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Electricity Markets for DC Distribution Systems: Design Options

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Abstract: DC distribution systems (DCDSs) are a promising alternative to AC systems because they remove AC-DC conversions between renewable sources and loads. Their unique features compared to AC include low system inertia, strict power limits and power–voltage coupling. In a liberalised electricity market, merely applying an AC market design to a DCDS cannot guarantee the latter's supply security and voltage stability; new markets must be designed to meet DC challenges. This article identifies the key design options of DCDS electricity markets. To identify these options, we develop a comprehensive design framework for local electricity markets; to our knowledge, we provide the first such analysis. Whereas previous studies focus on separate aspects of DCDS markets, we widen the scope to include the role of market architecture and investigate the arrangements of sub-markets. As an illustration, we demonstrate three promising DCDS market designs that can be defined in our framework, and provide a first assessment of their performance.

Keywords: electricity market design; direct current; distribution system; local market; flexibility

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1. Introduction

A high proportion of future electric power will be generated by direct current (DC) renewable sources [1–3] and consumed or stored locally by DC or DC-ready devices [4,5]. For instance, micro wind turbines, flywheels, and the motors and heating/cooling devices with variable-speed drives have a DC link (AC-DC or AC-DC-AC conversion). The rise of DC generation and consumption—characterised as prosumption—brings challenges. For instance, on the one hand, more rooftop PVs inject volatile power into distribution networks; on the other hand, vehicle electrification and the deployment of heat pumps may create new load peaks [1] that are an order of magnitude higher than conventional residential load peaks. Energy storage systems (especially batteries) are typically DC by nature, but the need for twice AC-DC conversions has reduced their energy efficiency. These changes pose challenges to the legacy alternating current (AC) distribution system, which typically has low power capacity, high energy losses and complex control due to synchronisation and AC-DC conversions. DC distribution systems (DCDSs), by contrast, facilitate the integration of renewable sources, loads and storage systems by removing such conversions. Compared to AC, a DCDS does not need complex control of synchronisation, inrush current, three-phase imbalances and reactive power [6,7]. Technically, it is also feasible to upgrade existing AC lines into DC lines with remarkably higher power capacity; such upgrades only demand simple changes in tower heads and insulation [8]. While AC networks have simpler voltage transformation and protection mechanisms, a DCDS has higher power capacity, energy efficiency, reliability and simpler control and is a potential competitor to AC systems [6,9,10].

Although regulations empower prosumer participation in electricity markets [11,12], the existing AC markets cannot be applied to a DCDS. The latter's unique technical features, including low system inertia, strict power limits and power–voltage coupling [13], pose new challenges to the market design. First, DCDS substations, either connected to AC or DC transmission systems, are typically converters with much stricter power limits than AC transformers [14]. While the latter have a higher tolerance to temporary overloading, the precision of converter design and manufacturing leaves little room for DC converters to be overloaded. However, rapid electrification and large-scale renewable integration may soon push these substations to congestion. Second, a DCDS mainly consists of non-spinning devices, and its system inertia is much lower [15] than interconnected AC systems with large inertia [1]. Hence, substation congestion management is crucial to a DCDS, because the latter may suffer from severe voltage disturbances once the match between local supply and demand is broken. Third, DC nodal voltage is solely linked to power flow [16]; this is different from AC in which voltage magnitude and power flow can be controlled separately. To sum up, a DCDS is a local system by nature: its network issues, including voltage deviation and network congestion [17], highlight the local value of flexibility and call for energy exchange among flexible prosumers. Merely applying AC market designs to DC may cause voltage stability issues, which motivates the design of new markets tailored to DCDS. Researchers proposed pricing mechanisms to resolve DC congestion and voltage deviations [14,18,19], but few have investigated the economic DCDS operation in a liberalised electricity market. This article is inspired by the overlooked potential of DC at the distribution level and focuses on DCDS markets' short-term economic efficiency, namely minimising system operational costs.

Studies on local electricity markets have focused on prosumer-friendly energy trading [20,21], distribution congestion management [22,23], local ancillary services [24,25] and market implementation [25,26]. However, the broad scope of electricity market research has resulted in market designs with the following negative consequences. First, market designs that ignore crucial design goals are doubtful in terms of credibility and feasibility of implementation. Second, markets aiming at one specific challenge cannot be applied directly to the real world, in which multiple interrelated challenges exist. Third, researchers who study a limited set of design variables have not thoroughly justified this choice of scope. Finally, previous works aimed at single sub-markets did not investigate the strong linkage among the sub-markets, which crucially affect the overall market performance [27,28]. All the above calls for a systematic design framework and specified design options for local electricity markets, yet, to date, there is no consensus on such a framework to our knowledge.

