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Piao, L.

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ELECTRICITY MARKETS FOR DIRECT CURRENT DISTRIBUTION SYSTEMS

LONGJIAN PIAO

ELECTRICITY MARKETS FOR DIRECT CURRENT DISTRIBUTION SYSTEMS

Dissertation

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by

LONGJIAN PIAO

Master of Science in Electrical Engineering,
Technische Universität Berlin, Berlin, Germany, and
Shanghai Jiao Tong University, Shanghai, China
born in Anshan, Liaoning, China

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

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献给我的家人

To my family :)

CONTENTS

SUMMARY

Direct current distribution systems (DCDS) are a promising alternative to alternating current (AC) systems because they remove AC–DC conversion between sources and loads that cause energy losses. Compared to AC systems, a DCDS has higher power capacity, energy efficiency and reliability, and no need for synchronisation—suitable where a large amount of renewable power is generated and consumed locally in DC.

A DCDS has unique features that affect its implementation: low system inertia, strict power limits and power–voltage coupling. Hence, simply applying markets designed for AC cannot guarantee a DCDS's supply security and voltage stability. This dissertation aims to identify DC-tailored local market designs that facilitate a DCDS's operational efficiency and reliability under uncertainty.

To identify promising DCDS market designs from all feasible options, we developed and applied a comprehensive design framework for local electricity markets. It is based on an engineering design process of identifying goals, determining design space, testing and evaluation. Whereas previous studies focused on individual commodities, we widened the scope to include the role of *market architecture*. Its main element is the choice of sub-markets for energy delivery, the provision of DC-substation capacity, and voltage regulation. For each selected *sub-market*, we analysed the design options for the general organisation, bid format, allocation and payment, and settlement. Considering the design complexity, we performed three rounds of market design according to the agile development principle: a qualitative assessment, a quantitative analysis without uncertainty, and a quantitative analysis under uncertainty.

In Step 1, we analysed the design options and identified three types of DCDS market designs according to the above framework, each featuring a unique architecture. First, the *integrated market* (IM) design explicitly links three sub-markets (for energy, substation capacity and voltage regulation) to incorporate all system costs into energy prices. It aims to create price signals that encourage prosumers to resolve congestion and voltage issues, but the challenges are privacy concerns and sophisticated market clearing. Second, the *locational energy market* (LEM) design relieves congestion with nodal prices–by linking the energy and substation capacity markets–whereas a system operator regulates the voltage. Third, the *wholesale energy price* (WEP) market design passes such prices directly to local prosumers, whereas the system operator resolves all network issues.

In Step 2, we quantitatively analysed how the market design addresses DC technical characteristics, such as volatile energy prosumption that challenges DC-substations. We built a deterministic optimisation model to evaluate three market designs, with a one-minute resolution to reflect the local prosumption volatility. Recognising that both total demand and demand flexibility may increase significantly in the future, we included a high share of electric vehicles (EVs) to test the market robustness. Simulations of a realistic urban DCDS demonstrated that the IM and LEM designs manage network congestion and voltage deviation even with a large share of EVs. It is found out that the main

challenge to distribution-level market design is network congestion, mainly due to flexible prosumption at low-price hours. Voltage deviation and cable power capacity are not limiting factors of an urban DCDS market design. However, simply passing wholesale prices to local prosumers (like in the WEP design) is discouraged, as it may cause severe congestion and substantial flexibility investments.

In Step 3, we demonstrated the economic efficiency and reliability of the LEM design also under uncertainty. The performance of a local energy market is dominated by the uncertainty from stochastic local power prosumption, fluctuating wholesale energy prices, and unforeseen EV availability. We presented a novel agent-based model to evaluate the LEM design's performance in realistic scenarios. This model describes typical electric-vehicle user preferences and their bidding strategies with different levels of range anxiety. To stress-test LEM, we created challenging scenarios with a high share of solar generation and EVs. It performed efficiently and reliably in simulations, based on the high-resolution 2018 Pecan Street database and the IEEE European Low Voltage Distribution Test Feeder, even with a high share of EVs. We demonstrated that regardless of the bidding strategy, the LEM achieves efficient DCDS operation, as long as the network constraints are not too tight. Hence, we conclude that the simple LEM design—with only price–quantity bids and DC-substation capacity constraints—is the best feasible option among the three designs.

Although both DCDS technologies and the concept of local energy markets are still under development, we presented viable market solutions based on the best practices in the emerging DC technology, thereby clearing its market-side implementation barrier. The most economically-efficient yet technically feasible market design, at least in urban DCDS applications, is the LEM design. It supports fast market clearing and real-time control over flexible devices to resolve DC substation congestion. Other market designs, namely the IM and WEP, were proven to have practical limitations.

In the future, we recommend testing, improving and verifying the LEM design in field tests with real prosumers and various flexibility sources. This dissertation made assumptions and simplifications on both the technical system and the market operation, thereby leaving room for further development. First, the optimisation model and the agent-based model could be improved to enable more realistic market simulations. Second, a simple, user-friendly yet efficient agent module should be developed to enable high-frequency energy transactions in a DCDS. Third, follow-up research should estimate upon prosumers' bidding and investment incentives: the impact of additional price components—transmission and distribution system costs, national taxes and levies. Fourth, we should also evaluate the influence of prosumer values—including privacy, energy equality and energy self-sufficiency—on the local energy market design.

SAMENVATTING

Gelijkstroomdistributiesystemen (direct current distribution system, DCDS) zijn een veelbelovend alternatief voor AC systemen omdat zij AC-DC-omzettingen tussen bronnen en belastingen vermijden. Een DCDS heeft een hoger vermogen van het netwerk, hogere energie-efficiëntie en betrouwbaarheid, een eenvoudigere regeling en is geschikt vooreen toekomst met veel hernieuwbare energie die lokaal wordt opgewekt en verbruikt.

DCDS hebben unieke kenmerken die hun implementatie beïnvloeden: lage systeeminertie, strikte vermogenslimieten en koppeling van vermogen en spanning. Daarom kan het simpelweg toepassen van de markten die ontworpen zijn voor AC-systemen de leveringszekerheid en de spanningsstabiliteit van een DCDS niet garanderen. Deze dissertatie heeft als doel om op DC afgestemde, lokale marktontwerpen te identificeren die een efficiënte en betrouwbare werking van DCDS onder onzekerheid kunnen faciliteren.

Om uit alle mogelijke opties veelbelovende DCDS-marktontwerpen te identificeren, hebben wij een ontwerpproces voor lokale elektriciteitsmarkten ontwikkeld en toegepast. Gebaseerd op een engineering-ontwerpproces, bestaan de stappen hiervan uit het identificeren van doelstellingen, het bepalen van de ontwerpruimte, testen en evalueren. Terwijl eerdere studies zich richten op individuele markten, verbreden wij de scope naar de rol van de *marktarchitectuur*. Het belangrijkste element ervan is de keuze van de deelmarkten voor energielevering, voor de levering van omvormercapaciteit en voor de spanningsregeling. Voor elke geselecteerde *deelmarkt* hebben we de ontwerpopties geanalyseerd met betrekking tot de algemene organisatie, het format van de biedinging, de allocatie en betaling, en de settlement. Vanwege de complexiteit van het ontwerp hebben wij het marktontwerp in drie ronden ontwikkeld volgens het agile ontwikkelingsprincipe: een kwalitatieve beoordeling, een kwantitatieve analyse zonder onzekerheid, en een kwantitatieve anlayse met onzekerheid.

Stap 1 analyseerde de ontwerpopties en identificeerde drie soorten DCDS-markten, elk met een unieke architectuur. Een *geïntegreerde markt* (IM) koppelt drie deelmarkten expliciet om alle systeemkosten in de energieprijzen op te nemen. Het is de bedoeling prijssignalen te creëren die prosumenten ertoe aanzetten congestie- en spanningsproblemen op te lossen, maar de uitdagingen liggen op het vlak van de privacy en een verfijnde market clearing. Een *lokale energiemarkt* (LEM) lost congestie op met nodal pricing - door de markten voor energie en convertercapaciteit te koppelen - terwijl een systeembeheerder de spanning regelt. Een marktontwerp met *groothandelsprijzen voor energie* (wholesale energy price, WEP) berekent de groothandelsprijzen rechtstreeks door aan de lokale verbruikers, terwijl de netbeheerder alle netwerkproblemen oplost.

Stap 2 analyseerde kwantitatief hoe het marktontwerp rekening moet houden met de technische eigenschappen van gelijkstroom, zoals de uitdaging die de volatiele energieprosumptie vormt voor de DC-converter. We hebben een deterministisch optimalisatiemodel gemaakt om de drie marktontwerpen te evalueren, met een resolutie van één minuut om de volatiliteit van het prosumptievermogen weer te geven. Zowel de

totale vraag als de vraagflexibiliteit kunnen in de toekomst aanzienlijk toenemen, dus hebben we een groot aantal elektrische voertuigen (EV) opgenomen om de robuustheid van de marktontwerpen te testen. Simulaties van een realistisch, stedelijk DCDS toonden aan dat de IM en LEM ontwerpen netwerkcongestie en spanningsafwijkingen kunnen goed managen, zelfs met een groot aantal EVs. We ontdekten dat de grootste uitdaging voor het marktontwerp van een distributiesysteem netwerkcongestie is, voornamelijk ten gevolge van flexibele prosumptie op uren met lage prijzen. Spanningsafwijkingen en kabelvermogencapaciteit zijn geen beperkende factoren voor een stedelijk DCDS-marktontwerp. Het simpelweg doorgeven van groothandelsprijzen aan lokale prosumenten (zoals in het WEP-ontwerp) wordt echter niet aangeraden omdat dit ernstige congestie kan veroorzaken die aanzienlijke investeringen in flexibiliteit vereist.

Stap 3 demonstreerde de economische efficiëntie en betrouwbaarheid van het LEM-ontwerp onder onzekerheid. De prestaties van een lokale energiemarkt worden in grote mate beïnvloed door de onzekerheid met betrekking tot lokaal stroomverbruik, schommelende groothandelsprijzen voor elektriciteit en onzekere beschikbaarheid van EVs. We presenteren een nieuw agentgebaseerd model (ABM) om het LEM-ontwerp in realistische scenario's te evalueren. Het model gebruikt standaardvoorkeuren van gebruikers van elektrische voertuigen en hun biedstrategieën met verschillende niveaus van range anxiety. We ontwerpen uitdagende scenario's met een hoog aandeel van zonne-energie en EVs om het LEM ontwerp te stresstesten. Het marktontwerp presteerde efficiënt en betrouwbaar onder onzekerheid in simulaties op basis van de hoge resolutie 2018 Pecan Street dataset en het IEEE EULV Test Feeder, zelfs bij een hoog aantal EVs. We toonden aan dat de LEM zorgt voor efficiënt management van een DCDS, ongeacht de biedstrategie van de EVs, zolang de netwerkbeperkingen niet te krap zijn. Daarom concluderen wij dat het eenvoudige LEM-ontwerp, met enkel prijs-hoeveelheid biedingen en een capaciteitsbeperking op de DC-converter, de best haalbare optie is van de drie ontwerpen.

Terwijl zowel DCDS-technologie als het concept van lokale energiemarkten nog in ontwikkeling zijn, hebben wij een haalbaar marktontwerp ontwikkeld op basis van de beste praktijken in de opkomende DC-technologie, waardoor de belemmering voor de implementatie ervan aan de marktzijde wordt weggenomen. Het LEM-ontwerp is het economisch meest efficiënte marktontwerp dat ook technisch haalbaar is. Het is ontworpen om een snelle marktvereffening en real-time controle over flexibele apparaten te ondersteunen om congestie in de DC-convertor op te lossen. Andere marktontwerpen, namelijk de IM- en WEP-ontwerpen, blijken praktische beperkingen te hebben.

Het LEM-ontwerpmoet nu nog getest, verbeterd en geverifieerd worden in veldproeven met echte prosumenten en flexibiliteitsbronnen. Wij zijn uitgegaan van veronderstellingen en vereenvoudigingen met betrekking tot zowel het technische systeem als de marktwerking waardoor er ruimte is voor vervolgonderzoek. Ten eerste kunnen het optimalisatiemodel en het ABM worden verbeterd voor realistische marktsimulaties. Ten tweede moet een eenvoudige, gebruiksvriendelijke maar efficiënte agentmodule worden ontwikkeld voor de hoogfrequente energietransacties. Ten derde moet met vervolgonderzoek het effect van extra prijscomponenten op de bied- en investeringsprikkels van prosumenten worden geschat. Ten vierde moet ook de invloed van belangen van prosumenten - privacy, energiegelijkheid en energiezelfvoorziening - worden geëvalueerd.

ZUSAMMENFASSUNG

Gleichstromverteilungssysteme (direct current distribution system, DCDS) sind eine vielversprechende Alternative zu AC-Systemen, da sie die AC-DC-Umwandlung zwischen Energiequellen und -lasten und auch die Energieverluste vermeiden. Im Vergleich zu AC-Systemen bietet ein DCDS eine höhere Leistungskapazität, Energieeffizienz und Zuverlässigkeit und erfordert keine Synchronisierung. Es ist geeignet, wo ein großer Teil von erneuerbaren Energien lokal in DC erzeugt und verbraucht wird.

DCDS weisen einzigartige Merkmale auf, die sich auf ihre Umsetzung auswirken: geringe Systemträgheit, strenge Leistungsgrenzen und Leistungs-Spannungs-Kopplung. Daher kann die Versorgungssicherheit und Spannungsstabilität eines DCDS nicht durch die Anwendung von AC-Marktdesigns gewährleistet werden. Diese Dissertation zielt darauf ab, auf DC zugeschnittene lokale Marktdesigns zu identifizieren, die einen effizienten und zuverlässigen DCDS-Betrieb unter Unsicherheit ermöglichen können.

Um aus allen Optionen vielversprechende DCDS-Marktdesigns zu identifizieren, haben wir einen umfassenden Designrahmen für lokale Strommärkte entwickelt und angewandt. Er basiert auf einem ingenieurwissenschaftlichen Designprozess: Identifizierung von Zielen, Bestimmung des Designraums, Testen und Bewertung. Während sich frühere Studien auf einzelne Designvariablen konzentrierten, haben wir den Rahmen erweitert und die Rolle der *Marktarchitektur* mit einbezogen. Das wichtigste Element davon ist die Auswahl von Teilmärkten für die Energielieferung, die Bereitstellung von DC-Konverterkapazitäten und die Spannungsregelung. Für jeden *Teilmarkt* analysieren wir die Designoptionen für die allgemeine Organisation, die Gebotsform, die Zuteilung und Bezahlung sowie die Abrechnung. Wegen der Designkomplexität wird das Marktdesign nach dem Prinzip der agilen Entwicklung in drei Runden durchgeführt: eine qualitative und zwei quantitative Analysen, jeweils ohne und mit Unsicherheit.

In Schritt 1 analysierten wir die Optionen und identifizierten drei Marktdesigns für DCDS mit einzigartigen Architekturen. Der *integrierte Markt* (IM) vereint drei Teilmärkte ausdrücklich miteinander, um alle Systemkosten in die Energiepreise einzubeziehen. Die Preissignale ermutigen Prosumenten, Netzengpass- und Spannungsprobleme zu lösen, aber die Herausforderungen liegen im Datenschutz und in der komplexen Markträumung. Der *lokale Energiemarkt* (LEM) entlastet Netzengpässe mit Knotenpreisen – durch Verknüpfung der Märkte für Energie und Konverterkapazität, während ein Netzbetreiber die Spannung reguliert. Das Marktdesign vom *Großhandel-Energiepreis* (wholesale energy price, WEP) gibt die Großhandelspreise direkt an die lokalen Prosumenten weiter und verlässt sich darauf, dass der Netzbetreiber alle Netzprobleme löst.

