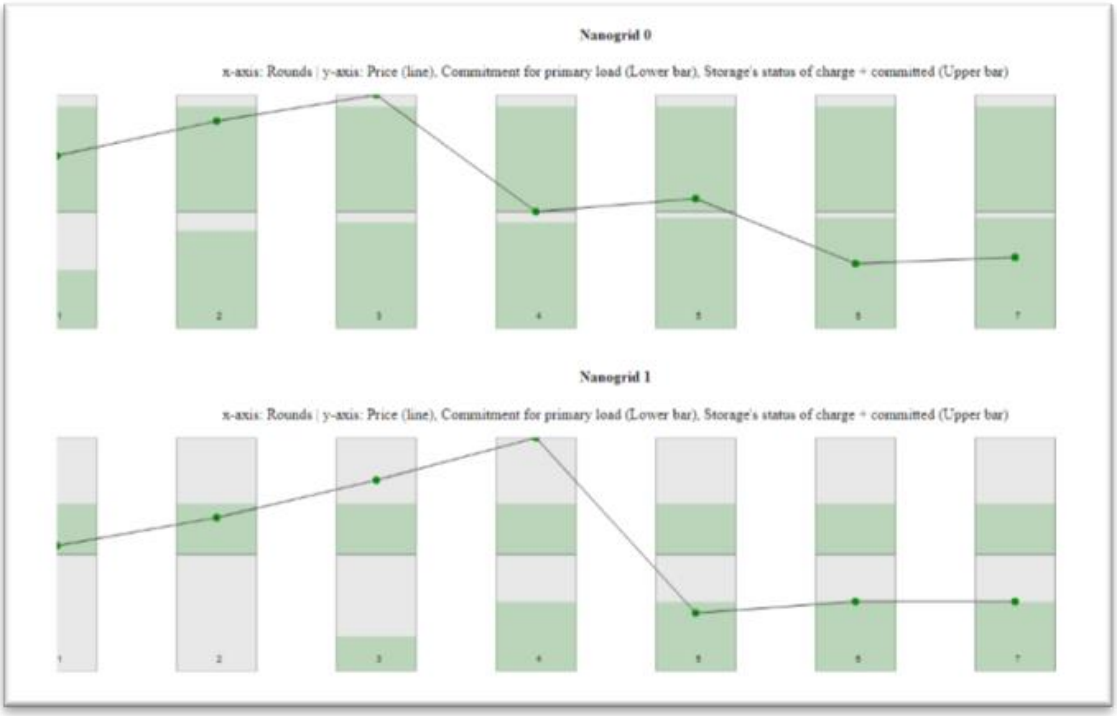

Figure 4.6: Observing price revision for each buying nanogrid with changes in local state and success of last bid

Fig 4.6 represents the historical observations of bid price changes of a buyer nanogrid across several trading rounds in a single time slot. The smooth black lines represent the comparative price change. The lower half of the bar represents the primary load fulfilment and the upper half represents the storage related fulfilment. Similarly, Fig 4.7 similarly represents the observations for seller nanogrids. The horizonal grey line indicates the minimum selling price for each nanogrid.