This article provides such a comprehensive market design framework based on an engineering design process (Section 2), and, with it, identifies the key variables that determine a DCDS market's performance. First, we enumerate the common goals of local electricity markets (Section 3). Second, we recognise the design variables that crucially impact market efficiency, and then evaluate the consequences of the choice of each design option (Sections 4 and 5). Whereas previous studies focus on separate markets, we widen the scope to include the role of market architecture and investigate the arrangement of sub-markets. As an illustration, we demonstrate three promising DCDS market designs within our framework (Section 6): *integrated market design*, *locational energy market design*, and *locational Flex market design*. The latter two pay prosumer flexibility (Flex) directly via Flex contracts. We introduce each market's principle and organisation, and then briefly discuss its advantages and challenges. As we conclude in Section 7, this article represents the first step towards a comprehensive DCDS market design and is a preparatory step towards a quantitative study of DCDS markets.

2. Market Design Framework

As we have seen, to date, there is no consensus on a general design framework for local electricity markets. This article develops such a framework based on an engineering design process. We adopt qualitative methods such as literature review and systematic analysis.

Figure 1 illustrates our design framework for local electricity markets, where each block corresponds to a section of this paper. It is based on an engineering design process of identifying goals, determining the design space, testing and evaluation [29]. This article focuses on the first two stages. Whereas previous studies focus on separate markets, we widen the scope to include the role of architecture and investigate the arrangement of sub-markets, as suggested by Stoft [27]. Accordingly, we divide the space into *architecture design*—choice and arrangement of sub-markets—and *sub-market design* that decides detailed trading rules.

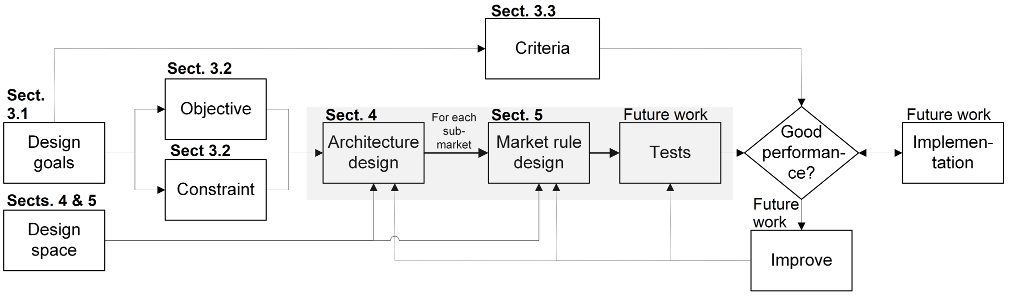

Figure 1. Design framework for local electricity markets.

Notably, as shown in Figure 1, we include a feedback loop and allow step-by-step improvements along with the test and implementation, inspired by the concept of agile design [30]. An electricity market involves complex systems and multiple stakeholders, thus the market design should be done in several iterations, starting with a minimum level of testing [31]. Since both technical systems and prosumers change rapidly, there is no single best market per se but one should improve the designs continuously during the test and implementation.

Electricity market design is an interdisciplinary study involving power systems, economics, computer science and social–environmental issues. Each discipline sets unique and sometimes contradictory requirements. As the *World Energy Trilemma* [32] suggests, the goals of energy security, energy equity and environmental sustainability challenge each other, thus the design must balance them carefully. Section 3 elaborates some unique goals of local markets, such as open access, transparency and simplicity. The negotiable goals become *objectives*, whereas the others become *constraints*. To validate a market design, we need *criteria* that define the minimum required level for each of these goals.

The design space describes the freedom to adjust design variables [33] and represents the feasible region of a design problem, where each variable represents one dimension with a set of design options. Although a large design space allows for diversified markets, it also complicates the choice and validation. We aim to limit the space and focus on those variables crucial to market efficiency.

Market architecture design: The market architecture describes the choice and arrangement of sub-markets [27], each serving a technical function required for system operation. Stoft [27] suggests that the choice of sub-markets, their types, the linkages between sub-markets are three key design variables for market architecture. For local markets, however, we identify the linkage to wholesale markets as the fourth design variable.

Sub-market design: In each sub-market, properly designed rules yield competitive prices and prevent gaming [31] by regulating information and prosumer behaviour. The selection of the design variables is based on a literature review over general electricity markets, balancing markets and flexibility markets. Based on the stages of market operation [34], we categorise the design variables into the general organisation, bid format, allocation and payment, and settlement.

Market designs without comprehensive tests may contain serious flaws that lead to failures [31]. Before implementation, a market must be thoroughly tested against uncertainty and complex prosumer behaviour, by agent simulations or rigorous field tests for instance. One should start with bottom-line tests to identify fundamental design flaws before bringing them into further studies [31]. A set of criteria, unbiased and preferably quantitative, should be used to judge if the design goals are met. We briefly discuss the role of criteria in Section 3.3 and leave the test and implementation for future work.