In Schritt 2 haben wir eine quantitative Analyse durchgeführt, wie das Marktdesign die technischen Merkmale der DC-Versorgung berücksichtigen sollte, wie z. B. den volatilen Energieverbrauch für einen DC-Konverter. Wir haben ein deterministisches Optimierungsmodell entwickelt, um drei Marktdesigns bei schwankendem Energieverbrauch mit einminütiger Auflösung zu bewerten. Weil sowohl die Gesamtlasten als auch ihre

Flexibilität in Zukunft erheblich steigen können, haben wir einen hohen Anteil an Elektrofahrzeugen (EV) mit einbezogen, um die Robustheit der Marktdesigns zu testen. Simulationen eines realistischen städtischen DCDS haben gezeigt, dass die IM- und LEM-Design selbst bei einem hohen Anteil an EV mit Netzengpässen und Spannungsabweichungen umgehen können. Wir haben festgestellt, dass die größte Herausforderung für das Marktdesign auf Verteilerebene die Netzüberlastung ist, die hauptsächlich auf den flexiblen Verbrauch zu Niedrigpreiszeiten zurückzuführen ist. Spannungsabweichungen und Leitungskapazitäten sind keine limitierenden Faktoren für ein städtisches DCDS-Marktdesign. Von einer einfachen Weitergabe der Großhandelspreise an lokale Prosumenten (wie im WEP-Design) wird jedoch abgeraten, da dies zu erheblichen Netzengpässen und umfangreichen Flexibilitätsinvestitionen führen kann.

In Schritt 3 haben wir die wirtschaftliche Effizienz und Zuverlässigkeit des LEM-Designs unter Unsicherheit nachgewiesen. Die Marktoperation wird in hohem Maße durch die Ungewissheit des stochastischen lokalen Stromverbrauchs, schwankenden Großhandelspreisen und die unvorhergesehene Verfügbarkeit von EV beeinflusst. Deshalb haben wir ein neues agentenbasiertes Modell vorgeschlagen, um das LEM-Design in realistischen Szenarien zu testen. Das Modell beschreibt typische Präferenzen von EV-Nutzern und ihre Gebotsstrategien bei verschiedenen Range-Anxiety. Wir haben anspruchsvolle Szenarien mit einem hohen Anteil an Solarstromerzeugung und EV entworfen. In Simulationen, die auf der hochauflösenden Pecan-Street-Datenbank 2018 und IEEE EULV Test Feeder basieren, zeigte das System eine effiziente und zuverlässige Leistung unter Unsicherheit, selbst bei einem hohen Anteil an EV. Wir haben gezeigt, dass alle die Gebotsstrategien können einen effizienten DCDS-Betrieb zu gewährleisten, solange die Netzengpässe nicht zu eng sind. Das einfache LEM-Design, bei dem nur Preis-Mengen-Gebote und Netzengpassbeschränkungen für die DC-Konverter gelten, ist die beste realisierbare von den drei Optionen.

Obwohl sich sowohl die DCDS-Technologien als auch das Konzept der lokalen Energiemärkte noch zu entwickeln sind, haben wir praktische Lösungen für die Marktdesigns entwickelt, die auf den besten Praktiken der aufkommenden DC-Technologien basieren und so die Barriere für die marktseitige Umsetzung beseitigt. Das wirtschaftlich effizienteste Marktdesign, das auch technisch machbar ist, ist das LEM-Design. Es ist so konzipiert, dass es eine schnelle Markträumung und die Echtzeitsteuerung flexibler Geräte unterstützt, um Netzengpässe bei DC-Konvertern zu beseitigen. Andere Marktdesigns, nämlich das IM- und das WEP-Design, haben sich in der Praxis als begrenzt erwiesen.

In Zukunft sollten wir das LEM-Design in Feldversuchen mit echten Prosumenten und verschiedenen Flexibilitätsquellen testen, verbessern und verifizieren. In dieser Dissertation wurden Annahmen und Vereinfachungen sowohl für das technische DC-System als auch für den Marktbetrieb getroffen. Im Vergleich dazu können das Optimierungsmodell und das agentenbasierte Modell noch verbessert werden, um realistischere Marktsimulationen zu ermöglichen. Ein einfaches, benutzerfreundliches und dennoch effizientes Agentenmodul sollte entwickelt werden, um die hochfrequenten Energietransaktionen zu ermöglichen. Weiter sollten wir die Auswirkungen zusätzlicher Preiskomponenten auf die Angebotsabgabe und die Investitionsanreize der Prosumenten bewerten. Schließlich müssen die Auswirkungen der Verbraucherwerte, nämlich Privatsphäre, Energiegleichheit und Energieautarkie, auch bewertet werden.

总结

直流配电系统（direct current distribution system, DCDS）是交流配电系统的一个强有力的替代方案。前者消除了电源与负载之间的交直流转换及网损，因此功率容量更大、能源效率更高、可靠性更强，控制更加简易，适合接纳未来电力系统中的大量可再生电源以及直流负载。

尽管直流配电系统的性能优于交流，但其特有的低系统惯性、严格的功率限制和功率——电压耦合特性也将为其运行带来挑战。若将交流电力市场直接投入直流系统运行，将无法保证后者的供电安全和电压稳定。本论文旨在找出适合直流的本地配网电力市场设计，确保直流配电系统在不确定性条件下高效、可靠运行。

为了从所有可行方案中找出最有前途的市场设计，我们提出了一个完备的本地电力市场设计框架。该框架基于工程设计流程，包含目标确定、标定设计空间、测试、评估等几大步骤。此前研究大多集中于单种电力商品，而本文则着重强调了市场架构的作用。市场架构（market architecture）主要针对电力子市场进行选择，包括本地电能市场、变电站容量市场以及调压市场，同时规定这些市场之间的耦合形式。对于每一个选定的子市场（sub-market），我们按组织方式、投标格式、分配与支付、结算四个步骤，对交易规则进行综合设计。考虑电力市场的复杂性，我们根据敏捷开发原则执行了共计三轮市场设计：定性评估，确定性下的定量分析以及不确定性下的定量分析。

第一步，我们根据上述框架分析了市场设计的诸多选项，从而确定了三种不同架构下的直流配电市场设计。一体化市场设计（integrated market, IM）明确地将三个子市场（即电能、变电站容量和调压市场）耦合起来，从而把所有系统成本均纳入电价中。它用价格信号鼓励产销者解决网络阻塞和电压问题，但隐私问题和复杂的市场清算将成为挑战。本地电力市场设计（locational energy market, LEM）将电能和变电站容量市场进行耦合，通过节点电价缓解阻塞，而由系统运营商单独负责调压。批发电价市场设计（wholesale energy price, WEP）则将批发电价直接传递给本地产销者，而系统运营商负责解决所有网络问题，但其在产品定义、定价和防范市场力等方面仍存在挑战。

第二步，我们定量分析了市场设计应如何满足直流的技术要求，因为负荷波动会对直流变电站构成挑战。建立确定性优化模型，利用分钟级的负荷波动评估三种市场设计。考虑到未来电能的总需求及需求弹性都将显著增加，我们通过大规模电动汽车接纳的情景测试了市场的稳健性。实际的直流配电系统仿真表明，即使城市中有大量电动汽车存在，IM和LEM设计也能解决网络阻塞和电压偏离问题。我们发现，配网市场的设计难点主要来自低电价时段的用电高峰，以及它所带来的网络阻塞，而电压偏差和电缆容量通常并不是城市直流配电网的瓶颈。仿真也表明，不应简单地将批发价格传递给本地的产销者（如WEP设计下），否则将导致严重的网络阻塞及大量的资产投资。

第三步，我们验证了上述LEM市场设计在不确定性下的经济性和可靠性。本地电力市场的性能很大程度上受不确定性的影响，包括本地电力消费波动、批发电价波动以及电动汽车接入情况等。我们提出了一个新的智能体模型（agent-based model, ABM），该模型描述了典型的电动汽车用户偏好及其不同里程焦虑程度下

的竞价策略。在Pecan Street 2018高分辨率数据库与IEEE欧洲低压配电测试馈线的压力测试中，我们发现，即使光伏与电动汽车电动车份额非常高，LEM仍然能够高效、可靠地运行。由此证明，在网络约束不严格的情况下，所有竞价策略均可实现LEM在直流配电系统中的高效运行。LEM虽然仅含价格——数量投标信息与直流变电站容量限制，但却是三种设计中的最佳可行方案。

尽管直流配电技术和本地电力市场等概念仍有待发展，我们仍可以基于当下直流技术的最新进展为其进行市场设计，从而清除其市场方面的准入壁垒。在城市直流配电中，LEM是最经济且技术上最可行的市场设计，通过快速的市场结算以及对柔性设备的实时控制，解决了直流变电站的阻塞问题。同时，我们也验证了IM和WEP在现实运行中仍旧存在诸多局限。

未来，我们将在实地测试中利用真实的产销者与柔性负荷对LEM进行测试、改进和验证。本论文对直流配网和市场运行做了假设和简化，仍有进一步改善的空间。首先，应改进优化模型和智能体模型，以提高市场仿真的真实度。其次，应开发一个简单、用户友好且高效的智能体模块，以支持直流市场所需的高频交易。第三，应考虑市场中其他价格成分对消费者的投标与投资动机的影响——包含输配电系统成本与其他税费等。第四，应进一步评估隐私、能源平等和能源自给等消费者价值对本地电力市场设计的影响。

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Longjian Piao
Bayreuth, 1 May 2022

LIST OF ABBREVIATIONS

ABM	agent-based model (modelling)
AC	alternating current
DC	direct current
DCDS	direct current distribution system
DSO	distribution system operator
EULV	European low voltage distribution test feeder
EV	electric vehicle
Flex	local prosumer flexibility
IM	integrated market
LEM	locational energy market
LFM	locational Flex market
LMO	local market operator
PTU	programme time unit
PV	photovoltaic
SOC	state of charge
WEP	wholesale energy price

LIST OF PARAMETERS

t	dispatch interval in set $\mathscr{T} = \{1,\dots,T\}$
g	PV array in set $\mathscr{G} = \{1,\dots,G\}$
l	inelastic load in set $\mathscr{L} = \{1,\dots,L\}$
w	wholesale energy market
e	EV in set $\mathscr{E} = \{1,\dots,E\}$
f	Flex battery in set $\mathscr{F} = \{1,\dots,F\}$
n	power node in set $\mathscr{N} = \{1,\dots,N\}$
a	sparse index set for lines in set $\mathscr{A} = \{1,\dots,A\} \subset \mathscr{N} \times \mathscr{N}$
p_t^g	power production of inflexible PV generator g at time t
p_t^l	power consumption of inelastic load l at time t (negative)
p_t^w	power imported from the wholesale market at time t, $p_t^w \in [-\overline{p^w}, \overline{p^w}]$
p_t^e	power charged into EV e at time t (negative), $p_t^e \in [\underline{p^e}, 0]$
p_t^f	power output of Flex battery f at time t, $p_t^f \in [-\overline{p^f}, \overline{p^f}]$
$p_t^{f+(-)}$	power discharged (charged) by Flex battery f at time t, $p_t^{f+(-)} \in [0, \overline{p^f}]$
v_t^n	voltage at node n at time t, $v_t^n \in [\underline{v}, \overline{v}]$
p_t^n	net power injection into node n at time t
i_t^n	net current injection into node n at time t
ω^a	line resistance of line $a \in \mathscr{A}$
p_t^a	power flow of line $a \in \mathscr{A}$ at time t, $p_t^a \in [-\overline{p^a}, \overline{p^a}]$
f_t^a	current flow of line $a \in \mathscr{A}$ at time t, $f_t^a \in [-\overline{f^a}, \overline{f^a}]$
$t_{a(d)}^e$	time of arrival (departure) of EV e, $1 \leq t_a^e < t_d^e \leq T$
u_t^e	range anxiety factor of charging EV e at time t, $u_t^e \in [0,1]$
$b_{t,u=x}^e$	bidding price of EV e at time t with range anxiety x
$p_{t,u=x}^e$	bidding power of EV e at time t with range anxiety x, $p_t^e \in [\underline{p^e}, 0]$
q_t^e	energy that the LMO allocates to EV e at time t
r_t^e	SOC of EV e at time t, $r_t^e \in [0,1]$
$r_{a(d)}^e$	SOC of EV e upon arrival (departure)
r_t^f	SOC of Flex battery f at time t, $r_t^f \in [0,1]$
η^e	energy efficiency of EV e charging
$\eta^{f+(-)}$	energy efficiency of Flex battery f discharging (charging)
c^e	energy capacity of EV e
c^f	energy capacity of Flex battery f
λ^f	depreciation cost of Flex battery s per amount of discharged energy
λ_t^w	wholesale energy price at time t

1

INTRODUCTION

1.1. WHY DIRECT CURRENT?

The energy sector is transitioning to a more renewable and flexible system. Power distribution systems are embracing an increasing share of distributed energy resources. The ongoing electrification of residential and commercial consumption is changing the pattern of energy consumption. This is causing challenges to the distribution network, which is not dimensioned for this scenario. Electric vehicles (EVs), home batteries and other flexible loads may contribute to a considerable share of peak loads. Since renewable supply and energy demand often do not coincide, the distribution systems need to be adapted to improve energy efficiency, maintain system reliability and postpone expensive network expansions.

Currently, we are using alternating current (AC) systems, designed for conventional, fossil-fuelled turbine generators and rotating motors to connect emerging direct current (DC) devices. However, a high proportion of renewable power sources such as photovoltaic (PV) systems and most wind turbines generates DC power by nature [5]–[7]. The generated power is usually consumed or stored locally by DC devices [8], [9], such as EVs and home batteries. Connecting DC devices with AC requires AC-DC conversions and typically leads to higher energy losses, lower reliability and a need for complex control for unnecessary synchronisation and conversion.

Direct current distribution systems (DCDSs) are a promising alternative to legacy AC systems, because they remove AC-DC conversions between renewable sources and loads that cause inefficiencies. A high proportion of future electric power will be generated by DC renewable sources [5] and consumed or stored locally by DC-ready devices [8]. Connecting these via bipolar DC[1] offers higher power capacity, energy efficiency, reliability and the capability of meshed operation, especially in systems with bidirectional power flow [10]. Meanwhile, DC converters can be cheaper than AC transformers in the future,

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Parts of this chapter have been published in [1]–[4].

[1] A bipolar DC operation can provide up to twice power capacity compared to that of the unipolar operation. We simulated unipolar DC in Chapter 3 but switched to bipolar in Chapter 4 to accommodate higher demand.

because the former uses much less raw materials such as copper and iron [11]. The use of DC converters also improves a DCDS's control flexibility and system response speed, thanks to the fewer conversion steps between PV panels, batteries and electronic loads, as indicated in [12]. All these features will make DCDSs outperform the existing AC systems in the foreseeable future.

1.2. WHEN DC MEETS ELECTRICITY MARKETS

Although DCDSs outperform AC systems, their unique operational features, including low system inertia, strict power limits and power-voltage coupling [1], demand a DC-tailored electricity market design for an efficient and reliable system operation. We will briefly discuss these DC features below. The DCDS operation should be compatible with liberalised electricity markets imposed by law in many countries. Electricity markets are implemented to facilitate the efficient operation of their power system (short-term) and to guide the investment decision of their generation capacity (long-term). This dissertation focuses on the local system operation and its short-term market design, aiming to decrease a DCDS's operational costs by using the network capacity more efficiently.