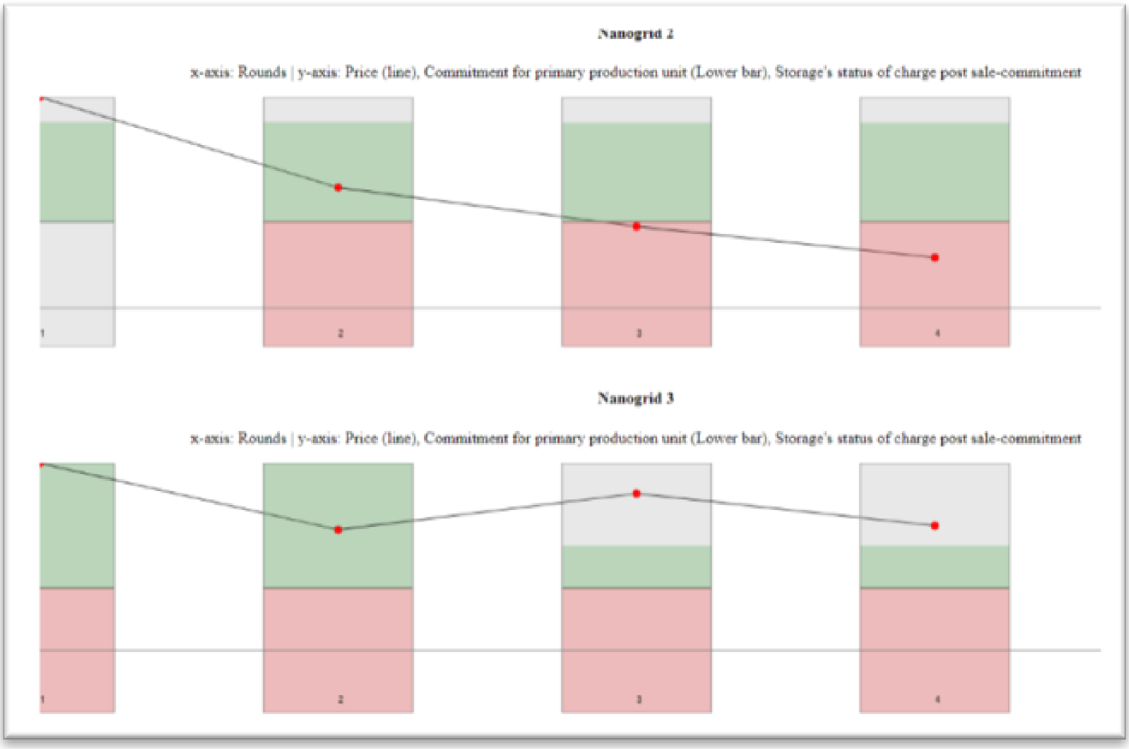

Figure 4.7: Observing price revision for seller nanogrids

The prototype offers an ability to manually or automatically simulate the TE system across various scales of rounds and time slots. Table 4.2 presents an exhaustive list of interactive components in the proposed TE system. A necessary sub-set of these components were also implemented for the uniform price double auction.

Figure 4.8: Proposed TE system across multiple time slots

This process of multiple rounds in a single time slot is further extended to multiple time slots. Fig 4.8 depicts the summary of an individual time slot along with interactive buttons which allow the user to simulate the system in various ways.

Table 4.2: List of interactive components

No.	Interactive Component in the prototype
1	Adjust state of charge, demand forecast, and initial price
2	Run a single round manually
3	Execute and pause a single time slot with multiple rounds automatically with an animation
4	Conclude a single time with multiple rounds automatically
5	Run a single time slot manually
6	Execute and pause multiple time slots automatically

4.3 Implementation of uniform price double auction

Fig 4.9 provides a snapshot of the uniform price double auction implementation. This simulation also uses the same initial conditions for each participant over multiple time slots. Each thin red curve represents the price-quantity curve for an individual seller. Two of these curves are aggregated together to represent the overall selling curve (thick red curve). Similarly, the thinner green curves represent the buyer nanogrids and the thick green curve represents the aggregated buyer behaviour.