Due to our focus on short-term economic dispatch, we make the following assumptions. First, for globally efficient market operation, we assume that a converter connects a DCDS to the utility grid, and the price fluctuations of the wholesale markets are passed to final customers. Second, we adopt the general microeconomics assumption that prosumers are self-interested and operate their devices to maximise utility. Third, since a DCDS market requires high-frequency trading, we assume that automatic agents control devices and trade on prosumers' behalf. Fourth, since national energy policies decide taxes and levies, we assume the latter to be outside the scope of local market design.

3. Design Goals

Adopting the design framework of Section 2, this section commences the DCDS market design by stating the goals. Section 3.1 categorises the common market design goals of energy policy documents and technical reports. Section 3.2 divides the goals into objectives and constraints. Section 3.3 briefly discusses the criteria that decide whether the above goals are met or not.

3.1. Listing of the Design Goals

Energy policy documents and technical reports have revealed the goals of electricity markets, as categorised in Table 1 [12,35]. The primary goal is *productive and allocative efficiency*, where efficient prices coordinate efficient prosumption [1]. Next, an efficient market requires *reliable system operation*. Another crucial goal is to *involve prosumers* into the market. Finally, markets should be *practical to implement* in real life. Some goals are inevitably contradictory and require a balance.

Table 1. Design goals of local electricity markets.

Category	Goal	Role
Economic efficiency	efficient production efficient allocation completeness incentive-compatibility complete risk-hedging cost recovery liquidity & competitiveness	objective objective constraint constraint constraint constraint objective
System reliability	sufficient network capacity voltage regulation power balance	constraint constraint constraint
Prosumer involvement	non-discriminatory access information transparency privacy fairness simplicity	constraint objective objective objective objective
Implementability	technical feasibility scalability stakeholder agreement compatibility with wholesale markets consistency with regulations	constraint objective objective objective objective

The market's primary goal is to *produce and allocate resources efficiently* [12]. It should be *complete* so that each tradeable commodity (for which universal participation, exchangeability and cost causation of a service is guaranteed) is exchanged at low transaction costs [27]. Incentive-compatible prices should let prosumers support DCDS [34] as they reflect a resource's scarcity in time [36] and space [37]. A market should provide complete risk-hedging tools [38] and pay off investments in the long run [1]. Given the few players, it should also improve market liquidity [34] and competitiveness [39].

Efficient market operation depends on *system reliability* [40]. The power prosumption of a community-level grid is highly stochastic and hardly predictable, leading to network congestion [37] and voltage deviations [41]. Such issues must be solved immediately in a DCDS, especially if a DC substation cannot be overloaded; otherwise, a low-inertia DCDS must balance local prosumption immediately by unplanned curtailments.

Another goal is *prosumer involvement* [23]: a market should grant prosumers non-discriminatory access [42]. Information transparency [12] facilitates optimal allocation at the cost of prosumer privacy [43]. The allocation and pricing should be fair [35] so that prosumers pay for their actual contribution [23]. The trading rules should be simple enough for prosumers to master [23].

Finally, a market should be *implementable* [37] regarding technical feasibility, scalability, existing stakeholders and regulations. Market clearing mechanisms should be tractable and scalable [44,45]. The market should respect existing stakeholders [46,47], be compatible with wholesale markets [24] and consistent with regulations [42], thereby removing implementation barriers.

3.2. Objectives and Constraints

We further divide the design goals into objectives and constraints, as listed in Table 1 on the right side. A *constraint* limits the design space and lists feasible options, whereas an *objective* evaluates them in order to select design options that meet the goals. Economic efficiency is the fundamental goal and our primary objective. Since wrong incentives reduce economic efficiency, market completeness and incentive-compatibility become constraints. A market should offer stakeholders complete risk-hedging tools and steady revenue to recover investments; hence, they are also considered constraints. Reliability is crucial to power systems and is a constraint: A market should mitigate substation congestion and voltage deviations by matching supply and demand immediately. Prosumer involvement and implementability also play a key role, where the two constraints are non-discriminatory access (in order to support small prosumers) and the technical feasibility (regarding computational and communication complexity). The other goals, by contrast, become the objectives of the market design.

3.3. Criteria

To conclude whether a market design meets the goals, we need unbiased *criteria* that define the minimum required level for each goal. Criteria assist our design choices by: (1) excluding markets that violate design constraints; (2) suggesting the most promising designs with the help of objectives; and (3) indicating the direction of future improvements. This article does not discuss the full set of criteria but gives two examples. As discussed in Section 3.2, reliability is a key concern of power system operation and is a crucial constraint for DCDS market operation. For instance, a DCDS requires immediate power balancing due to strict converter power limits; a violation of this requirement will either lead to unplanned curtailments or a system-wide voltage collapse. Thus, we propose two quantitative criteria, namely a maximum substation congestion ratio (such as 10%) and a maximum nodal voltage deviation (such as ±30V), to verify different market designs for a DCDS. Such verification demands detailed modelling of a DCDS's power network and market players.