Low System Inertia. In AC distribution networks, system frequency is coupled to the transmission network through a substation. If a local power imbalance happens, the inertia of all AC generators immediately provides (or absorbs) large amounts of kinetic energy to compensate this power imbalance, whereas the system frequency is kept close to its nominal value. In a DCDS, however, power generation is largely dependent on non-spinning units such as PV panels and fuel cells. The system's mechanical inertia is very low [13] and cannot be counted on to support a DCDS's voltage level.

Strict Power Limits. A DCDS relies on converter-based substations and device interfaces to loads and generators. Unfortunately, such converters are typically designed to have little overload capacity. If local generators cannot meet the local demand due to network congestion, the system voltage will drop rapidly and the DCDS operation will collapse quickly. To prevent this, one can increase the system inertia by installing synchronverters [13] with power-intense storage systems, such as flywheels or supercapacitors, but they are very costly at present. Another approach is to mitigate congestion by real-time[2] coordination of local power prosumption. This approach avoids large investments but requires real-time coordination between prosumers, for instance under the framework of a local energy market.

Power–Voltage Coupling. DC voltage control cannot be performed by reactive power compensation, as in AC [3], but only by active power control. Unlike AC networks where line inductance dominates (active) power flow, line resistance dominates a DCDS' power flow [14]. This leads to a direct coupling between power and voltage (P-V): in a resistive DC network, sending out (or absorbing) large amounts of power can substantially raise (or lower) the nodal voltage in the area. Nodal voltage is a key system indicator in DC.

The above DC-specific characteristics require a new local electricity market design tailored to a DCDS, whereas merely applying the above AC market designs to a DCDS may affect the latter's reliability [3]. The AC markets, designed for a large synchronised

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[2] This dissertation distinguishes the resolution of real-time market operation (one second to 15 minutes) from that of real-time congestion management (milliseconds, out of our research scope).

power system, cannot resolve the unique DC issues such as converter congestion and voltage issues. The potential consequences, including unexpected power supply interruption and poor voltage stability, will negatively affect the public acceptance of the promising DC technology.New markets must be designed tailored to a DCDS, so that the latter can be accepted by both the public and the power sector.

Nonetheless, it is still helpful to review the existing market designs (for AC distribution systems) and make them a reference to the DCDS market design. They mainly aim to encourage active customer participation in energy dispatch, network management (especially overload pretension), and the offering of local ancillary services. For network capacity allocation, there exist three categories of network capacity allocation strategies in the literature [15]–[17]. The first category is locational pricing, where prices reflect temporal and locational resource scarcity [18], [19]. The second category is direct load control (DLC), which controls customers' power devices directly to perform centrally optimal dispatch. It includes controlled demand response, renewable curtailment and redispatch [20]. It is theoretically efficient, but since not all prosumers appreciate real-time intervention, they may opt out from the control or exploit the control mechanisms for their benefit. The third category is available transfer capability (ATC), in which the estimated available network capacity between price zones is allocated through explicit auctions. However, the ATC of a distribution network is hard to evaluate due to a low level of aggregation and the resulting high degree of uncertainty. Studies on local market design focus on locational incentives because they are theoretically optimal and compatible with the market-based operation.

Researchers proposed pricing mechanisms to resolve congestion and voltage deviations [21]–[23], but few studied the DCDS operation in a liberalised electricity market. As a market design can crucially affect the operational efficiency and reliability of a DCDS, we would like to close the research gap by finding out those market designs that encourage customers to support an efficient and reliable DCDS operation. This dissertation 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.

1.3. RESEARCH QUESTIONS

This dissertation represents a first attempt to apply market design theory to state-of-the-art DC distribution technology. It begins by revealing the specific requirements for DC-grid market operation and ends with realistic actor simulations for DCDS market design, representing a futuristic scenario. Our study of DC markets should bring DC researchers closer to the end users of a DCDS and draw their attention to the invisible hands, i.e., the monetary incentives that keep the system running efficiently.

The main goal of introducing an electricity market is to improve the economic efficiency of the system operation, so that local customers benefit from an increase in their welfare. Meanwhile, such market designs should always yield reliable DCDS operation so that overloading on converters or lines or voltage problems must be resolved immediately. Moreover, such markets should be tested in realistic and futuristic scenarios with uncertain energy production and consumption. Because uncoordinated flexible loads, e.g., from EV charging, can heavily challenge a distribution network's economic efficiency and reliability [24].

We identify promising DCDS market designs with high economic efficiency and system reliability via an exploration of the entire design space. Several requirements constrain this design space, or the freedom of choice in this market design. First, a design should be technically feasible, meaning that it does not pose too high computational requirements and it should be compatible with the current wholesale energy markets. Second, as a local market design directly involves end customers (namely small prosumers), it should be prosumer-friendly so that their trading rules are easily explainable and acceptable to end prosumers.

The above market design requirements help formulate the main research question of this dissertation, namely:

Which market designs that are both technically-feasible and prosumer-friendly facilitate efficient and reliable operation of a DC distribution system under uncertainty?

We propose sub-questions to answer this main research question in three steps.

Q1 Which design variables determine a DCDS market's performance in economic efficiency and system reliability? Which design offers high potential for such performance?

This sub-question defines the design space of the DCDS-tailored energy markets and indicates which design choices lead to market designs with a high economic efficiency and reliability. Here the design space refers to the freedom of choice in the electricity market design, regarding the choice of tradeable commodities and the detailed trading rules for each commodity. Next, quantifiable performance indicators, or criteria, should be proposed to benchmark different market designs' performance regarding economic efficiency and reliability. Finally, by qualitative reasoning, we identify market designs with potentially higher performance, then estimate their key features and challenges that will be further investigated using quantitative assessment.

Q2 Which DCDS market design has high economic efficiency and system reliability in the presence of complete information?

As a continuation of Q1, this sub-question further examines the identified market designs with quantitative assessments. Considering the complexity of market design, Q2 assumes zero uncertainty and complete information availability, to evaluate the performance of each market design in theory. If a market design shows poor performance even in such ideal conditions, we disqualify this design. Those who pass this examination will proceed to the next step: testing under uncertainty.

Q3 Is there a market design that preserves a DCDS's economic efficiency and system reliability, given the influence of prosumer behaviour under uncertainty?

This sub-question represents our final research step, in which we evaluate the DCDS market designs qualified by Q1 and Q2 in realistic situations. A local energy market is typically challenged by the intermittent local generation (e.g., from PV panels) and unpredictable energy consumption under stochastic wholesale power prices. A proper modelling tool should represent small prosumers' preferences and their autonomous behaviour in energy markets, in which multiple sources of uncertainty exist. Only by verifying a market design's performance in such a complex and realistic situation can we validate it further in demonstration sites and small to large-scale applications.

1.4. APPROACH AND OUTLINE

To identify promising DCDS market designs from all feasible options, we propose a comprehensive design framework for local electricity markets. Chapter 2 elaborates on this framework in detail. It is based on an engineering design process of identifying goals, determining the design space, testing and evaluation [25]. 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 [26]. Accordingly, we divide the space into architecture design—choice and arrangement of sub-markets—and sub-market design that decides detailed trading rules. We explore through this space to identify three promising market designs, namely the *integrated market* design, *wholesale energy price* market design and *locational energy market* design. Given the complexity of the market design, we adopt a step-by-step process following agile development [27].

To test market designs first in theory (Chapter 3) and then in real-life situations (Chapter 4), we develop simulations based on optimisation models and agent-based models, respectively. Notably, we include a feedback loop and allow step-by-step improvements along with the test and implementation, inspired by the concept of agile design. 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 [28]. Finally, we discuss the effect of each market design on different stakeholders and the implementation of the market designs (Chapter 5).

The rest of this dissertation is organised as follows.

Chapter 2 elaborates on our market design method: an adapted framework based on an engineering design approach [25]. What are the goals that a good local electricity market design should meet? In market design theory, which key variables determine such a market's performance concerning the above goals, especially economic efficiency and system reliability? We create a comprehensive design framework by reviewing and categorising the present market designs for the existing power systems.

Adopting this framework, the chapter continues to explore the entire design space for DCDS electricity market design. Among all possible sets of choices, which design has the highest potential to meet all these goals? A qualitative analysis of the entire design space helps us identify promising DCDS market designs, namely the *integrated market* design, the *wholesale energy price* market design and the *locational energy market* design, each representing a unique market architecture.

Chapter 3 quantitatively evaluates the performance of the above mentioned three market designs in theory, where the market operator has complete information and market players act towards mutual benefit. We adopt a deterministic optimisation model to simulate a DCDS's performance regarding economic efficiency and system reliability. The result shows that, among the three candidates, the *wholesale energy price* market design, based on flexibility trading, should be avoided because it gives prosumers wrong incentives and leads to very low market efficiency.

Chapter 4 quantitatively estimates the three market designs' performance in realistic situations, where the market operator has limited information from prosumers because they cannot forecast it or are not willing to share it. To mimic prosumer behaviour, we propose agent models that describe prosumer preferences and their bidding strategies. With agent-based simulations, we prove that among the three candidates, the *locational* *energy market* design can work with both inactive and pro-active residents, i.e., those who want to exploit the market rules.

In Chapter 5, we reflect on the performance of the proposed market designs and briefly discuss the other important factors of the market design. These factors include implementation barriers, investment incentives, strategic behaviour, application fields and disruptive technology developments, all of which may have a profound influence on the markets' operation and implementation.

Finally, Chapter 6 concludes the dissertation by summarising our findings of three market designs, listing the contributions and limits of this work, and suggesting future works on DCDS electricity market design.

2

DESIGN OPTIONS

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 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 chapter 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. We demonstrate three promising DCDS market designs that can be defined in our framework, and provide a first assessment of their performance.

2.1. INTRODUCTION

A high proportion of future electric power will be generated by direct current (DC) renewable sources [5]–[7] and consumed or stored locally by DC or DC-ready devices [8], [9]. 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 [5] 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

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This chapter has been published in Energies 2019;12:2640 [1].

(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 [29], [30]. 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 [31]. 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 [29], [32], [33].

Although regulations empower prosumer participation in electricity markets [34], [35], 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 [3], 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 [21]. 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 [36] than interconnected AC systems with large inertia [5]. 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 [37]; 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 [38], 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 network congestion and voltage deviations [21]–[23], but few have investigated the economic DCDS operation in a liberalised electricity market. This work is inspired by the overlooked potential of DC at the distribution level and focuses on the short-term economic efficiency of a DCDS market, namely minimising system operational costs.

Studies on local electricity markets have focused on prosumer-friendly energy trading [39], [40], distribution congestion management [16], [41], local ancillary services [42], [43] and market implementation [43], [44]. 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 [26], [45]. 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 chapter provides such a comprehensive market design framework based on an engineering design process (Section 2.2), 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 2.3). Second, we recognise the design variables that crucially impact market efficiency, and then evaluate the consequences of the choice of each design option (Sections 2.4 and 2.5). 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 2.6): *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 2.7, this work represents the first step towards a comprehensive DCDS market design and is a preparatory step towards a quantitative study of DCDS markets.

2.2. MARKET DESIGN FRAMEWORK

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

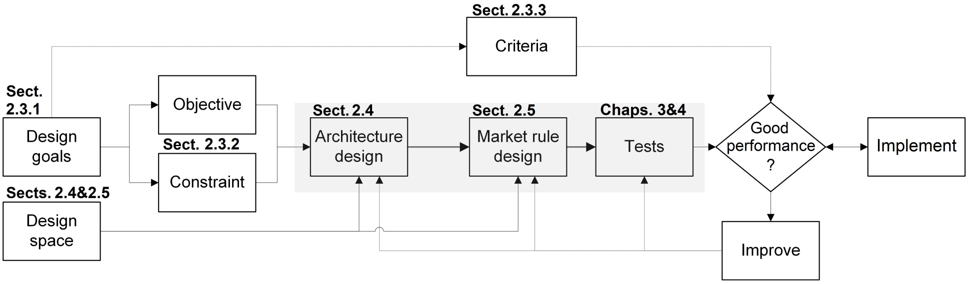

Figure 2.1: Design framework for local electricity markets.

Figure 2.1 illustrates our design framework for local electricity markets, where each block corresponds to a section of this chapter. It is based on an engineering design process of identifying goals, determining the design space, testing and evaluation [25]. This chapter 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 [26]. Accordingly, we divide the space into *architecture design*—choice and arrangement of sub-markets—and *sub-market design* that decides detailed trading rules.

Notably, as shown in Figure 2.1, we include a feedback loop and allow step-by-step improvements along with the test and implementation, inspired by the concept of agile design [27]. 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 [28]. 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* [46] suggests, the goals of energy security, energy equity and environmental sustainability challenge each other, thus the design must balance them carefully. Section 2.3 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 [47] 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 [26], each serving a technical function required for system operation. Stoft [26] 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, 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 [28] 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 [48], 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 [28]. 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 [28]. 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 2.3.3 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.

Table 2.1: Design goals of local electricity markets.

category	goal	role
economic efficiency	efficient production	objective
	efficient allocation	objective
	completeness	constraint
	incentive-compatibility	constraint
	complete risk-hedging	constraint
	cost recovery	constraint
	liquidity & competitiveness	objective
system reliability	sufficient network capacity	constraint
	voltage regulation	constraint
	power balance	constraint
prosumer involvement	non-discriminatory access	constraint
	information transparency	objective
	privacy	objective
	fairness	objective
	simplicity	objective
implementability	technical feasibility	constraint
	scalability	objective
	stakeholder agreement	objective
	compatibility with wholesale markets	objective
	consistency with regulations	objective

2.3. DESIGN GOALS

Adopting the design framework above, this section commences the DCDS market design by stating the goals. Section 2.3.1 categorises the common market design goals of energy policy documents and technical reports. Section 2.3.2 divides the goals into objectives and constraints. Section 2.3.3 briefly discusses the performance criteria.

2.3.1. LISTING OF THE DESIGN GOALS

Energy policy documents and technical reports have revealed the goals of electricity markets, as categorised in Table 2.1 [35], [49]. The primary goal is *productive and allocative efficiency*, where efficient prices coordinate efficient prosumption [5]. 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.

The market's primary goal is to *produce and allocate resources efficiently* [35]. 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 [26]. Incentive-compatible prices should let prosumers support DCDS [48] as they reflect a resource's scarcity in time [50] and space [51]. A market should provide complete risk-hedging tools [52] and pay off investments in the long run [5]. Given the few players, it should also improve market liquidity [48] and competitiveness [53].

Efficient market operation depends on *system reliability* [54]. The power prosumption of a community-level grid is highly stochastic and hardly predictable, leading to network congestion [51] and voltage deviations [55]. 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 by unplanned curtailments.

Another goal is *prosumer involvement* [41]: a market should grant prosumers non-discriminatory access [56]. Information transparency [35] facilitates optimal allocation at the cost of prosumer privacy [57]. The allocation and pricing should be fair [49] so that prosumers pay for their actual contribution [41]. The trading rules should be simple enough for prosumers to master [41].

Finally, a market should be *implementable* [51] regarding technical feasibility, scalability, existing stakeholders and regulations. Market clearing mechanisms should be tractable and scalable [58], [59]. The market should respect existing stakeholders [60], [61], be compatible with wholesale markets [42] and consistent with regulations [56], thereby removing implementation barriers.

2.3.2. OBJECTIVES AND CONSTRAINTS

We further divide the design goals into objectives and constraints, as listed in Table 2.1 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.