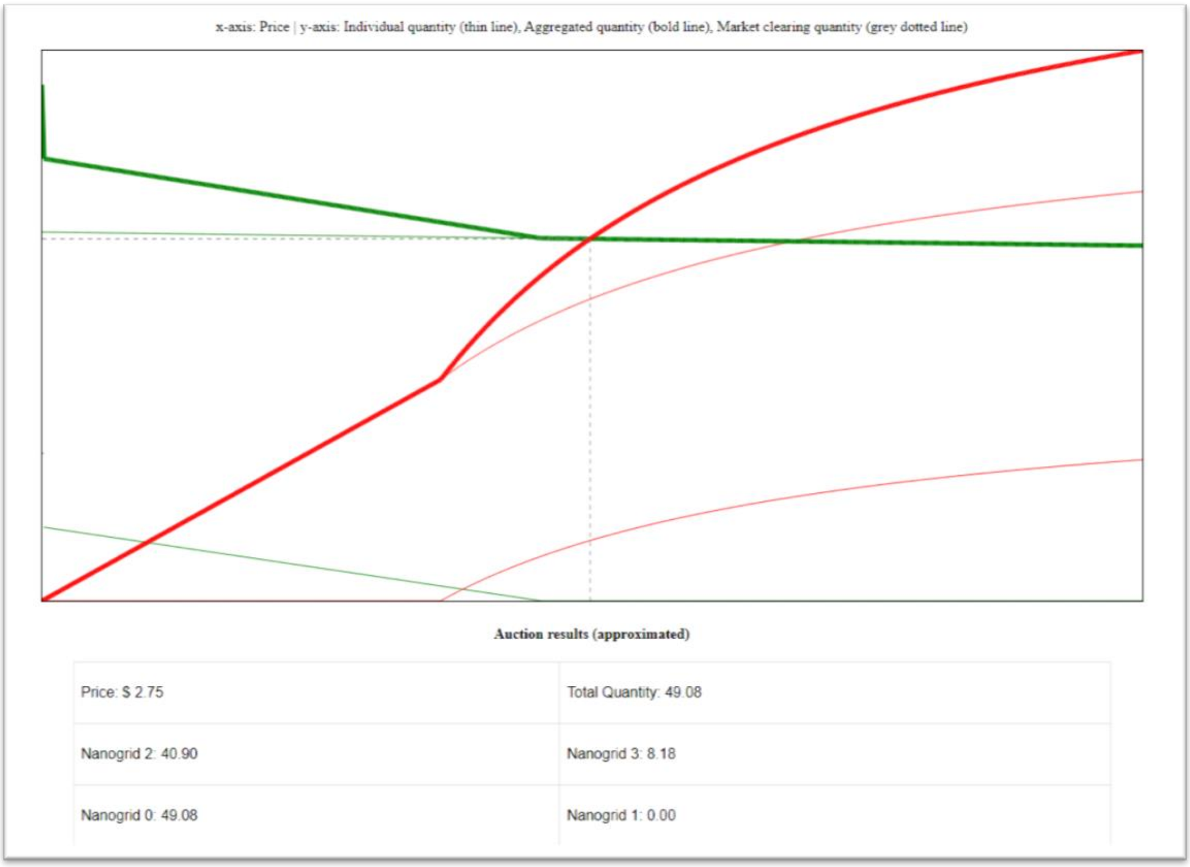

Figure 4.9: Implementation of Uniform price double auction

4.4 Development and deployment

The prototype is an interactive, dynamic, browser-based simulation with animated visualizations available for internal use. It is hosted on an EC2 virtual machine on Amazon Web Services as shown in Fig 4.10. The visualizations act as a tool for better comprehension and investigation of the behaviour of the participants and the auction system. The user can interact with the prototype on the webpage. The trading rounds, over single and multiple time slots, get executed and visualizations get dynamically updated based on the user choice of input.

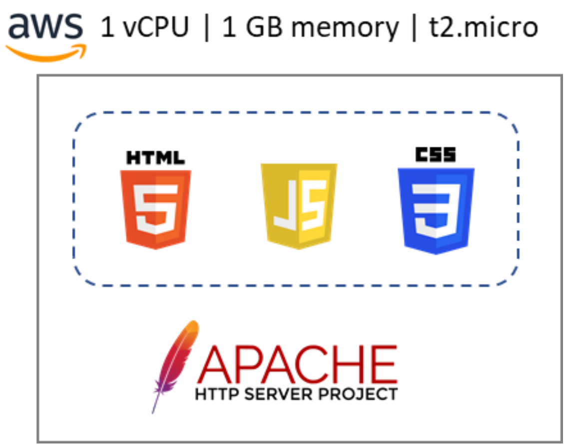

Figure 4.10: A notional representation of prototype deployment

No pre-built library (or software package) was used in developing and implementing this the prototype as well as visualizations and the entire project was built from scratch. The webpage is designed to be served at several browsers. Google Chrome is the preferred browser for this implementation.