4. Market Architecture Design Variables

Sections 4 and 5 investigate the design space of DCDS markets, namely a set of design variables and their options. For each variable, we aim to answer: How is the variable defined? What is its role in the overall market design? Which options are there and what does each option imply?

This section identifies the design variables for market architecture—the choice and arrangement of sub-markets—then lists different options and evaluates their features. Table 2 lists the four design variables on the left, i.e., the choice of sub-markets, their types, the linkages between sub-markets, and the linkage to wholesale markets. The first three are identified by Stoft [27], whereas the fourth one is from our analysis. For each design variable, Table 2 lists the options on the right.

Table 2. Electricity market architecture: design variables and their options.

Design Variable	Design Options
Choice of sub-markets	energy/substation capacity/voltage regulation
Market type	bilateral/organised
Linkage between sub-markets	explicit/implicit
Linkage to wholesale markets	complete/partial

4.1. Choice of Sub-Markets

The choice of sub-markets determines the commodities a market remunerates. It lays the foundation for the incentive scheme. To avoid *missing market* problems [1], a market design should reward all tradeable commodities; a commodity still plays a role even if it is not paid directly [27].

The DCDS operation relies on power dispatch, congestion management, plus various ancillary services regarding voltage regulation, contingency supply, safety, protection and power quality [13]. When deciding which commodities to reward, one should consider non-discriminatory access, completeness (and no repeated remuneration), transaction costs and transparent operation [27]. According to these criteria, (electrical) energy, network capacity (substation capacity in particular) and voltage regulation are qualified for a sub-market [13]. By contrast, the services for contingency supply, safety, protection and power quality have either high entry barriers (technical requirements for instance) or low tradeability (challenging to measure for instance). Therefore, such services should be provided by a distribution system operator (DSO) or regulated by DC network codes. To sum up, energy, network capacity and voltage regulation are the three candidate sub-markets of a DCDS.

4.2. Market Type

The market type describes the arrangement of trading, and it affects the available information in the market. An organised market, such as a pool (with side payments) or an exchange (without these), adopts central clearing and facilitates information exchange [48]. It uses standardised contracts to lower transaction costs but has high requirements for computation and communication infrastructure. Since a DCDS requires small-amount, high-frequency trading, organised markets are advantageous in efficiency, transparency and transaction costs. A bilateral market (based on bulletin boards or brokers) allows peer-to-peer trading and diversified contracts [49], but the information exchange is less efficient and transparent, thus reducing the market efficiency and DCDS security.

At the first stage of implementation, one may choose not to set up a sub-market but instead create a pricing scheme for substation capacity or voltage regulation. If market players are not familiar with such markets, an incentive-compatible pricing signal could still guide them to use resources efficiently.

4.3. Linkage Between Sub-Markets

The linkage between sub-markets is “the heart of market architecture”, which naturally arises because of time, location and financial arbitrage [27]. Implicit linkages are common between sub-markets: in a DCDS, for instance, energy and voltage regulation markets are closely linked due to power–voltage coupling. Implicit linkages lead to information exchange and arbitrages between sub-markets. An explicitly-linked market [50], by contrast, integrates various commodities into one. Figure 2 lists all candidate sub-markets—energy, substation capacity and voltage regulation—and five possible linkages between them (solid lines for explicit linkages and dash lines for implicit ones).

The linkages should contribute to economic efficiency and reduced market complexity [27]. For instance, if the linkages between all sub-markets are explicit, we obtain an *integrated* market that merges various commodities into one (Figure 2d). Explicit linkages may increase market efficiency thanks to improved coordination, but may not if it the value of both sub-markets is not correctly represented [27]. Otherwise, we obtain multi-commodity electricity markets with separate prices for each commodity. Figure 2a represents a locational energy market (hereinafter, a sub-market is referred to as a market if it is clear from the context), which links the substation capacity to energy market via locational energy prices. Figure 2b represents a locational voltage regulation market, where the local flexibility (Flex) for voltage regulation is priced differently at each node of the DCDS. Figure 2c represents an energy market with voltage-based pricing. Finally, Figure 2e represents a market where three sub-markets are organised separately. Further study should balance economic efficiency and the extra complexity an explicit linkage brings.

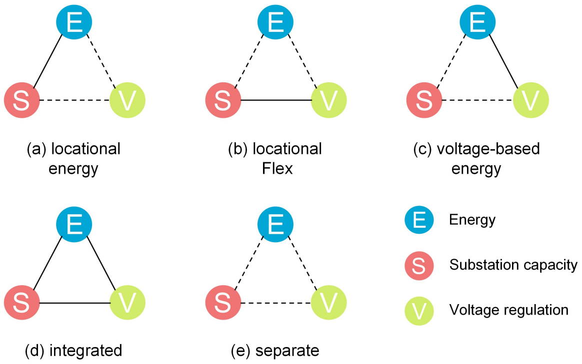

Figure 2. Choice of sub-markets and their linkages.