2.3.3. 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 chapter does not discuss the full set of criteria but gives two examples. As discussed in Section 2.3.2, 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.

2.4. MARKET ARCHITECTURE DESIGN VARIABLES

Sections 2.4 and 2.5 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 and which options are there?

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 2.2 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 [26], whereas the fourth one is from our analysis. For each design variable, Table 2.2 lists the options on the right.

Table 2.2: 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

2.4.1. 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 [5], a market design should reward all tradeable commodities; a commodity still plays a role even if it is not paid directly [26].

The DCDS operation relies on power dispatch, congestion management, plus various ancillary services regarding voltage regulation, contingency supply, safety, protection and power quality [3]. When deciding which commodities to reward, one should consider non-discriminatory access, completeness (and no repeated remuneration), transaction costs and transparent operation [26]. According to these criteria, (electrical) energy, network capacity (substation capacity in particular) and voltage regulation are qualified for a sub-market [3]. 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.

2.4.2. MARKET TYPE

The market type describes the arrangement of trading and 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 [62]. 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

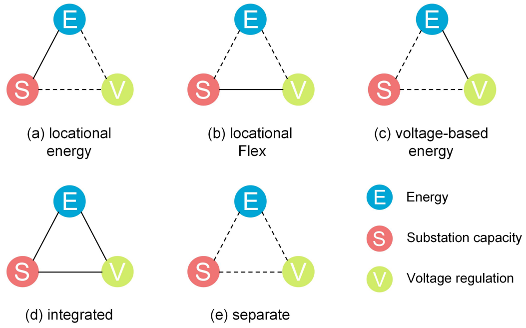

Figure 2.2: Choice of sub-markets and their linkages.

and transaction costs. A bilateral market (based on bulletin boards or brokers) allows peer-to-peer trading and diversified contracts [63], but the information exchange is less efficient and transparent, 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.

2.4.3. 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 [26]. 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 [64], by contrast, integrates various commodities into one. Figure 2.2 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 [26]. For instance, if the linkages between all sub-markets are explicit, we obtain an *integrated* market that merges various commodities into one (Figure 2.2d). 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 [26]. Otherwise, we obtain multi-commodity electricity markets with separate prices for each commodity. Figure 2.2a 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 2.2b represents a locational voltage regulation market, where the local flexibility for voltage regulation is priced differently at each node of the DCDS. Figure 2.2c represents an energy market with voltage-based pricing. Finally, Figure 2.2e represents a market where three sub-markets are organised separately. Further study should balance economic efficiency and the extra complexity an explicit linkage brings.

2.4.4. LINKAGE TO WHOLESALE MARKETS

The above design variables are identified in wholesale markets [26]. 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 [42]. 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 [65], 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 [66] for a more comprehensive review of such linkages.

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.

2.5. SUB-MARKET DESIGN VARIABLES

Section 2.4 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 2.3 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 [48], [67], [68], balancing markets [69], [70] and flexibility markets [42], [43], [71].

Based on different stages of market operation [48], 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.

2.5.1. 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*, 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 [72]: one-sided or double-sided. A one-sided market has either a monopoly (like capacity auctions) or a monopsony (like frequency regulation markets), whose significant market power reduces economic efficiency. By contrast, a double-

Table 2.3: 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/...

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 [35]. 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 [73]. Disclosing truthful information may yield more efficient allocation [71], yet it should be safe and beneficial to prosumers (one option is to publish anonymous or aggregated bids) [74]. Hence, one should balance information transparency and privacy.

2.5.2. 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 [75] 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 [70], price [76], or quantity [77]. 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 [67], 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 [67], whereas an earlier one provides more flexibility.

Locational information: The locational information, included in prosumer bids, indicates the spacial scarcity of a resource [78]. 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.

2.5.3. 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 [79]; 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 [67]. 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 [67]. 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 [5], we suggest avoiding price caps or keeping them sufficiently high [60], for instance to the value of the lost load.

2.5.4. 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 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 [80]. 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 [48].

Settlement pricing directions: The settlement pricing direction defines whether the deviation of a contract is settled at different prices for long and short positions [81]. 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 [82]. Since high uncertainty distorts market efficiency and prosumer welfare, a DCDS market should offer risk-hedging tools, such as forward markets [83], options [84], or stochastic clearing with risk measures [75].

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 2.4: A brief comparison of three market designs.

design	IM	LEM	LFM (WEP)
linkage	all sub-markets	energy – network capacity	Flex – network capacity
commodity	integrated product	locational energy + Flex	energy + locational Flex
Flex payment	implicit	explicit, location non-specific	explicit, location-specific
advantages	incentive-compatible, optimal in theory	promoting Flex deployment, liquid Flex market	promoting free energy trading and Flex deployment, Flex at right places
challenges	privacy, sophisticated market clearing, unpredictable price	standard Flex contract, Flex pricing, Flex at wrong places; distorted incentive, tariff fairness (if a DSO sells Flex)	standard Flex contract, Flex pricing and market liquidity

2.6. THREE PROMISING MARKET DESIGNS

This section demonstrates three illustrative examples of DCDS market designs and provides a first qualitative evaluation of our design method in Section 2.2. Table 2.4 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*[1]. Regarding market architecture (Section 2.4), we chose designs with all the required sub-markets. Regarding sub-markets (Section 2.5), 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 2.4, Rows 2–4 list the market features and the last two rows compare their advantages and disadvantages.

2.6.1. INTEGRATED MARKET 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 2.2d. 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.

2.6.2. LOCATIONAL ENERGY MARKET DESIGN

The second design, as shown in Figure 2.2a, 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 [85], which is widely adopted in the US wholesale markets.

The voltage regulation of a DCDS requires local changes in energy prosumption and is therefore dependent on local flexibility. The DSO, who is responsible for voltage reg-

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[1] It is later referred to as the *wholesale energy price (WEP) design* because it better describes its key feature.

ulation, can provide this as a system service or contract it from prosumers in an explicit Flex market. Although LEMs have been studied for DC [21]–[23], 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.

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 [20]. 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.

DSO Provides Voltage Regulation. It represents the current DSO model: Flex is a service provided by the DSO, who passes the costs along to prosumers in its tariffs [20]. A DSO may own or rent flexible devices and use them for voltage regulation [33]. 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.

2.6.3. WHOLESALE ENERGY PRICE DESIGN

The third design, depicted in Figure 2.2b, explicitly links Flex and network capacity markets in a *locational Flex market* (LFM, or *wholesale energy price* design, WEP), 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 [86] and aims to attract Flex investments to where they are needed.

The organisation of an LFM is similar to a standalone Flex market, 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 a Flex market. 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 [87], [88], 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.

2.7. SUMMARY

This chapter 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 product definition, pricing and market power prevention issues.

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 2.3. 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.

In the next chapter, we will further adopt this framework to design electricity markets tailored to DCDSs.

3

MARKET DESIGN WITH COMPLETE INFORMATION

DC distribution systems are a promising alternative to existing AC distribution systems. They connect customers to local energy sources without conversion, thus reducing power losses. However, the unique features of DC impose strict requirements for system operation compared to AC. Within the context of a liberalised energy market, this chapter demonstrates three promising market designs—an outcome of a comprehensive engineering design framework—that meet those DC requirements. They are an integrated market *design, which incorporates all system costs into energy prices; a market design that passes* wholesale energy prices *directly to prosumers; and a* locational energy market *design that relieves congestion with nodal prices. An optimisation model estimates the three market designs' performance by simulating a realistic DC distribution system, featuring a high share of electric vehicles. Results indicate that the integrated market design is optimal in theory but computationally infeasible in practice. The wholesale energy price design, aiming at constraint-free energy trading requires substantial investments in flexibility. The locational energy market design yields nearly optimal operation in urban networks and is considered the best feasible market design for DC distribution systems.*

3.1. INTRODUCTION

Converting power distribution networks to direct current (DC) can increase network capacity and reduce energy losses [21], thus providing a promising alternative to alternating current (AC) systems [89]. Both photovoltaic (PV) generation and much contemporary power consumption are DC in nature. Hence, connecting them via DC distribution systems (DCDSs) is more efficient than via AC [90]. The increase in network capacity by switching to DC is an additional benefit in an environment where transport electrification and PV generation lead to significant increases in power flows.

This chapter has been published in Energy 214 (2021) 118876 [2]. The American spelling is replaced by British spelling to keep the consistency of this dissertation.

In DCDSs, network issues due to rapid electrification (notably electric vehicles, EVs) and PV installation have a different impact than in AC networks [91]. For example, DC substations use converters that typically have little tolerance to instant overloads, whereas AC substations based on transformers may tolerate an overload up to an hour. The conventional strategy of network reinforcement is costly and slow and still may not satisfy the increasing peak load. If enough network capacity is available over time, shifting flexible loads is a more efficient solution [92]. To stimulate prosumer participation, price-based coordination strategies have been proposed within the context of electricity markets [86], where energy prices reflect the system's technical characteristics. However, popular intervention strategies in AC networks—including those based on dynamic network capacity or reactive power control—cannot comply with DC characteristics and are therefore not applicable to a DCDS. Because DCDSs typically have lower system inertia, stricter power limits and a stronger power-voltage coupling effect [3].

The literature provides three categories of network capacity allocation strategies for distribution systems (all focused on AC). The first category is monetary incentives [17]: prices that reflect temporal [18] and locational [19] resource scarcity. The second category is direct load control [16], where a central dispatcher directly controls prosumers' power devices according to an optimal schedule. It includes controlled demand response, renewable curtailment and redispatch [20]. The third category is based on available transfer capability [15], in which the estimated available network capacity between price zones is allocated through explicit auctions. However, the capacity of a distribution network is hard to evaluate due to a low level of aggregation and a high degree of uncertainty. This chapter focuses on monetary incentives, because they comply with electricity market regulations [34], [35] and can incentivise prosumers to boost system efficiency. We thus investigate how local market design should be adjusted to meet a DCDS's technical requirements, thereby improving the market efficiency.

Researchers have proposed market-based coordination schemes for distribution networks as summarised in [93], [94], but most of them are designed to meet today's regulations for AC networks and may not be directly implemented in DC. Ref. [20] proposes an optional local flexibility market for prosumers with an aggregator playing a key role. Ref. [95]presents five coordination schemes between transmission and distribution system operators, but no one allows prosumers to access the market without an aggregator. These aggregator-based coordination schemes may not be able to manage DC congestion precisely at a 1-min resolution. Moreover, they do not incentivise efficient allocation of network capacity (as is the case with the current regulation). By contrast, Refs. [96], [97] discuss network-constrained local energy trading, whereas [96] adopts price-based control for EV charging, and [97] discusses the bidding strategies for the aggregator of prosumers. Unfortunately, prosumers cannot trade energy directly in both cases, but we argue that direct prosumer participation (without aggregators) can create better incentives and higher market efficiency. Hence, we explore market designs tailored to DC, including those beyond current market regulations.

A few authors have studied economic DCDS operation, such as the optimal operation of AC/DC microgrids under uncertain market prices and renewable generation [98], [99]. Mohsenian-Rad et al. [100] presented a decentralised control framework where price incentives encourage prosumers to offer ancillary services. Asad et al. [101] proposed a fair nodal price covering the real costs of energy prosumption. However, neither pricing scheme resolves DCDS congestion. Karambelkar et al. [102] proposed an exact optimal power flow formulation, where locational marginal prices mitigate voltage deviation and line congestion. Such a pricing scheme can hardly be implemented because solving such a problem is computationally challenging. Thus, we are eager for a promising DCDS market design that meets the simultaneous requirements of economic efficiency, system reliability and computational feasibility.

Our previous work identified three technically feasible DCDS market designs using a comprehensive engineering design framework: stating goals, listing options, performance tests, evaluation, and improvement [1]. The three designs are an *integrated market (IM)* design that incorporates all system costs in energy prices; a market design that passes *wholesale energy price (WEP)* directly to prosumers while counting on distribution system operators (DSOs) to resolve network issues; and a *locational energy market (LEM)* design that relieves congestion with nodal prices while letting the DSO regulate voltage. The IM optimises DCDS operation with prosumer preferences, but the computational complexity and privacy concerns hinder its implementation. The WEP passes wholesale prices on to prosumers then requires a DSO to relieve congestion. The LEM based on linear power flow is computationally feasible but introduces a small dispatching error. These market designs are categorised as *price-based control*, *local flexibility markets* and *local energy markets* [93]. This chapter evaluates them quantitatively.

We expose each market design's potential by stress-testing its performance with large numbers of EVs. We adopt an optimisation model to quantitatively evaluate the design goals of economic efficiency, system reliability and computational feasibility. In this model, prosumers operate their devices under local energy prices without knowing their effect on the market. We assume that prosumers fully share their preferences and run devices for their benefit; clearly, poor performance in this model means even worse in reality. We stress-test our market designs with a significant share of PV generation, to which we add a futuristic volume of EVs. EV charging flexibility can be a major advantage to economic DCDS operation. However, it also leads to grid overloads under wrong incentives, thereby creating peak loads orders higher than today.

This chapter contributes to the literature with the first quantitative assessment of market designs tailored to a DCDS. Following a comprehensive design framework, we analyse the performance of three market designs in [1] quantitatively using an optimisation model. Realistic simulations suggest that converter congestion is the primary concern of the DCDS operation, especially in the presence of volatile energy prosumption and large numbers of EVs. By contrast, constraints regarding nodal voltage and cable capacity are not a limiting factor in an urban DCDS and can presumably be removed from its market design. Our studies on DCDS markets also shed light on new market designs for low-voltage AC distribution systems, where increasing numbers of prosumer devices are interfaced with converters.

3.2. THREE POTENTIAL DCDS MARKET DESIGNS

In exploring the design space for DCDS electricity markets, the previous chapter identified the three market designs. This section briefly summarises these market design,s as seen in Table 3.1. First, all the designs have a complete market architecture: all tradeable

Table 3.1: Comparison of three DCDS market designs, adapted from [1].

design	IM	WEP	LEM
linkage	all sub-markets	voltage–network	energy–network
commodity	integrated product	energy, locational Flex	locational energy
flexibility	paid implicitly	paid explicitly	paid implicitly
advantages	optimal in theory, no need for Flex battery	no change with institution, easy to implement	fast market clearing, close to optimal in urban grids
challenges	computational complexity	congestion and voltage regulation	no voltage regulation incentive, <5% less accurate

commodities, including network capacity and voltage regulation services, are rewarded. Second, all have a complete linkage to wholesale electricity markets. Third, they all apply uniform pricing, namely no distinction between energy sell and buy prices. We changed the name of the locational flexibility market design to wholesale energy price (WEP) design since the latter better describes its key feature.

INTEGRATED MARKET (IM) DESIGN

The IM design based on direct control rewards power generation but also the provision of network capacity and voltage regulation services, all in a single integrated commodity. Assuming complete information, this market performs security-constrained economic dispatch with a non-linear power flow model, which accurately measures voltage drops and losses. An independent local market operator (LMO) collects information from the DSO and the prosumers, who submit complex bids including energy needs, constraints, preferences and costs. Then the LMO allocates energy and other resources to maximise the economic welfare of local prosumers. With sufficient flexibility, the IM design yields an optimal system operation in theory, unlike the next two designs. Prosumers are remunerated for their marginal contribution to the total economic welfare. This remuneration creates a time-dependent, locational energy price, which also covers the congestion and voltage regulation payments. In practice, the IM design will face computational challenges because of the complex market clearing algorithms.