The project was written using three 3 client-side languages (HTML, CSS and JavaScript). The components, their roles, dependencies and interactions are described below:

HTML:

a) Definition of DOM elements (headings, canvas, body)

b) Allocation of a pre-defined style class (in CSS) to each DOM element

c) Labelling of each DOM element with unique IDs for dynamic updates using JavaScript

CSS:

a) Style classes defined for input table

JavaScript:

a) Capture of user inputs in form of initial state conditions and prices

b) Simulation of entire energy marketplace, behaviour of each nanogrid and overall auction system

c) Ability to observe dynamic animated visualizations for examination, and conclude the auction to analyse the results

Chapter 5

Discussion

5.1 Evaluation

It was observed that more than 87% of the time slots saw completion of trade in less than or equal to 4 rounds (Fig.5.1). The chosen bidding strategy enables the participants to ensure fulfilment of demand (buyers) and offloading of any excess un-storable capacity (sellers), in the initial set of rounds. Fig.5.2 shows an auction scenario where the auctioneer applies lenient rules for trading slot closure to allow a higher number of rounds. Oscillating prices can be observed in later rounds, since once the primary needs are met, participants operating with limited market information, use a trial-and-error process to engage in negotiations with the objective of making a profit.

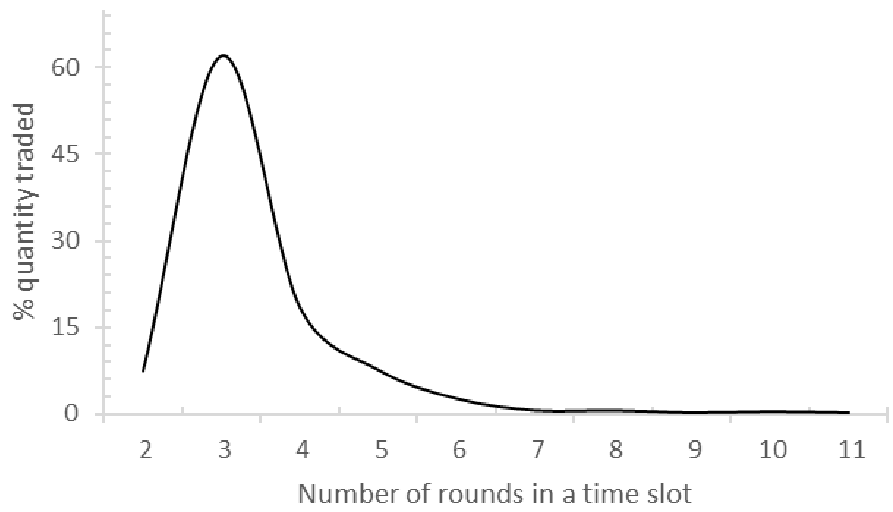

Figure 5.1: Frequency distribution of rounds needed to close the trading in a time slot (500 time slots).

Figure 5.2: A comparative bid price history for four participants across different rounds in a single time slot

We use a uniform-price power auction to benchmark and evaluate the performance of our proposed auction in terms of price volatility [30]. The Price volatility Index (PVI) measures the degree of change in market clearing prices (MCP) across different cycles (or time slots). It is defined as “the root mean square (RMS) of the differences between two consecutive market clearing prices over a period of time”.

Both auction mechanisms were compared under the same test scenario with an identical set of grid participants, initial state conditions and slot-wise energy requirements. The proposed auction yielded a Price Volatility Index (PVI) of 11.47 for buyers and 8.47 for sellers (Fig 5.3). Since the proposed TE system uses discriminatory prices for each transaction across several rounds, a weighted average of bid and ask price of successful transactions is used to depict the price for a given time slot.