4.4. Linkage to Wholesale Markets

The above design variables are identified in wholesale markets [27]. For local markets, we identify the linkage to wholesale markets as the fourth design variable, indicating how a local sub-market connects to a corresponding wholesale market [24]. Our motivation is twofold. First, a local market should facilitate prosumer participation in the wholesale market. Second, local resource allocation should aim at the global optimum. Prosumers should be exposed to wholesale market prices so that they share local resources efficiently in a broad marketplace. Here, the design criterion is the completeness [51], i.e., if each sub-market in a DCDS is linked to a wholesale market. A partial linkage hinders globally efficient resource allocation and separates prosumers from the wholesale market. Readers may refer to Tohidi et al. [52] for a more comprehensive review of such linkages.

4.5. Summary

This section identifies some critical design variables of DCDS market architecture and analyses their options. The market architecture sets the foundation for a market design, based on which we set rules for each sub-market. Its design variables are the choice of sub-markets, market type, linkages between sub-markets, and linkage to wholesale markets. Further study should investigate the linkage between sub-markets and its impact on the overall market performance.

5. Sub-Market Design Variables

Section 4 lists the sub-markets of a DCDS and discusses their arrangement. For each sub-market, this section identifies the crucial design variables that affect its efficiency and competitiveness. To the best of our knowledge, Table 3 lists some critical design variables; for each identified variable, the table shows the options on the right. The selection of the variables is based on literature review of general electricity markets [34,53,54], balancing markets [55,56] and flexibility markets [24,25,57].

Based on different stages of market operation [34], we further categorise the design variables into four groups: general organisation, bid format, allocation and payment, and settlement. The *general organisation* decides buyers and sellers. The *bid format* regulates the information gathered from prosumers. The *allocation rules* determine the economic efficiency of the allocation, while the *pricing rules* sets monetary incentives. Finally, the *settlement rules* guarantee the delivery of commodities.

Table 3. Electricity sub-markets: design variables and their options.

Category	Design Variable	Design Options
General organisation	buyer and seller	one-sided/double-sided
	entry requirements	universal/tech-specific, voluntary/mandatory
	info disclosure	fully transparent–fully hidden
Bid format	bid content	simple/complex
	time resolution	1 s–15 min
	gate closure time	1 s–24 h
	locational info	global/zonal/nodal
Allocation & payment	objective	economic efficiency/renewables/self-sufficiency/...
	pricing mechanism	uniform/discriminatory
	price cap	yes/no (or sufficiently high)
Settlement	method	physical/financial
	pricing directions	one-price/two-price
	risk-hedging tools	no/forward market/options/stochastic clearing/...

5.1. General Organisation

The general organisation decides buyers, sellers and the available market information. The design variables are: (1) *the arrangement of buyers and sellers*; (2) *entry requirements*, the conditions for prosumer participation; and (3) *information disclosure policy* related to prosumers' privacy.

Arrangement of buyers and sellers: The arrangement of buyers and sellers defines the supply and demand side of a market. It has a major influence on the market structure, namely, different parties' market share and their competition. The design variable is the bidding sides [58]: one-sided or double-sided. A one-sided market has either a monopoly (for instance, in substation capacity auctions) or a monopsony (for instance, in frequency regulation markets), whose significant market power reduces economic efficiency. By contrast, a double-sided market promotes competitions on both sides and is preferred when possible.

Entry requirements: Entry requirements are the conditions (or obligations) for a prosumer to enter a market. An entry barrier can be a minimum size of bidding quantity or qualification of performance; such barriers prevent non-discriminatory access and thus reduce market liquidity. If open access is a major consideration, we should remove technology-specific entry requirements, so that flexible generation, flexible loads and storage systems are equally treated [12]. Mandatory participation yields more predictable market volume and prices, but all the prosumers should accept it.

Information disclosure policy: The information disclosure policy decides to which detail prosumers should reveal private information. While public information (local prosumption forecasts and wholesale prices) should be fully transparent to support prosumers' decisions, bids and allocation results contain sensitive, private information [59]. Disclosing truthful information may yield more efficient allocation [57], yet it should be safe and beneficial to prosumers (one option is to publish anonymous or aggregated bids) [60]. Hence, one should balance information transparency and privacy.

5.2. Bid Format

The bid format determines the information gathered for allocation. The design variables are: (1) the *bid content*, the information a prosumer's bid contains; (2) *time resolution* of allocation; (3) *gate closure time*, the deadline for bid submission; and (4) the inclusion of prosumer's *locational information*.