WHOLESALE ENERGY PRICE (WEP) DESIGN

The second design allows prosumers to trade energy directly at wholesale prices but counts on the DSO to regulate network operation. The DSO can introduce a *local flexibility market* to purchase flexibility form prosumers. Previous studies typically define flexibility payments based on a prosumer's actual energy delivery, thereby creating a distorted incentive of *pay-for-not-doing*. By contrast, this design defines *Flex*, an option to adjust a flexible prosumer's power devices, as an explicit, standard commodity that a prosumer sells to the DSO.

In daily operation, prosumers schedule power devices themselves based on wholesale prices, whereas the DSO estimates the DCDS's load factor based on historical data and forecasts. Then the DSO announces the Flex demand and invites prosumers to submit Flex offers. Finally, the DSO takes the lowest-price Flex offers and dispatches them in real-time for network regulation. If all prosumers participate in this Flex market, we will reach the same level of economic efficiency as in the IM design. Because a DSO would look for the same least-cost solution considering the grid constraints. The only difference is that a DSO would pay EV owners to relieve the congestion they themselves created. As a result, EV charging costs would be lower than in the IM design, but they would be borne by the DSO and would presumably be transferred back to prosumers as socialised system costs.

The WEP design explicitly treats system services as commodities, thereby creating new business models for energy storage and demand response systems. The proposed Flex market acknowledges the local value of Flex [86] and aims to attract Flex investments where network congestion and voltage deviations occur. However, a Flex market is not likely to yield an optimal system operation because it provides perverse incentives to flexible loads: it rewards some schedules that worsen congestion. Meanwhile, its product pricing and standardisation are challenging, because flexible devices typically have different operational costs and constraints.

LOCATIONAL ENERGY MARKET (LEM) DESIGN

In the third design, an LMO allocates energy optimally within network capacity limits under the nodal pricing principle. The LEM design adopts a linear power flow model in energy trading, which explicitly links the energy and network capacity markets. LEM is cleared to minimise generation costs and the transactions are settled at locational energy prices. Apart from energy trading, the DSO provides voltage regulation services using flexible devices such as batteries. The LEM design is in line with the current business model for DSOs, who provide system services and passes the costs along to customers. This design is less optimal than the IM, but it is computationally less challenging and can ensure system reliability with less prosumer information.

3.3. OPTIMISATION MODEL

This section estimates the theoretical potential of each DCDS market design with an optimisation model, where we assume complete information availability. We do not include a WEP model but use historical price series instead. Our focus is to develop and test local energy market designs that can resolve DC network issues. As EV charging only represents a fraction of wholesale energy demand today, we assume that local market clearing with EVs does not affect the wholesale energy price (WEP). This is a limitation of our work: future work should investigate the interaction between the wholesale and local energy markets.

We study an urban residential DCDS with sufficient capacity to meet the household load today, but is challenged by a high share of EVs and PV panels in future. This scenario is suitable because flexible loads such as EV charging might 1) create an order of magnitude higher load than today and 2) cause severe network problems. Market designs for DCDSs should be fit for such a scenario. Our model assumes that both household consumption and PV generation are inflexible and may not be curtailed, and that EVs are the only flexible prosumers. The simulation starts at noon and lasts 24 hours for overnight EV charging. It adopts a 1-min resolution to highlight the consequences of even brief congestion of the DC substation converter. Unlike AC transformers, DC converters typically cannot sustain brief overloads and require more precise system operation.

Below we show how to model the three market designs as an optimisation problem.

3.3.1. INTEGRATED MARKET MODEL

The IM market design has, by definition, only one market which rewards the provision of energy, network capacity and voltage regulation services. Voltage and network constraints are integrated into the optimisation problem and are therefore considered simultaneously with energy dispatch. The allocation mechanism is a one-step deterministic optimisation problem and is settled at a 1-min resolution with DC smart meters. This model serves as a reference for the WEP and LEM models.

OBJECTIVE AND DECISION VARIABLES

This model minimises local prosumers' energy net import costs.

$$\min_{p_t^w, p_t^e} C = \sum_{t \in \mathcal{T}} \lambda_t^w p_t^w \Delta t \tag{3.1}$$

The decision variable is the EV charging power p_t^e, whereas the power imported from the wholesale market p_t^w is a dependent variable. The objective function (3.1) is subject to the constraints regarding the network (3.2)–(3.10) and EVs (3.11)–(3.16). If Flex batteries are present—although unnecessary for the IM design—the function is further subject to the Flex battery constraints (3.18)–(3.22).

NETWORK CONSTRAINTS

Substation converter power limit

$$-\overline{p^w} \leq p_t^w \leq \overline{p^w} \quad \forall t \tag{3.2}$$

where $\overline{p^w}$ is the available substation converter capacity.

Nodal power injection

$$p_t^{n=1} = p_t^w \quad \forall t \tag{3.3}$$

$$p_t^n = \sum_{g \in \mathcal{G}^n} p_t^g + \sum_{l \in \mathcal{L}^n} p_t^l + \sum_{e \in \mathcal{E}^n} p_t^e + \sum_{f \in \mathcal{F}^n} p_t^f \quad \forall t, \forall n \neq 1 \tag{3.4}$$

where $\mathcal{G}^n, \mathcal{L}^n, \mathcal{E}^n, \mathcal{F}^n$ are the sets of generators, loads, EVs and Flex batteries at node n. A node's net generation equals the sum of the power flowing out.

Nodal power expression (non-linear)

$$p_t^n = i_t^n v_t^n \quad \forall t, \forall n \tag{3.5}$$

Nodal voltage limit

$$v_t^{n=1} = v_{ref} \quad \forall t \tag{3.6}$$

$$0 < \underline{v} \leq v_t^n \leq \overline{v} \quad \forall t, \forall n \neq 1 \tag{3.7}$$

Nodal current balance

$$i_t^n = \sum_{m|(n,m)\in\mathscr{A}} f_t^{(n,m)} - \sum_{m|(m,n)\in\mathscr{A}} f_t^{(m,n)} \quad \forall t, \forall n \tag{3.8}$$

Line current flow

$$\omega^{(m,n)} f_t^{(m,n)} = (v_t^m - v_t^n) \quad \forall t, \forall (m,n) \in \mathscr{A} \tag{3.9}$$

Line current limit

$$-\overline{f^a} \leq f_t^a \leq \overline{f^a} \quad \forall t, \forall a \tag{3.10}$$

EV CHARGING CONSTRAINTS

EV charging power

$$p_t^e = 0 \quad \forall t \in [0, t_a^e) \vee [t_d^e, T], \forall e \tag{3.11}$$

$$\underline{p^e} \leq p_t^e \leq 0 \quad \forall t \in [t_a^e, t_d^e), \forall e \tag{3.12}$$

EV State-of-Charge (SOC) update

$$(r_{t+1}^e - r_t^e)\, c^e = -\eta^e p_t^e \Delta t \quad \forall t \neq T, \forall e \tag{3.13}$$

EV SOC limit

$$0 \leq r_t^e \leq 1 \quad \forall t, \forall e \tag{3.14}$$

$$r_{t_a^e}^e = r_a^e \quad \forall e \tag{3.15}$$

$$r_{t_d^e}^e \geq r_d^e \quad \forall e \tag{3.16}$$

3.3.2. WHOLESALE ENERGY PRICE MARKET MODEL

Prosumers directly face WEPs in this market design. EVs, the only flexible prosumers in this model, are charged to minimise energy purchase costs. If the market clearing results violate a DCDS's technical constraints, namely equations (3.2), (3.7) and (3.10), the DSO resolves such problems outside the energy market with Flex batteries. Since the WEP design requires such batteries, it yields higher capital costs than the IM. With this model, we attempt to indicate the order of magnitude of the cost increase.

OBJECTIVE AND DECISION VARIABLES

The objective function is shown in (3.17). The first term describes the total energy net import costs (considering energy losses), whereas the second term represents the Flex battery depreciation costs. Hence, the optimisation model may dispatch batteries for system service provision but also for energy arbitrage—when energy price differences can cover battery depreciation costs.

$$\min_{p_t^w, p_t^f} C = \sum_{t\in\mathscr{T}} \lambda_t^w p_t^w \Delta t + \sum_{t\in\mathscr{T}} \sum_{f\in\mathscr{F}} \lambda^f p_t^{f,dis} \Delta t \tag{3.17}$$

The decision variable is the Flex battery power p_t^f, whereas the power imported from the wholesale market p_t^w is a dependent variable. The constraints are from the network (3.2)–(3.10), EVs (3.11)–(3.16) and Flex batteries (3.18)–(3.22).

FLEX BATTERY CONSTRAINTS

Batteries are unnecessary for the IM and LEM design but are crucial to the WEP design.

Flex battery charging power

$$\underline{p^f} \leq p_t^f \leq \overline{p^f} \quad \forall t, \forall f \tag{3.18}$$

$$p_t^f = \eta^{f+} p_t^{f+} - \eta^{f-} p_t^{f-} \quad \forall t, \forall f \tag{3.19}$$

Flex battery SOC update

$$(r_{t+1}^f - r_t^f)\, c^f = -p_t^f \Delta t \quad \forall t \neq T, \forall f \tag{3.20}$$

Flex battery SOC limit

$$0 \leq r_t^f \leq 1 \quad \forall t, \forall f \tag{3.21}$$

$$r_{t=1}^f = r_{t=T}^f \quad \forall f \tag{3.22}$$

3.3.3. LOCATIONAL ENERGY MARKET MODEL

Compared to the IM model, the LEM model leaves out voltage drops and energy losses, namely (3.5)–(3.7). Instead, the DSO uses Flex batteries to meet constraint (3.7) in real time. Consequently, the LEM typically results in a power dispatching error up to 5% in our simulation, so we also introduce such an amount of reserve margin when allocating the network capacity.

The objective function of the LEM is the same as the IM, namely equation (3.1). The optimisation problem is subject to EV constraints (3.11)–(3.16) and the following network constraints. Compared to the IM, constraints (3.2)–(3.4) remain the same, but constraints (3.5)–(3.10) for non-linear power flow modelling are removed. Constraints (3.8) and (3.10), expressed in current in the IM, are replaced by (3.23) and (3.24), expressed in power in the LEM model.

Nodal power balance

$$p_t^n = \sum_{m|(n,m)\in\mathscr{A}} p_t^{(n,m)} - \sum_{m|(m,n)\in\mathscr{A}} p_t^{(m,n)} \quad \forall t, \forall n \tag{3.23}$$

Line power limit

$$-\overline{p^a} \leq p_t^a \leq \overline{p^a} \quad \forall t, \forall a \tag{3.24}$$

3.3.4. IMPLEMENTATION AND EVALUATION

The optimisation model is formulated mathematically using Pyomo [103]. The IM and WEP models present a non-linear programming problem solved by IPOPT. By contrast, the LEM model presents a linear programming problem solved by Gurobi. We check whether a market design leads to a technically feasible DCDS operation by simulating its cable power flow and nodal voltage deviation. We adopt PyPSA [104], a power system simulation tool, for this purpose: the EV dispatch plans as our model output are passed to PyPSA as inputs.

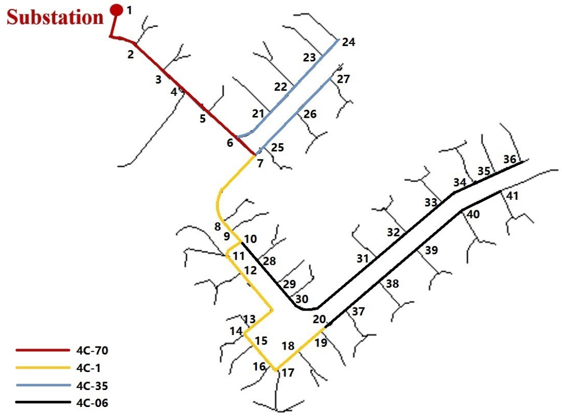


Figure 3.1: Simplified 41-node IEEE-EULV feeder, adapted from Ref. [105]

3.4. EXPERIMENT DESIGN

Having developed the mathematical model, we use it in a simulation experiment. The purpose of the simulation is to stress-test three market designs with a large share of EVs that cause DC substation overloads. We combine a well-described IEEE reference network with three typical scenarios describing household consumption, PV generation and EV availability. Contrary to the 15-min resolution used in AC markets, we adopt a 1-min resolution to evaluate the impact of instant congestion on a DC network. Each design is assessed by economic efficiency, reliability and computational complexity.

3.4.1. IEEE-EULV DISTRIBUTION TEST FEEDER

The simulated DCDS is based on the IEEE European Low Voltage Distribution Test Feeder (EULV) [105]. In our case, the low-voltage AC network is replaced by a unipolar 350V DC system. The old AC transformer is replaced by a DC substation converter with a rated capacity of 100kW, whereas the AC cables are used for DC distribution with only a few adaptions. We assume the DC substation to be lossless because the efficiency of DC converters is up to 99%. The cable rating is set according to Table 3.2. We simplified the feeder to a 41-node one (Figure 3.1) while preserving its basic topology.

Table 3.2: IEEE EULV cable power rating under unipolar 350VDC operation, based on [105].
(In Chapter 4, the power rating is doubled under bipolar ±350VDC operation.)

line	resistance (Ω/km)	power (kW)
4c_.06	0.469	55
4c_.1	0.274	75
4c_.35	0.089	105
4c_70	0.446	105

3.4.2. PROSUMERS

We model inflexible household consumption and PV generation with time-series power profiles, with a resolution of 1-min. The IEEE-EULV feeder [105] provides 55 household load profiles with a 1-min resolution for 24 hours, which constitute the DCDS's inflexible base load up to 54.5kW. The PV systems can generate up to 100kW peak power, allowing the DCDS to be energy self-sufficient on an average summer day. The generation profiles of 32 PV panels, also in a 1-min resolution, are based on the measurements from the UK [106]. Independent of PV ownership, 25 households own EVs. We assume that all EVs have a battery capacity of 24 kWh (based on Nissan Leaf) and should be fully charged overnight; their energy needs are based on the driving patterns from [107], [108]. The maximum EV charging power is 7kW, and we consider EV charging efficiency to be 95% in a DCDS—–higher than with AC thanks to the removal of AC-DC conversion. The EV charging flexibility, represented by the minimal energy need, charging period and charging location (as shown in Table 3.3), is the primary flexibility source of the studied DCDS. Both PV panels and EVs are located randomly.

Table 3.3: EV charging profile, based on Verzijlbergh (2013) [108]

name	arrival	departure	distance (km)	arrival SOC	location
EV1	13:12	10:11	3.1	97.4%	N9
EV2	18:34	09:26	35.2	70.7%	N18
EV3	15:21	09:31	14.5	87.9%	N41
EV4	14:26	08:41	7.8	93.5%	N5
EV5	18:54	11:21	16.8	86.0%	N33
EV6	15:27	09:13	10.9	90.9%	N29
EV7	16:05	09:16	24.8	79.3%	N27
EV8	15:02	10:27	5.7	95.3%	N8
EV9	18:33	09:06	50.8	57.7%	N38
EV10	18:58	11:07	21.7	81.9%	N20
EV11	19:11	11:31	28.2	76.5%	N34
EV12	19:25	09:26	109.2	9.0%	N35
EV13	18:26	13:21	11.8	90.2%	N21
EV14	18:45	09:16	58.8	51.0%	N31
EV15	17:17	09:07	31.0	74.2%	N17
EV16	19:22	15:04	3.2	97.3%	N7
EV17	18:25	09:13	40.1	66.6%	N19
EV18	18:59	09:11	77.0	35.8%	N2
EV19	18:46	10:11	45.2	62.3%	N13
EV20	19:22	09:04	65.9	45.1%	N10
EV21	17:58	07:38	4.3	96.4%	N36
EV22	22:17	08:38	4.5	96.3%	N16
EV23	16:01	09:08	19.5	83.8%	N24
EV24	19:24	09:09	91.8	23.5%	N39
EV25	19:48	15:09	7.9	93.4%	N35

Note: EV SOC upon arrival is estimated by the driven distance and an average power consumption of 0.2kWh/km. EVs are fully charged upon departure.