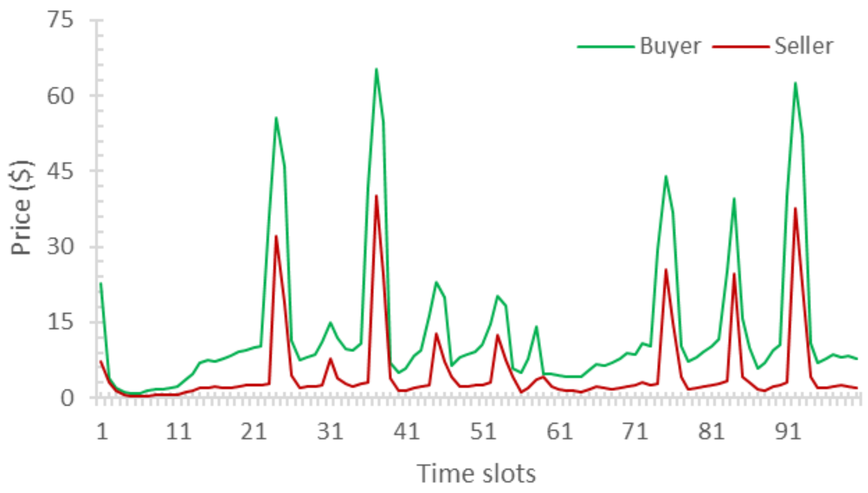

Figure 5.3: Average successful ask and bid prices over different time slots

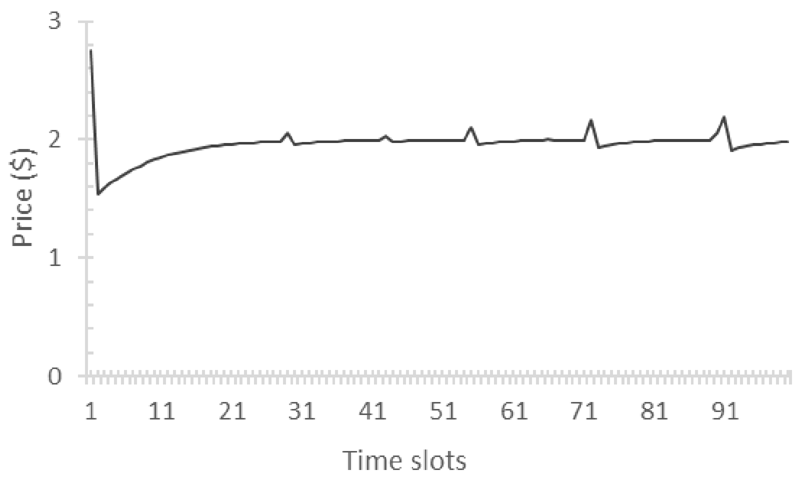

Figure 5.4: Market clearing prices across different time slots in a static auction based uniform price scenario

However, the uniform price double auction uses a single market clearing price for all participants in each time slot. A lower PVI of 0.13 (Fig 5.4) was observed for uniform price auctions with a more stable clearing price across time slots.

A higher PVI can be attributed to the fact that auction inputs contain limited information and participants need to engage in a trial-and-error process to discover prices and make trades. Thus, the ability of a TE system to operate using limited information (with simple bidding requirements and single limit orders) may cause some degree of price volatility. Price volatility can be tolerated to some extent in this scenario since these are high-volume small-ticket transactions meant to serve last minute unmet requirements.

5.2 Future work

The reduction of observed price volatility can be further explored. A hardware demonstration can further improve the quality of simulation and possibly yield more interesting observations. In the current simulation, each participant is designated either as a “buyer” or a “seller”. One of the next steps would be to allow participants to act as prosumers i.e. exercise their own choice to act as either a buyer or a seller in a time slot based on local and grid conditions. The central auctioneer in the design can act as a single point of failure. Thus, the auctioneer services can be designed as a trusted distribution system. Alternatively, the design of an auctioneer can also be explored as a trust-less mechanism, where a participant (or more of them) resolves the auction. The bidding strategy uses information from current slot requirements to optimize its bid. This can be further extended with use of machine learning to analyse past trading patterns as well as factoring in of energy requirements across different time slots. The emergent behaviour of the auction system in such a scenario might be different.

A further refined design of dynamic ad-hoc auction mechanism can yield emergent characteristics that can possibly satisfy all the performance objectives of a real-time TE system. Encouraging empirical results further motivate the need for a mathematical validation of the results and proof of scalability. Such a TE system also needs to qualify as a verifiably fair mechanism for trusted use [31].

Some of the next design enhancements include a suitable choice of granularity and information richness in market signalling responses (broadcasted or unicasted, from the auctioneer to the TE system participants) to improve the quality of bids in the next rounds. The speed of convergence must also be carefully configured, and incentivized, as a very rapid closure hinders the ability of the participants to negotiate and develop prices.

Negotiation between participants can be encouraged at relatively coarser time scales and rapidness can be further incentivized at more-frequent finer time scales. The concept of smart contracts [21] and additional transaction fees [23] can be utilized to accelerate convergence. Other potential dimensions, including a preference for capacity offloading to renewables (supply side) and non-interrupted power to critical users (demand side) also need to be considered.