Bid content: The bid content is the information a prosumer's bid contains. More information potentially increases market efficiency but challenges computational tractability. Simple bids with price and quantity are commonly used in power exchanges, whereas complex bids with additional costs, constraints and location [61] are used in power pools. In energy and substation capacity markets, simple bids may be sufficient because the services are identical. In flexibility markets, however, players are much different in operational constraints so complex bids may be necessary.

Time resolution: A bid resolution is the fineness of allocation or payment in time [56], price [62], or quantity [63]. A low-inertia DCDS is vulnerable to real-time substation congestion, so the market needs small-amount, high-frequency trading. Regarding this, the price and quantity resolutions can be set high to facilitate prosumer participation. However, the time resolution, which is bound by 1 s (DCDS response speed) and 15 min (wholesale market response speed), should be chosen carefully. Although a higher time resolution matches local supply–demand more accurately [53], it increases the computational and communication burden of the market clearing.

Gate closure time: The gate closure time is the deadline for bid updates. Its lower bound is set at the acceptable uncertainty level, and the upper bound is limited to the system response time. Both bounds are much lower in a DCDS market than in wholesale markets. Variable renewables push up the upper bound to one day to address uncertainty; DC converters and flexible devices push down the lower bound to 1 s thanks to their prompt response. A later gate closure allows the use of more accurate, updated information [53], whereas an earlier one provides more flexibility.

Locational information: The locational information, included in prosumer bids, indicates the spacial scarcity of a resource [64]. A DCDS relies on locational information for congestion management and voltage regulation. Nodal pricing ameliorates this reliance through incentive-compatible prices, but it has challenges with large numbers of nodes. Zonal pricing is sufficient if congestion only occurs at some critical points (such as substations) that divide the DCDS into several price zones.

5.3. Allocation and Payment

The allocation rules decide to whom and how a market allocates resources. The payment rules, on the other hand, reward the accepted bids adequately, thereby setting the bidding incentives. Both rules affect market efficiency and prosumers' welfare. The design variables are: (1) the *objective*, the desired direction of resource allocation; (2) the *pricing mechanism* for the allocation; and (3) the *price cap* that limits a commodity's price.

The objective: The objective quantitatively describes the desired direction of resource allocation. The primary objective of a DCDS market is economic efficiency under reliability constraints. Other objectives such as integration of local renewables or community energy self-sufficiency may be considered as well.

Pricing mechanism: The pricing mechanism defines at which price a deal is closed [65]; it lays the basis of the incentive scheme. Payment is either universal (such as in uniform price auctions) or discriminatory (such as in pay-as-bid auctions) among market parties [53]. Universal pricing schemes are incentive-compatible and more predictable. However, marginal pricing may yield high prices; in such cases, we may consider discriminatory pricing, although it can be vulnerable to strategic bidding.

Price cap: A price cap (or floor) sets the maximum (or minimum) price of a commodity. In European wholesale markets, the energy price cap ranges from 150 to 3000 Euro/MWh [53]. Although it is meant to protect consumers against extreme prices, it limits prosumer's scarcity rents and affects incentive-compatibility. To avoid *missing money* problems [1], we suggest avoiding price caps or keeping them sufficiently high [46], for instance to the value of the lost load.

5.4. Settlement

Finally, a market operator should settle transactions to guarantee the delivery of commodities. The design variables are: (1) the *method* to deliver a commodity; (2) the *pricing direction* when settling deviations; and (3) *risk-hedging tools* to deal with market uncertainties.

Settlement method: The settlement method defines the way a commodity is delivered. It is: (1) physical, if the commodity must be delivered in real time; or (2) financial, when cash payments are sufficient [66]. A physical settlement guarantees supply security (typically with penalties for non-delivery), but the limited market liquidity may invite market power. A financial settlement yields higher liquidity thanks to arbitrageurs and is preferable in forward markets for risk hedging [34].

Settlement pricing directions: The settlement pricing direction defines whether the deviation of a contract is settled at different prices for long and short positions [67]. It affects incentive-compatibility and investment incentives. The one-price settlement acknowledges the equal position of flexible generation, demand response and storage. However, their dispatching costs are different in real time, so we may consider a two-price settlement to make payments incentive-compatible.

Risk-hedging tools: A DCDS has high operational uncertainty that risks the reliability and market efficiency. Such uncertainty stems from generation availability, load fluctuation, wholesale markets, bidding behaviour, among others [68]. Since high uncertainty distorts market efficiency and prosumer welfare, a DCDS market should offer risk-hedging tools, such as forward markets [69], options [70], or stochastic clearing with risk measures [61].

5.5. Summary

This section lists the design variables of local electricity market rules and analyses their options. For each sub-market, we must set rules for general organisation, bid format, allocation and payment, and settlement. The choice of a design variable must carefully balance conflicting design goals; further quantitative studies might be warranted. Variables for which this is relevant include the information disclosure policy, time resolution, gate closure time and allocation pricing rules.