Flex batteries are necessary in some market designs for system service provision. The WEP design explicitly requires Flex batteries, because EV charging is self-scheduled and is unavailable for network intervention. For the LEM design, Flex batteries are only needed in the case of large voltage deviations. By contrast, the IM design does not strictly need such batteries, because all EVs provide flexibility that the DSO can use to meet a DCDS's technical constraints. We place seven identical Li-Ion batteries, each with a maximum power of 20kW and a 15-min full-load time (mainly to relieve local congestion), at the two longest branches of the IEEE-EULV feeder. Their charging and discharging energy efficiency are set to 95%. These batteries' final SOC is set the same as its initial value, namely 50% in our case.

3.4.3. SCENARIOS

We aim to create realistic power profiles of a DCDS with houses, PVs, EVs, and Flex batteries. Hence, we propose three typical but challenging scenarios to describe the local PV generation and the WEPs (affected by offshore wind generation). The DC characteristics [1] require that DCDS markets should be cleared more frequently than AC energy markets (typically with a 15-min resolution). Due to the paucity of per-minute, high-resolution load data, we can only perform a 24-hour optimisation of hardware and operational costs at that resolution.

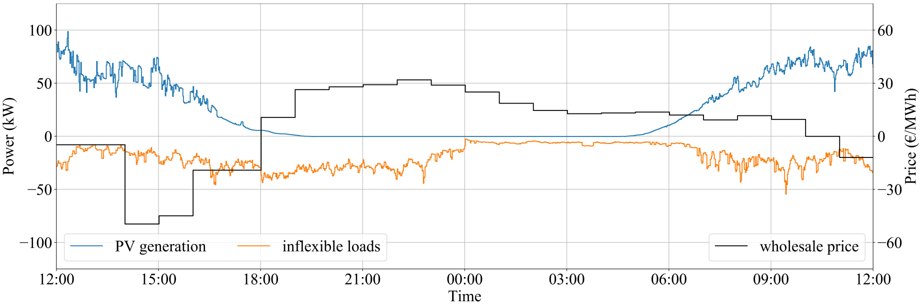
1. *S1 Sunny-Windy*: A windy summer day when local PV panels and offshore wind farms generate much power, resulting in negative WEPs at noon.
2. *S2 Sunny*: A calm summer day when local PV panels generate much power. The excess generation creates reverse power flow and voltage swells. The WEP curve is relatively flat except in the evening.
3. *S3 Windy*: A windy winter day with low PV generation and low WEPs at dawn. EV demand for cheap energy will cause substation congestion and voltage sags.

Figure 3.2 illustrates the input data. The inflexible load is the same in the three scenarios. In Scenario S3, PV generation is especially low and so is the WEP due to offshore wind generation. The WEPs are from EPEX-SPOT [109].

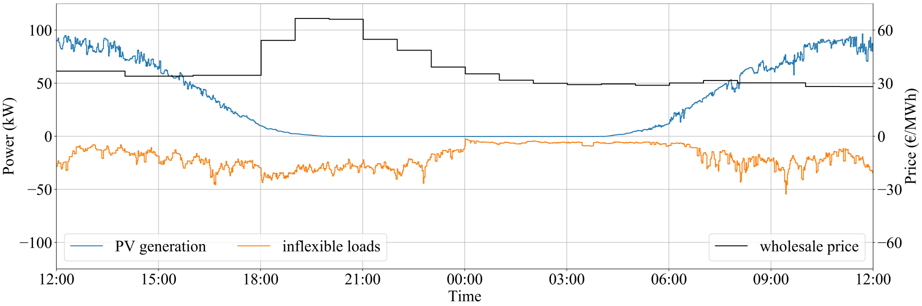
3.4.4. PERFORMANCE CRITERIA

Table 3.4 lists the market design goals [51], [110] and our choice of performance indicators. We do not focus on long-term cost minimisation except for cases that require additional investments in batteries.

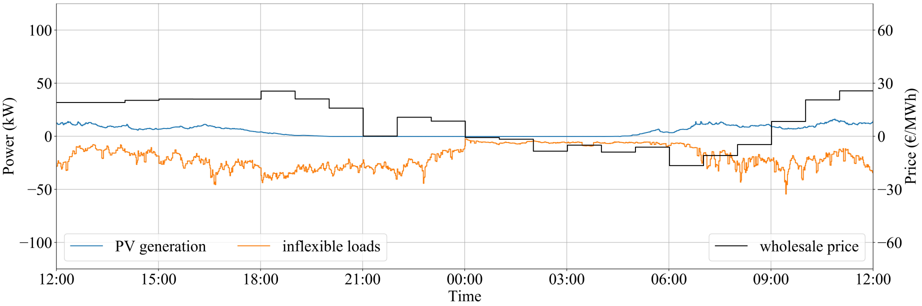
This section compares the performance of the three market designs in the three scenarios. We evaluate to what degree each market design helps lower the overall system costs within the boundary of a DCDS.



(a) S1 Sunny-Windy.



(b) S2 Sunny.



(c) S3 Windy.

Figure 3.2: Simulation scenarios: local PV generation, household consumption and WEP affected by offshore wind generation.

Table 3.4: Selected criteria for local electricity market design, adapted from Ref. [1]

category	goal	criterion
economic efficiency	efficient prosumption long-term cost efficiency	total operational costs min. battery investment
system reliability	sufficient network capacity voltage safety	max. substation & cable loading max. voltage deviation
implementability	computational feasibility	solver time

Table 3.5: Performance of three market designs in three scenarios, simulated by PyPSA.

scenario	S1: Sunny-Windy			S2: Sunny			S3: Windy		
	IM	WEP	LEM	IM	WEP	LEM	IM	WEP	LEM
total operational costs (€)	8.03	7.46	8.04	0.03	0.27	0.06	1.79	2.95	1.80
... energy import (€)	8.03	6.59	8.04	0.03	0.05	0.06	1.79	1.83	1.80
... battery depreciation (€)	0.00	0.88	0.00	0.00	0.22	0.00	0.00	1.12	0.00
battery investment* (k€)	0.00	25.66	0.00	0.00	19.44	0.00	0.00	68.76	0.00
max substation load (%)	72.92	73.16	74.67	79.55	100.00	98.35	100.00	100.00	98.50
max cable load (%)	70.50	97.88	95.70	75.76	97.14	96.05	97.85	97.79	96.46
max voltage deviation (%)	3.08	4.12	3.48	3.19	4.31	4.44	4.96	5.04	4.84
solver time (sec)	933	2530	0.94	173	459	1.08	1660	2010	1.06

* Li-Ion battery investment costs based on a 824 €/kW net present value and a 0.25h full load time [111].

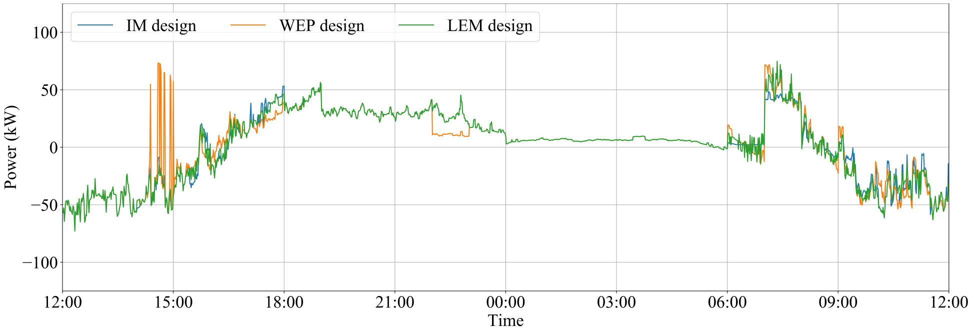
3.5. SIMULATION RESULTS

The simulation results, summarised in Table 3.5, indicate that 1) all three market designs can guarantee reliable DCDS operation; 2) the choice of market design has a limited impact on total operational costs; and 3) this choice largely affects long-term costs due to battery investments. The IM design is theoretically optimal but computationally challenging. The WEP design requires substantial flexibility investments and is therefore disqualified. By contrast, the LEM with linear power flow modelling is promising, because it balances the goals of economic efficiency and computational feasibility.

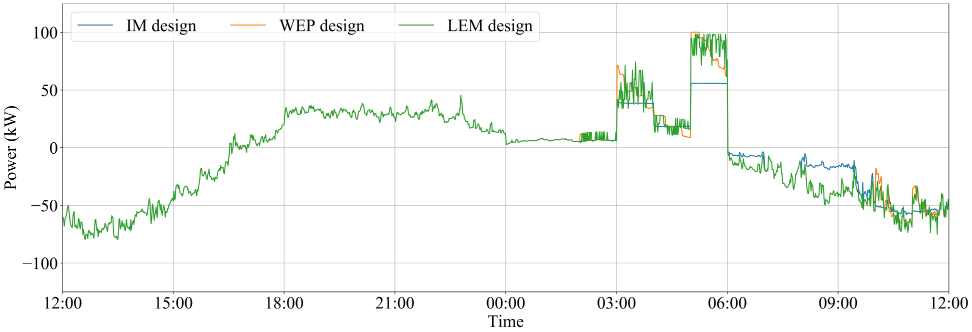
3.5.1. ECONOMIC EFFICIENCY

Total Operational Costs. Included are the energy net import costs and Li-Ion battery depreciation costs (estimated for 0.05 €/kWh, if dispatched). The WEP is the only design that needs Flex batteries: in Scenario 3, battery depreciation adds an extra €1.12 to the total operational costs, making the WEP the most expensive design. Below we elaborate on the energy net import costs. Typically, energy import costs are marginally higher with the WEP design than with the IM and LEM design, as shown in Table 3.5. This is perhaps counter-intuitive, as in the WEP design, individual EVs minimise their wholesale energy costs. However, this leads to an expected overload of the converter. The DSO remediates this situation by discharging Flex during peak hours and charging them at valley hours. Consequently, the actual wholesale energy import is not as well optimised as in the other designs, as seen in Figure 3.3(c). An exception is the WEP design in Scenario 1, in which the daily energy net import cost (€6.59) is lower than in the other designs (€8.03 and €8.04).

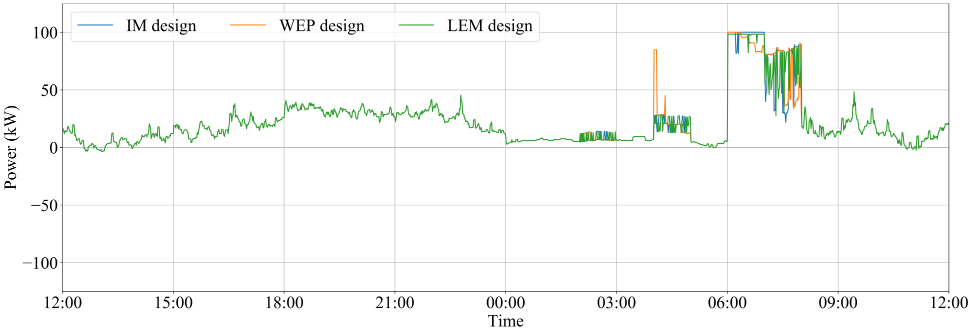
Minimal Battery Investment. The IM and LEM designs do not require Flex batteries in our scenarios, but the WEP design has a high demand for Flex batteries, because it triggers simultaneous EV charging during low-price hours. Such a need for Flex batteries can be avoided with a market design that gives locational incentives. As depicted in Figure 3.4(b), the usage of the seven identical batteries depends on their location, thus avoiding cable congestion and energy losses. In our simulations, the most congestion happens on the cable between N7 and N8, whereas voltage deviations mostly occur at the furthest nodes. Hence, the DSO would potentially pay more to the batteries at such critical locations.



(a) S1 Sunny-Windy.

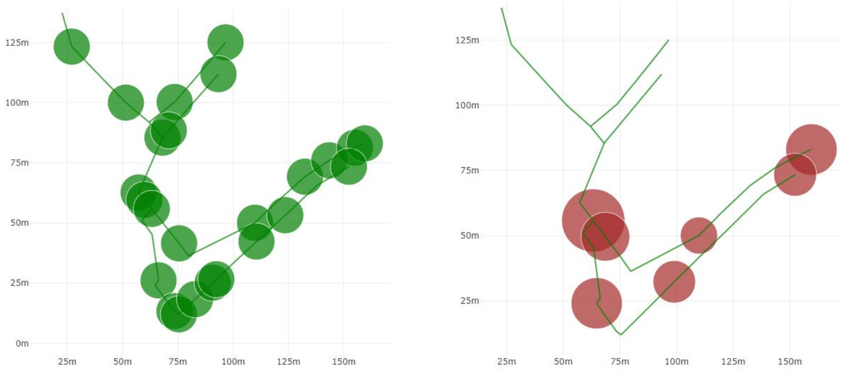


(b) S2 Sunny.



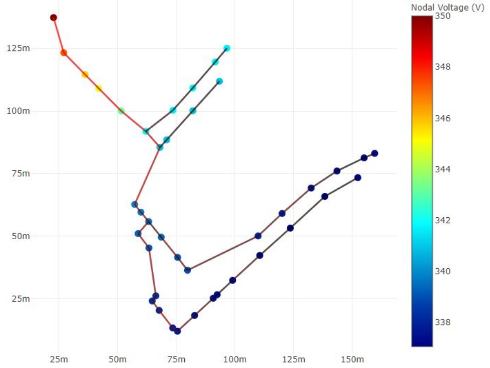
(c) S3 Windy.

Figure 3.3: Market design comparison: power imported from the wholesale energy market via the DC substation, simulated in PyPSA. (a) S1 Sunny-Windy: power consumption always stays within the substation capacity. (b) S2 Sunny: EV charging is high when WEP is low (03:00-04:00, 05:00-06:00). (c) S3 Windy: EV charging is high when WEP is low (06:00-08:00). In each scenario, the imported power of the three market designs are similar except the hours with low WEPs.



(a) EV charging load.

(b) Flex battery power.



(c) cable power and nodal voltage.

Figure 3.4: S3 Windy, WEP design: prosumer power distribution, cable loading and nodal voltage at 06:01 (+1). (a) EV charging load. (b) Flex battery power output. (c) Cable power flow and nodal voltage.

3.5.2. SYSTEM RELIABILITY

Substation & Cable Loading. As indicated in Table 3.5, all the market designs can efficiently manage DC substation congestion. The IM design coordinates EV charging best because it has complete information and can fully exploit network capacity. Cables next to the converter and the branching points are sometimes heavily loaded but never overloaded. The WEP design triggers simultaneous EV charging during the lowest-price hours, creating severe congestion at the DC substation that must be resolved by Flex batteries. We confirmed the feasibility of the LEM design with PyPSA. As introduced earlier, the LEM typically introduces a power dispatching error up to 5%, but but this did not affect the system operation because we reserved a 5% margin for the network capacity.

Voltage Deviation. Voltage deviation is not a limiting factor in our simulation. The IEEE-EULV feeder represents a small, densely-loaded urban residential network, in which voltage deviation plays a smaller role than network congestion. The IM and WEP designs yield lower voltage deviations and energy losses than the LEM design. Even for the LEM design, the largest observed voltage deviation of 5.04% is acceptable. However, Flex batteries may be needed in rural areas where longer cables create larger voltage deviations.