5.3 Learnings

The concept of nanogrid enables a bottom-up view of the grid. The exercise emphasized focus on how a large system can be built bottom up. It needed design of conceptual abstractions of participating units and a central coordinator and modelling of their individual and collective behaviour. While such a system must ideally be designed to operate in a trust-less environment, the current proposal assumes some degree of trust in a central auctioneer.

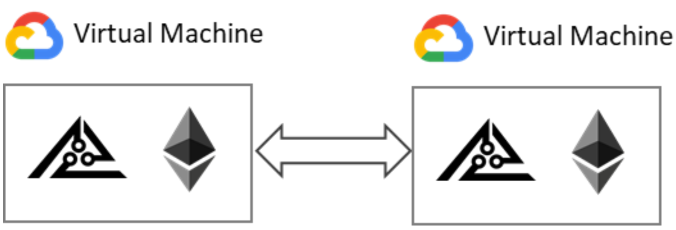

Figure 5.5: An implementation of private Ethereum network

A transaction system which enables trading of electricity and bottom up participation of nanogrids can also leverage a similarly designed payment settlement system based on blockchains. Public blockchain networks like Ethereum and Bitcoin are facing the challenge of transaction throughput scalability. One of the approaches to solve this problem is the introduction of an additional layer, often called Layer-2. This layer enables the participants to perform transactions ‘off-the-chain’. Layer-2 transactions can then be net settled with Layer-1, thereby reducing the number of actual transactions on the main chain.

One of the many initial approaches was the adoption of Layer 2 solution in the context of energy trading between nanogrids. Thus, blockchain Layer 1 was also explored as a pre-cursor to Layer 2 deployment. A private permissioned Ethereum network was implemented on 2 separate virtual machines (Fig 5.5). Once the blockchain was initialized, the capabilities to connect to the peers in the network, as well as, initiate and track transactions were deployed. Ethereum’s JavaScript based Geth client was used to interact with the blockchain.

5.4 Conclusion

In the dissertation, we indicate the use of electric vehicles and household-based solar, battery or combined systems as newer, smaller and pervasive DERs. I emphasize that these new forms of DERs come with complex attributes like i) a fluctuating SoC (State of Charge), ii) varying composition (fixed or schedulable loads and energy sources), iii) diverse sizes (a single electric vehicle to a community of households), and, iv) distributed and non-uniform points of connection (plugging at different locations at different times).

Moreover, these dynamic characteristics of DERs introduce transactional challenges of i) less predictability of last-minute supply and demand, ii) asymmetric information about availability of power and behaviour of other participants, and, iii) need for complete and granular internal information, about each bidder’s behaviour, in the auction inputs to enable price discovery.

Thus, real-time TE mechanisms, which can cater to such challenges, need to i) comply with grid constraints like matching of last-minute supply and demand needs, ii) conclude soon enough requiring minimal computation and communication, for highly frequent and large-scale use, and, iii) seek minimal information in bid submissions to encourage participation of large generating firms as well as smaller DERs.

One can see that the conventional energy trading system was designed keeping in mind a limited number of participants on a centralized grid. It uses uniform price auctions which need access to complete information about participant's individual preferences to determine the price of power. This implies that it may not be a good fit for the new and larger set of smaller distributed participants, who may not be willing to share their detailed information about usage patterns and other preferences with an auctioneer.

Therefore, the design of auctions, which can operate with partial information as an input, is a new and interesting research problem to pursue. I observed through the means of experiment that the proposed auction yielded a relatively higher price volatility in comparison to auctions with complete information. The participants can tolerate a volatility in price as they use this system to transact energy in small quantities to meet their last-minute unmet requirements.

Price volatility in an interesting emergent characteristic of the TE systems under comparison. Uniform price auctions witnessed a lower price volatility as they use a *top-down* approach to determine prices of power. The auctioneer gathers complete and granular market information to arrive at a *uniform* price of power for all participants.

On the other hand, our proposed system uses a *bottom-up* pricing approach to discover prices with partial information. Here, the participants use a trial-and error process to make individual experimental guesses about prices. Each participant has a limited access to market information and thus uses its bidding experience in the prior trading rounds to estimate price. The discovered price of power in this system is unique to each transaction and participant.