Table 4. A brief comparison of three market designs.

Market Design	**IM**	**LEM**	**LFM**
Explicit linkage	all sub-markets	energy–network capacity	Flex–network capacity
Commodity	integrated product	locational energy + Flex	energy + locational Flex
Flex payment	implicit	explicit, non-location-specific	explicit, location-specific
Advantages	optimal dispatch in theory, incentive-compatible price	promoting Flex deployment, liquid Flex market	promoting free energy trading and Flex deployment, Flex at right places
Challenges	privacy issue, sophisticated clearing algorithm, unpredictable price	standard Flex contract, Flex pricing, Flex at wrong places; if a DSO sells Flex: distorted incentive, tariff fairness	standard Flex contract, Flex pricing, less liquid Flex market

6. Three Promising Market Designs

This section demonstrates three illustrative examples of DCDS market designs and provides a first qualitative verification of our design method in Section 2. Table 4 compares the three promising designs that fit into our framework, i.e., *integrated market (IM) design*, *locational energy market (LEM) design* and *locational Flex market (LFM) design*. Regarding market architecture (Section 4), we chose designs with all the required sub-markets. Regarding sub-markets (Section 5), we chose simple, fast and efficient mechanisms that facilitate prosumer participation. Whereas the architecture distinguishes these market designs, the sub-market rules also affect their overall performance. In Table 4, Rows 2–4 list the market features and the last two rows compare their advantages and disadvantages.

6.1. Integrated Market (IM) Design

An integrated market design explicitly links all the three sub-markets to create an integrated product, which remunerates energy as well as substation capacity and voltage regulation. The principle of this design is illustrated in Figure 2d. The only commodity is the electrical energy available at a specific time and location. The real-time price reflects the temporal and locational scarcity of energy, whereas the price fluctuation implicitly remunerates prosumers for providing flexibility.

Such design represents a centrally organised market based on security-constrained economic dispatch, where the objective is economic welfare maximisation. For global market efficiency, the opportunity for trade between the local market and the wholesale market should be maximised. All prosumers are involved in the mandatory real-time market. They submit complex bids, including their devices' state, constraints and additional costs. Prosumers are charged (paid) by their marginal contribution to the system, resulting in real-time locational marginal prices.

This design provides incentive-compatible prices, but challenges are privacy and the need for sophisticated market clearing algorithms. While prosumers are not familiar with the integrated product, they need to submit private information; hence, the market requires their trust. Meanwhile, the sophisticated market clearing requires considerable computation and communication infrastructure. If flexibility is needed and present, this market design is theoretically optimal, unlike the next two designs that we discuss. Further, since local energy prosumption is volatile, the local energy price may be unpredictable, which could be mitigated by the introduction of a voluntary forward market.

6.2. Locational Energy Market (LEM) Design

The second design, as shown in Figure 2a, explicitly links energy and network capacity markets into a locational energy market (LEM) while leaving voltage regulation in a standalone market. The LEM optimally allocates energy under network constraints; an example is locational marginal (energy) pricing [71], which is widely adopted in the US wholesale markets.

As stated in Section 1, voltage regulation of a DCDS requires local changes in energy prosumption and is therefore dependent on local flexibility (Flex). The DSO, who is responsible for voltage regulation, can provide this as a system service or contract it from prosumers in an explicit Flex market. Although LEMs have been studied for DC [14,18,19], few researchers have discussed the use of Flex trading for DC voltage regulation. Below, we discuss a case with and one without an explicit Flex market.

6.2.1. Flex Market for Voltage Regulation

In this case, Flex is an explicit, standard commodity which the DSO purchases from prosumers. It is defined as an option to adjust prosumers' power in real time. Flex contracts directly remunerate prosumer flexibility in addition to their revenues from energy trading. Other parties who may purchase Flex include wholesale market players such as balance responsible parties or aggregators [72]. A Flex market creates new business models for storage systems and demand response. In this market design, Flex payments are universal across the DCDS and are not location-specific; compared to the next design, this one has higher liquidity thanks to larger supply. However, as the Flex market is not location-specific, there is no guarantee that Flex will be deployed where necessary. Since the LEM takes care of power matching, the Flex market can be settled less frequently to improve scalability.

6.2.2. The DSO Provides Voltage Regulation

This case represents the current DSO model: Flex is a service provided by the DSO, who passes the costs along to prosumers in its tariffs [72]. A DSO may own or rent flexible devices and use them for voltage regulation [10]. One challenge is that voltage deviations may increase because prosumers are not incentivised to limit them. Another challenge is to set distribution tariffs fairly: instead of maximising prosumer welfare, a DSO may overcharge prosumers or deploy Flex for extra profit.