3.5.3. COMPUTATIONAL FEASIBILITY

The LEM is solved in around one second, much shorter than the IM and WEP designs (173 to 2532 seconds), because it formulates a linear problem that can be solved quickly. With some input data, the non-linear solver IPOPT used for IM and WEP even cannot converge to a locally optimal solution. The computational complexity will become a challenge for the IM design, as it should be cleared at a high frequency. The same is true for the WEP design, but a DSO could settle for a less optimal solution—of course, at a higher cost to prosumers.

3.6. DISCUSSION

IM DESIGN

The IM design is only optimal under the unrealistic assumption of complete prosumer information. It uses system flexibility and network capacity most efficiently and therefore eliminates the need for Flex investments. Its non-linear power flow modelling can reduce energy losses by integrating more local generation, as indicated in Figure 3.3(b). Although the WEP is the lowest between 05:00–06:00, the IM still charges EVs with PV power during 08:00-09:30, thereby importing 12% less energy than in the LEM design. Since the reduced energy losses offset the slight increase in energy import costs, the IM design always has a narrow win with respect to total operational costs.

In practice, however, the IM design faces privacy concerns, computational challenges and complexity in market rules. First, the IM design is highly dependent on the availability and credibility of prosumer preferences. Prosumers may be unwilling to share private data with the LMO. Moreover, they might be unable to forecast or schedule their energy prosumption precisely with the presence of uncertainty. Second, the IM design with non-linear modelling requires a slower, non-linear solver. In our simulation, its solving time is 2 to 3 orders higher than the linear LEM design, and it cannot guarantee an optimal solution in all cases. Third, in practice, an LMO should coordinate not only EVs but also heat pumps, storage systems and other flexible devices. Each of these has unique and complex constraints, which further limits the IM design's scalability. Such a centralised market may be suitable for DC microgrids with the required communication infrastructure in place, but not for general DCDS applications.

WEP DESIGN

The WEP design creates new business models for flexibility by paying them explicitly for system service. The DSO directly purchases such flexibility for congestion management and voltage control, thus providing incentives for Flex investments at critical locations.

Nevertheless, this concept of *prosumers trade energy and the DSO solves the rest* is an expensive solution. First, the WEP design gives prosumers a wrong incentive in the short term. Directly passing WEPs to prosumers invites all EVs to charge simultaneously when the WEP is low. Such uncoordinated charging has created a peak load of 175kW in total, much more than a 100kW DC substation can supply. This load is even higher than the one under flat tariff charging, in which EV charging is distributed over time. Second, to serve the above peak load, the DSO must contract prosumer batteries worth €68,760, and it has to pay prosumers extra for Flex activation. This causes the WEP market design and other flexibility market designs—which directly pass WEP to prosumers—to be economically inefficient. These costs, later passed on to the network users as a system cost, can be simply avoided by a better market design. At best, the WEP design is suitable for the transition phase from a mostly inflexible to slightly flexible DCDS, but there is a risk of institutional lock-in.

The other concerns are market liquidity and competitiveness that come with limited Flex market players. With the IM and LEM design, all prosumers participate in locational energy trading. However, if the number of Flex providers is minimal, as in our WEP simulation, they may exercise market power, thus reducing the overall market efficiency. To make this design work, the DSO must contract with most of the flexible prosumers in the DCDS. Flex-based market designs also face challenges of product pricing and standardisation. Flexible devices have different operational costs and constraints in terms of power, energy and temporal flexibility. Only by standardising these Flex contracts can we guarantee the liquidity of a neighbourhood-level DCDS energy market.

LEM DESIGN

As a solution to IM's computational challenges, the LEM uses a linearised network model to optimise local prosumption within the network capacity constraints. LEM is fast and reliable because a linear solver can find a globally optimal solution quickly. Its power flow model is up to 5% less accurate than in the IM design, so the LMO should therefore apply a reserve margin of 5% on the converter capacity to avoid overloading. However, the resulting loss of economic efficiency is negligible—up to €0.03 per day.

Explicit voltage regulation is not necessary for urban grids with short distribution cables. As shown in our EULV case, the maximal voltage deviation was only 4.84%. However, since the LEM does not consider nodal voltage, they may exceed the norms. In such cases, the DSO can invest in small Flex batteries for voltage regulation.

The LEM design still requires much prosumer information as in the IM design, and therefore faces the same implementation challenges. In practice, it will be substantially less accurate. However, the advantages of high economic efficiency and computational feasibility still make this stand out as the most attractive market design.

3.7. SUMMARY

This chapter presents the first quantitative assessment of market designs tailored to DC distribution systems (DCDSs), taken from a previous study of its design options [1]. The *integrated market* (IM) design incorporates all system costs into energy prices. The *wholesale energy price* (WEP) design passes wholesale prices directly to local prosumers while counting on the distribution system operator to resolve congestion. The *locational energy market* (LEM) design relieves congestion with nodal prices.

We systematically analysed how DC technical characteristics may influence local energy market design: volatile energy prosumption challenges the DC substation converter. We built an optimisation model to evaluate three market designs quantitatively, with a 1-min resolution that describes volatile prosumption. Recognising that the total demand and demand flexibility may increase significantly in the future, we included a high share of electric vehicles to test the robustness of the market designs. Simulations on a realistic urban DCDS have demonstrated that all the three market designs can manage network congestion and voltage deviation, even in extreme situations with a large share of electric vehicles. Specifically:

1. Network congestion is the main challenge to distribution-level market design, because flexible prosumption will all be scheduled at low-price hours. We developed a LEM design that preserves system reliability, computational feasibility but is also as efficient as the theoretically optimal IM design.

2. Voltage deviation and cable power capacity are not limiting factors of the DCDS market design, at least in urban distribution networks. The adoption of bipolar DC grids can further eliminate these limits. We suggest future DCDS market designs to focus on DC substation congestion management because of its limited tolerance for overloads.

3. Simply passing wholesale prices to local prosumers, like in the WEP design, may cause severe congestion and require substantial network or flexibility investments. Local electricity markets, especially local flexibility markets (under heated discussion in the literature), should introduce congestion costs into energy bills, so that prosumers are not encouraged to aggravate congestion.

4. Our findings from DC market design are also relevant to markets for future AC distribution grids. The latter typically use converter-based substations and serve converter-interfaced devices including solar panels, electric vehicles and home batteries. Such AC grids share DC features like strict converter capacity limits.

The following aspects limit our results. First, the use of a deterministic optimisation model assumes complete information. Uncertainty regarding short-term wholesale energy market prices and local power prosumption is not included. Second, we did not include a wholesale energy price model in our local energy market design, whereas future work should investigate the interaction between wholesale and local energy markets. Third, we assumed that prosumers would be willing to share all their data, which may not be the practice. Fourth, flexibility was represented in the simulation by a set of identical electric vehicles. However, other flexible devices, such as batteries and heat pumps, will play an important role in practice. Finally, our data is limited to a 24-hour cycle of household consumers, limiting the simulation's representativeness. Our stress-test analysis demonstrates that the market designs perform well under extreme conditions.

Future studies should evaluate the LEM design in more realistic situations, in which the market operator is uncertain about future electricity demand, local generation [112] and WEPs. Prosumers are not always willing to share private data such as preferences, but DCDS networks are sensitive to even brief overloads. Consequently, uncertainties may arise regarding network congestion and future power prices. Agent-based simulations [113], [114] are suitable to study realistic settings, where we include the previously mentioned uncertainties, prosumers' privacy concerns and their bidding strategies. Furthermore, the market designs should also be tested in more realistic power networks with diverse flexible devices, under the influence of aggregators and taxes. Third, these market designs will need to meet a more comprehensive set of criteria, including incentive compatibility, risk-hedging and prosumer involvement.

4

MARKET DESIGN UNDER UNCERTAINTY

DC power distribution systems have the potential of increasing energy efficiency and network capacity, as compared to AC distribution grids, but they need a tailored market design that reflects their unique features. Our previous work identified a locational energy market design *to be a theoretically nearly optimal design. In this chapter, we present a novel agent-based model to simulate the performance of this market design in realistic scenarios. The model describes typical electric-vehicle user preferences and bidding strategies with different levels of range anxiety. We design challenging scenarios with a high share of solar panels and electric vehicles to subject the market to stress tests, using the high-resolution Pecan Street database. Uncertainty regarding prosumer behaviour is a determining factor for market performance, both concerning operational security and economic efficiency. Simulations suggest the market design's economic efficiency and operational security under uncertainty, even with a high share of electric vehicles.*

4.1. INTRODUCTION

This chapter elaborates a *locational energy market* design for direct current (power) distribution systems (DCDSs) presented in [1], [2] and tests it under uncertainty using an agent-based model. DCDSs are a promising alternative to the existing alternating current (AC) distribution systems and can replace the latter in future distribution systems with high renewable generation and bidirectional power flow [10]. By eliminating unnecessary AC/DC conversion, a DCDS offers higher energy efficiency, higher power capacity and greater control flexibility [1]. However, a DCDS has unique technical features such as low system inertia, limited overloading capability, and a direct connection between nodal voltage and active power flow [3]. These DC features require unique operational strategies with precise allocation mechanisms for energy and network capacity. In the context of a liberalised electricity market, a DCDS needs tailored market designs that

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This chapter has been submitted to Energy (under review) [4].

meet both market rules and unique DC features. Although various market mechanisms have been developed for AC distribution systems [93], [94], these mechanisms cannot guarantee the operational reliability of a DCDS with unique technical features [3].

Our previous work [1] proposed a design framework for local energy markets: identifying goals, listing options, testing, evaluation, and improvement. We investigated unique DC features—low system inertia, strict power limits and power-voltage coupling—that call for tailored market designs. We conducted a systematic search of the design space and identified three fundamentally different yet promising market designs, also consistent with [93], [115]: an *integrated market (IM)* design that allows a DSO to dispatch prosumer devices directly and includes all system costs in a single energy price; a market design that passes *wholesale energy price* directly to prosumers while leaving all network issues to the DSO; and a *locational energy market (LEM)* design that relieves congestion with local prices and leaves voltage regulation to the DSO.

In our second work [2], we evaluated the theoretical potential of these three market designs with a deterministic optimisation model. Assuming complete information and truthful bidding, we simulated these three markets in a realistic urban residential area with a high share of electric vehicles (EVs). Results confirmed the LEM design's economic efficiency and system reliability, compared to the theoretically optimal IM design. The latter, aggregating all prosumer flexibility for an efficient system operation, suggests the highest potential of a technically feasible market design. However, the IM design and other direct-control-based market designs [116] are hard to implement. The reasons are (1) the need for prosumers' private information; (2) limited prosumer autonomy in device operation; and (3) computational and communication burden, all posing a challenge to their wide application. The *wholesale energy price* design, by contrast, requires the least amount of prosumer information for coordination, thus preserving privacy about their life patterns and willingness to pay. However, such a weakly-coordinated design is proven to require unnecessarily high investments in flexibility options and is therefore disqualified from our further research. The LEM design, despite its simplicity, is shown to have the highest potential in terms of reliability while maintaining high market efficiency.

Therefore, we focus on the LEM design in this chapter as it is the most promising market design when a distribution network is moderately loaded and congestion is rare. However, in practice, prosumers in the LEM may not optimise from a collective point of view but have different preferences and bidding strategies. These strategies may lead to simultaneous energy prosumption, congestion in DC substations and accordingly high prosumer energy bills and/or unsatisfied power demand. Unfortunately, an optimisation model as in [2] is not sufficient to evaluate a market design's performance in the presence of prosumer behaviour and uncertainty. This open question still needs to be answered before we can prove that an efficient and reliable DCDS operation can be market-driven, as required by a liberalised energy market.

We aim to fill this knowledge gap by evaluating the economic efficiency and system reliability of a DC-tailored market design under uncertainty. This is particularly challenging because, in such situations, neither the local market operator (LMO) nor the DSO nor prosumers have complete information about the fluctuating power flow and local energy prices in the future. The uncertainty of photovoltaic (PV) generation and household consumption may result in volatile power flow that challenges a DCDS's reliability. Worse, the large-scale introduction of EVs and other flexible devices may result in a peak load that is an order of magnitude higher than today. For instance, EV owners may decide to charge EVs simultaneously during hours of low energy prices, leading to shortages and congestion pricing. Since the uncertainty of PV generation, household consumption and stochastic EV charging challenges a DCDS, a future-proof LEM design must be tested against such uncertainty.

This chapter quantitatively evaluates the LEM design's economic efficiency and system reliability against uncertainty and prosumer behaviour. The methodological approach adopted is agent-based modelling (ABM): suitable to evaluate a market design because its performance depends on the collective decision of autonomous entities [117], [118]. We simulate the adaptive bidding strategies of EVs, implement their interactions with the LMO, and then evaluate the market clearing results. We compare the performance of the LEM design against a deterministic optimisation benchmark and then validate the feasibility of the market outcome with a power system simulation–analysis tool PyPSA [104]. Finally, from simulation results on a widely-used IEEE test feeder, and high-resolution measurements from the Pecan Street database [119], we investigate LEM's economic efficiency and system reliability under uncertainty.

The main contribution of this chapter is to conceptualise a practically-feasible and easily implemented LEM design and to confirm its economic efficiency and stability under uncertainty. To our knowledge, we present the first comprehensive DCDS market design starting from our earlier research steps: qualitative analysis of feasible market designs [1] and quantitative analysis of them in theory [2]. Using behavioural models, namely ABM, we now simulate DCDS operations under uncertainty influenced by typical bidding strategies. The results confirm our theoretical analysis that the LEM design is efficient and reliable also under high uncertainty, and further suggest that efficient DCDS operation can indeed be market-driven, as required by liberalised energy markets, thereby removing the market-side barrier to large-scale DCDS deployment.

4.2. LOCATIONAL ENERGY MARKET DESIGN

This section briefly introduces the principle of the LEM design based on our earlier work [2]. We implement these market rules in the behavioural models of the LMO/DSO[1] and flexible prosumers (EVs in our case) in Sect. 4.3.

Figure 4.1(a) illustrates the principle of the LEM design and depicts the interaction between the LMO, the DSO and flexible prosumers. In this design, a prosumer is obliged to place price-quantity bids for the flexible part of her power consumption. How much energy a flexible prosumer is allocated depends on her energy bids and the market-clearing result of the LMO/DSO. Taking an EV as an example, a full charge is not guaranteed if the owner's energy bid price is low. An exception is given to traditional household power consumption with low shifting flexibility but high willingness to pay. Such inflexible demand is always served, for which prosumers are not obliged to place explicit energy bids. However, inflexible loads still pay the market-clearing price.