Thus, a higher price volatility can be attributed to the TE system's shift in price discovery from a top-down approach (auctioneer-led uniform pricing with complete information) to a bottom-up approach (participant-led discriminatory pricing with partial information).

The main contributions of this work include:

- A multi round periodic double auction which uses discriminatory pricing
- Simplification of bidding format with single limit orders & use of minimal information in price discovery
- Rapid convergence: i) Allows shorter periods of trading (close to real time) ii) Reduces communication frequency
- A performance evaluation of TE system with a prototype-based simulation

This work introduces an advancement in the evolution of TE system which can encourage the participation of smaller DERs on an equal footing with the larger participants. I use empirical results to demonstrate the feasibility of such a TE system with a prototype that simulates a miniaturized energy marketplace. It is imperative to further evaluate the system against scalability and robustness as next steps.

There is an evident transformation in the composition and mobility of a growing set of grid users which prompts a change in the way they participate in the electricity market. An ideal TE system, which can treat electricity as a resource as well as a commodity, must allow its participants to fulfil their energy requirements as well as negotiate for opportunistic trade. In this dissertation, I recognize this need, lay out a brief design, present an initial working mechanism and outline several considerations for further improvements. This work is a first step towards an ad-hoc energy interchange between prosumers which completes quickly, yields a reasonable price with minimum need for information sharing with untrusted parties.

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Appendix

Code construct

function run_a_round(){}

A function which executes a single trading round by inviting order placements from participating nanogrids and identifies and conducts successful transactions

function store_previous_round_price(){}

A function which stores in memory the previous round's bid prices for each nanogrid for a single time slot.

function find_weighted_average_price(argument_bid_output){}

A function which takes in an argument of auction round output and calculates the weighted average price for each nanogrid in the given time slot.

function check_slot_outage_excess(argument_total_slot_trade){}

A function which is invoked upon the closure of trading rounds, takes in the total quantity purchased or sold for the slot, and evaluates if there's an outage or an excess unsold power event during the slot.

function round_quantity(argument_bid_output){}

A function which is invoked in every trading round to calculate and store the history of trade quantities in each round and each time slot

function graph_price_values(){}

A function which stores in memory the history of bid price and SoC values for each nanogrid in each round for a single time slot.

function graph_primary_values(){}

A function which stores the history of status of fulfilment of primary requirements of the nanogrid

function round_percent(){}

A function which evaluates the percentage distribution of quantity traded across different rounds in a single time slot.

function update_demand_quantity(){}

A function which calculates the demand quantity for a buyer nanogrid at a given price on the basis of several local parameters.

function check_positive_demand(grid_number){}

A function which evaluates the sanity of a buyer-prepared bid against satisfactory conditions like non-zero values and returns a boolean flag.

function check_positive_sale_quantity(grid_number){}

A function which evaluates the sanity of a seller-prepared ask and returns a boolean parameter.

function update_seller_quantity(){}

A function which calculates the portion of capacity a seller must put on sale in a round for a given price estimate

function fulfillment_status(round_result){}

A function which is invoked at the end of each round to update the fulfilment status of each nanogrid both on the selling and buying side. It uses the quantity purchased or sold to calculate the ratio.

function update_demand_bid_price(){}

A function which revises the bid price at the end of each round depending on the degree of success in the previous rounds and the fulfilment ratio

function update_sale_bid_price(){}

A function which revises the ask price at the end of each round for each seller on the basis of capacity offloaded in the previous rounds

function create_bid_arrays(call_type,total_bid_array, prosumer_state_array){}

A function which creates 2-dimensional arrays of incoming orders to segregate seller and buyer inputs to the auction

function bid_matching(total_bid_array, prosumer_state_array){}

A function which takes in all the submitted orders as input, calls the respective sorting functions and matches the bids against asks to execute electricity trade

function sort_seller_bids(input_bids_array){}

A function which sorts the received seller asks in an increasing order and return a sorted array to the auctioneer

function sort_buyer_bids(input_bids_array){}

A function which sorts the received buyer bids in a decreasing order and return a sorted array to the auctioneer