6.3. Locational Flex Market (LFM) Design

The third design, depicted in Figure 2b, explicitly links Flex and network capacity markets in a *locational Flex market* (LFM), while keeping the energy market standalone. An LFM aims to bring prosumers into wholesale energy markets by resolving local network issues. It acknowledges the locational value of flexibility [73] and aims to attract Flex investments to where they are needed.

The organisation of an LFM is similar to a standalone Flex market in Section 6.2.1, except that the Flex prices vary by location. The market must strictly respect DC network constraints; as real-time Flex dispatch requires extensive information from prosumers, the LFM should be centrally organised and will be less scalable than the Flex market in Section 6.2.1. As the number of providers may be very limited, we adopt pay-as-bid auctions to mitigate gaming and to lower DSOs' Flex procurement costs.

Flex markets, including LFMs [74,75], are not well studied and may generate new challenges. First, Flex products and contracts are difficult to standardise due to their complex constraints. A Flex contract may set requirements for ramping speed, energy capacity, response delay and tracking accuracy. Notably, some Flex providers, such as storage systems and flexible loads, have strong inter-temporal constraints. Second, Flex pricing is challenging because it depends on both the condition of the DCDS and the state of each Flex device. Third, Flex markets may be susceptible to market power because of their low liquidity.

7. Conclusions

This article identifies the key design options of electricity markets for DC distribution systems (DCDSs). Compared to AC systems, a DCDS has higher power capacity, energy efficiency, reliability and simpler control—anticipating the future where a large amount of renewable power is generated and consumed locally in DC. We develop a comprehensive design framework for local electricity markets to structure alternative options. To our knowledge, we provide the first such analysis.

The unique features of DCDS, such as low system inertia, strict power limits and power–voltage coupling, make a DCDS market fundamentally different from AC: it requires short response times, precise congestion management (as DC converters cannot be overloaded) and a different approach to voltage regulation. A DCDS is a local system by nature where flexibility has a high local value and needs to be exchanged for economically efficient DCDS operation.

The major elements of a DCDS *market architecture* are *energy* delivery, the provision of *substation capacity*, and *voltage regulation*. It is possible to provide all three services by creating a sub-market for each, such as a local energy exchange, a substation capacity auction and a payment scheme for voltage regulation. However, we found that DC energy and voltage regulation markets are interlinked due to power–voltage coupling: DC nodal voltage is a function of flexible power generation and consumption. Compared to the case with a DSO regulating voltage, the inclusion of a prosumer-oriented Flex market may provide the same service with better price incentives and higher economic efficiency.

For each selected *sub-market*, we analysed the design options for the general organisation, bid format, allocation and payment, and settlement. However, the choice of some design variables must trade off conflicting design goals. The degree of *information disclosure* should balance information transparency and prosumer privacy. The *time resolution* should balance a DCDS's need for short response time (efficient prosumption) and the computational burden (technical feasibility). The *gate closure time* should balance a lower power matching error (efficient prosumption) and higher flexibility for DC voltage regulation (system reliability). The *allocation pricing* rules should balance incentive-compatibility and market competitiveness (few players).

Our systematic analysis of the design options led to three promising DCDS markets. First, the *integrated market design* explicitly links three sub-markets (for energy, substation capacity and voltage regulation) to create a single commodity—an integrated product. It aims at incentive-compatible, volatile price signals that encourage prosumers to resolve congestion and voltage issues, but the challenges are privacy concerns and the need for sophisticated market clearing algorithms. Second, the *locational energy market design* links energy and substation capacity markets but leaves voltage regulation separate. Although a DSO may provide the latter as a system service, the introduction of a Flex market may offer the same service with better prosumer incentives. Third, the *locational Flex market design* links Flex and network capacity markets, thereby encouraging prosumers to help regulate DC voltage at the most critical nodes. However, further study should resolve issues regarding product definition, pricing and market power prevention.

Building on our design framework, the next step is to analyse the design options using quantitative criteria, each corresponding to a design goal in Section 3. An important direction for future work is the development of quantitative models to compare the performance of different market designs. For market architecture, further studies should balance economic efficiency and the extra complexity an explicit linkage brings. For sub-markets, researchers should balance conflicting goals by adjusting four design variables, namely the information disclosure policy, time resolution, gate closure time and allocation pricing rules. This analysis could be, for example, based on the IEEE European Low-Voltage Test Feeder (upgraded to DC). Lastly, to develop DCDS markets that are technically feasible and economically efficient, researchers should test these market designs against uncertainty and strategic behaviour.

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Abbreviations

AC	Alternating Current
DC	Direct Current
DCDS	Direct Current Distribution Systems
DSO	Distribution System Operator
Flex	(local) flexibility
IM	integrated market
LEM	locational energy market
LFM	locational flexibility market
PV	photovoltaics

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