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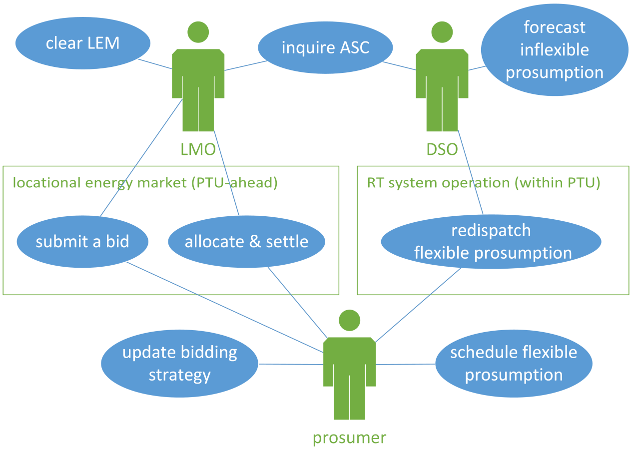
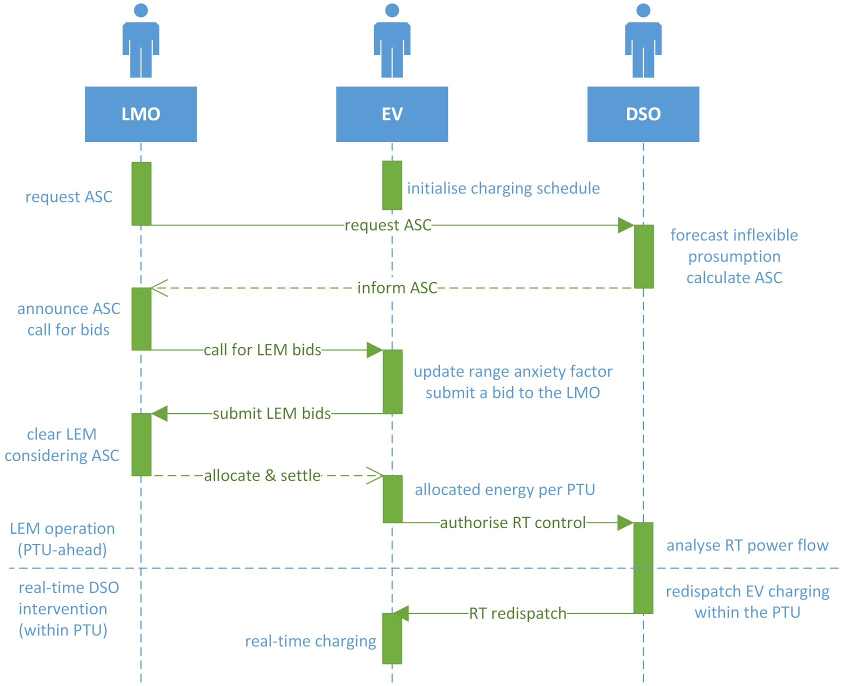
[1] Since an LMO and a DSO closely collaborate in this design, we call them an LMO/DSO except for cases where the role is clearly separate.



(a) a use case diagram. RT: real time.



(b) a sequence diagram.

Figure 4.1: The LEM design explained.

As shown in Figure 4.1(a), the LEM is cleared every programme time unit (PTU, typically 15 minutes) according to the following four steps. First, the LMO/DSO predicts inflexible prosumption and auctions the *auctionable substation capacity* (ASC)—the expected remaining substation capacity minus a reserve margin—to flexible prosumers. Second, flexible prosumers self-schedule their prosumption and bid accordingly for locally available energy, subject to the ASC. Third, the LMO/DSO allocates the energy with a supply-demand matching algorithm subject to the ASC; the market-clearing price is set according to the marginal pricing principle. If the substation power reaches the limit in real time, the DSO redispatches flexible prosumption such as EV charging. For flexible loads such as EVs, prosumers will not experience discomfort as the redispatch is done within the same PTU. Figure 4.1(b) illustrates the interactions between the LMO, DSO and a flexible prosumer (an EV as an example), which we further explain in Sect 4.3.1.

Inflexible prosumption prediction. Small, inflexible prosumers are typically unable to predict their PV generation or schedule their household consumption accurately. The LEM design requires an LMO/DSO to predict the following information for the next PTU as a reference to local prosumers: aggregate PV generation, aggregate residential consumption, and the wholesale energy price.

Flexible prosumption: self-scheduling and bidding. In the LEM design, flexible prosumers schedule their devices and submit energy bids in price-quantity pairs—similar to many existing energy markets [120]—one PTU in advance. This market-based self-scheduling reduces the operational uncertainty in real time because the LEM efficiently allocates energy and ASC among flexible prosumers shortly in advance. Such self-dispatch is limited to deciding the volume of energy bought or sold for the upcoming PTU. During the PTU, a DSO still has the right to redispatch flexible devices to prevent DC substation overloading. It is noted that the success of this simple but efficient market design relies on a certain degree of prosumer intelligence in scheduling, prediction and bidding. Although inflexible prosumers are not obliged to place bids in the LEM, their prosumption is also billed at the LEM's clearing price.

Constrained supply-demand matching. The LEM is designed to handle short periods of network congestion caused by flexible prosumption. Both wholesale and local market players contribute to the supply and demand in a LEM. An LMO/DSO estimates the substation capacity that needs to be reserved for inflexible prosumption. The remaining capacity, namely ASC, is auctioned to flexible prosumers (EVs in our model) together with energy trading. The auction adopts a network-constrained supply-demand matching algorithm that maximises economic welfare. Our earlier simulation of a residential area [2] indicated that the DC substation converter is most likely the only bottleneck facility of a DCDS. Distribution cables will not become the major bottleneck of a DCDS, as they have a significantly higher capacity when used for bipolar DC than for AC distribution. Hence, an urban residential DCDS will only need to shift parts of flexible consumption by a few hours to system operation reliable. The ASC estimate is based on a conservative prediction of inflexible prosumption.

Real-time intervention with flexibility. The LEM design requires a DSO to predict volatile inflexible prosumption; errors in this prediction may result in substation congestion, voltage sags or swells. To avoid substation overload, the DSO is allowed to redispatch flexible consumption (such as EV charging) in the current PTU without affecting prosumers' comfort, similar to the concept in [20]. Namely, the DSO has the option to ramp up/down flexible devices while guaranteeing that flexible prosumers will get the promised amount of energy at the pre-agreed price. Prosumers may be willing to grant DSOs this right in exchange for lower network tariffs. Alternatively, the DSO may be given a legal mandate to intervene in the operation of high-power devices.

4.3. MODEL CONCEPTUALISATION

This section presents an agent-based model (ABM) developed to evaluate how local prosumers' adaptive bidding strategies affect the LEM design under uncertainty. Sect. 4.4 reports a realistic case study using this ABM. Since much flexibility of a future DCDS comes from EV charging, the ABM should estimate the impact of EV charging on LEM's economic efficiency and reliability under uncertainty. Hence, we implement common EV charging behaviour under incomplete information. We assume EVs to be the only sources of flexibility, whereas household consumption and PV generation are inflexible. As a benchmark, we use the deterministic optimisation model presented in [2] to indicate the best possible market performance under complete information.

4.3.1. LEM DESIGN: AN AGENT-BASED MODEL

The LEM design allows EV owners to schedule EV charging for the next PTU via an energy trading platform of the LMO. Since EV charging preferences and bidding strategies are essential to the market outcome, we develop an ABM to simulate the impact of EV charging. We model two typical types of EV charging behaviour, namely urgent and wait-and-see (cost-minimising). In each PTU, all EVs submit an energy demand and willingness to pay for the next PTU to the LMO. The LMO then clears the market and allocates the energy for maximum economic welfare. In practice, an aggregator manages or automates the communication between the EVs and the LMO.

The sequence of the LEM operation is illustrated in Figure 4.1(b). One PTU ahead, the LMO requires the DSO to estimate the auctionable substation capacity (ASC) for flexible loads such as EVs. Our model conservatively predicts the inflexible consumption using a simple approach based on historical load profiles. More accurate predictions are possible using techniques like statistical, physical or machine learning–based methods, or a combination of these. With this estimation, the LMO announces the ASC and invites EVs to submit price-quantity bids for the next PTU, based on their updated charging strategy. Once the LMO receives all bids, it matches supply and demand subject to the ASC. Finally, the LMO informs EVs of the clearing results and settles the transaction with the market-clearing price. In real time, the DSO may intervene in EV charging for a DCDS"s operational security while delivering the promised energy in the PTU.

LOCAL MARKET OPERATOR AGENT

An LMO agent facilitates prosumer bidding and performs market clearing. Its clearing algorithm efficiently allocates energy and substation capacity among local prosumers (Algorithm 1). The algorithm matches the lowest energy bids and the highest energy asks subject to the ASC. In realisation, we treat wholesale supply and demand as two dummy bidders in the LEM, each bidding for or offering an energy volume equal to the ASC at the wholesale energy price. The outputs of the algorithm are the market-clearing price, the traded quantity, and the buyer-seller information. Usually, the local energy price remains equal to the wholesale energy price, unless congestion makes local producers, consumers or flexible devices such as EVs set the market-clearing price.

ELECTRIC VEHICLE AGENT

The EV agents schedule urgent or cost-minimising EV charging and then submit energy bids according to these schedules before departure. The charging schedule is based on EV availability and the expected wholesale energy price. When the market is cleared, an EV agent updates its charging strategy based on the clearing result and prepares the energy bid for the next PTU.

We describe EV agents' charging behaviour realistically based on the literature. Daina et al. [121] suggest three decision factors of EV owners: target energy level (EV driving range), effective charging time and charging costs. Among the EV drivers in their research, (1) 80–90% prefer a higher state of charge by departure; (2) 90% prefer not to postpone the departure; and (3) 60% accepts flexible charging schedules, whereas the other 40% prefer immediate charging. Hence, we model EV charging preferences based on arrival and departure times (no delay considered), the energy needed (until fully charged) and a default willingness to pay for a unit amount of energy.

In particular, we introduce a *range anxiety factor* [122], [123] to distinguish EV owners' charging preferences. As defined by Equations 4.1 and 4.2, a range anxiety factor is the ratio of energy to be charged to the maximum energy that can be charged by departure. Lower anxiety means the EV owner is willing to postpone charging to the periods with the lowest energy prices, as long as her EV can be fully charged by departure. The wait-and-see strategy is an adaptive charging strategy based on this range anxiety factor, which increases if the planned charging cannot be realised. Higher anxiety means an EV owner is willing to bid higher prices to see her bid accepted; a unit range anxiety factor means she prefers immediate full-power charging regardless of the energy price. We implement the behaviour of EV agents according to Algorithm 2. During peak hours, it happens that an EV is not completely charged by departure and must go to an external fast-charging station and pay a penalty for inconvenience and higher energy costs.

4.3.2. THE BENCHMARK: A DETERMINISTIC OPTIMISATION MODEL

This deterministic model [2] serves as a benchmark to the LEM model, indicating the best possible market performance under ideal conditions. It is a deterministic optimisation model with complete information availability: the LMO/DSO knows each EV's charging preferences and availability and can redispatch EV charging in real time for optimal system dispatch. The objective function minimises the DCDS operational cost (Equation 1 in [2]), subject to the DC substation capacity (Equations 2–4, 23, 24) and EV availability (Equations 11–16). The inputs are (1) inflexible household consumption, (2) PV generation, (3) wholesale energy prices and (4) EV charging preferences, whereas the outputs are (1) the EV charging schedule (namely the market clearing results), (2) the total system cost (namely the economic efficiency), and (3) the resulting power flow (namely the system reliability). As voltage deviations have limited influence on the power flow of a bipolar DCDS, we adopt a linearised power flow model to improve solution speed, then verify the feasibility of the solution using PyPSA [104].

Algorithm 1 LMO market clearing algorithm

```
Require: local power supply in bids, and local flexible power demand in asks
Require: ASC, based on the predicted inflexible local power prosumption
add dummy bid–ask representing wholesale market supply–demand limited by ASC
sort all bids and all asks by price
while both bid and ask exist do
    match the lowest bid and the highest ask
    update residual bid and ask, traded quantity and buyer-seller information
    market-clearing price ← price of the residual bid and ask
    if either the buyer or the seller is the wholesale market then
        decrease the ASC by the traded amount
    end if
end while
return market-clearing price, traded quantity and buyer-seller information
```

Algorithm 2 Range anxiety based energy bidding strategy for EV *e*

```
Require: charging schedule $t_a^e, t_d^e$, initial & target SOC $r_a^e, r_d^e$, battery rating $(c^e, \eta^e, \underline{p}^e)$
Require: expected wholesale energy prices $\lambda_t^w,\ t \in [t_a^e, t_d^e)$
$t \leftarrow t_a^e$
while $t < t_d^e$ and $r_t^e < r_d^e$ do
    calculate unit anxiety charging strategy $(b^e_{t,u=1}, p^e_{t,u=1})$: full-power charging until reaching the desired SOC
    calculate zero anxiety charging strategy $(b^e_{t,u=0}, p^e_{t,u=0})$: a greedy algorithm seeking the lowest possible bidding price
    update range anxiety factor $u_t^e$ according to Equation 4.1

        $$u_t^e = \frac{(r_d^e - r_t^e)\, c^e}{\eta^e(-\underline{p}^e)(t_d^e - t)} \quad \forall t \in [t_a^e, t_d^e), \forall e \in \mathcal{E} \tag{4.1}$$

    update bidding price $b_t^e$ according to Equation 4.2

        $$b_t^e = u_t^e b^e_{t,u=1} + (1 - u_t^e) b^e_{t,u=1} \quad \forall t \in [t_a^e, t_d^e), \forall e \in \mathcal{E} \tag{4.2}$$

    update bidding quantity $p_t^e$: $p_t^e \leftarrow p^e_{t,u=1}$ if urgent, or $p_t^e \leftarrow p^e_{t,u=0}$ if wait-and-see
    submit a bid $(b_t^e, p_t^e)$ to the LMO
    receive the energy allocation $q_t^e$ from the LMO
    update SOC: $r^e_{t+1} \leftarrow r^e_{t+1} + \frac{\eta^e q_t^e}{c^e}$
    $t \leftarrow t + 1$
end while
return submitted energy bids $(b_t^e, p_t^e),\ t \in [t_a^e, t_d^e)$
```

4.4. EXPERIMENT DESIGN

The objective of the experiments is to evaluate quantitatively the LEM design's economic efficiency and system reliability under uncertainty, compared to a deterministic optimisation model. In particular, we are interested in how well the LEM design deals with potential congestion and voltage problems that may challenge the reliability of an urban DCDS with many EVs. We create realistic scenarios as follows. First, the network represents a low-voltage DC distribution system for urban residential areas, in which intense energy consumption leads to network congestion. Second, the DCDS serves distributed renewable sources (such as rooftop PV panels) and realistic household loads, partly inflexible and partly price-elastic. We should use high-resolution prosumption measurements from pilot projects to reflect the impact of fluctuating prosumption on DC substations. Third, we include a futuristic number of EVs in the residential area, driven according to realistic patterns. Last, we consider a historical wholesale energy price at which local prosumers buy or sell energy collectively in the wholesale market.

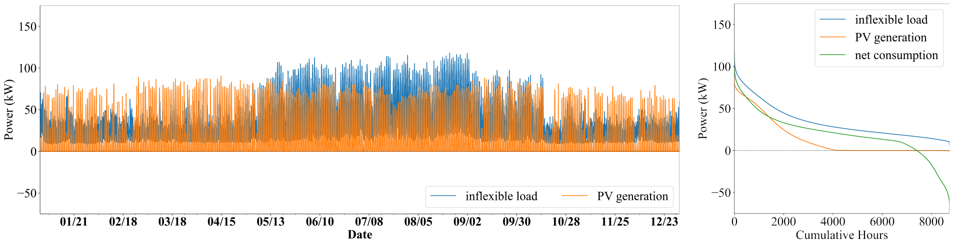
4.4.1. DATA SOURCES

As DCDSs are neither widely applied nor standardised yet, there is no reference example of a low-voltage DC test feeder. We chose a widely-used IEEE European low voltage distribution test feeder (EULV) [105] to represent a typical residential distribution system with household consumers, simplifying the 906-node network to a 41-node representation of its main branches. The 400V 3-phase AC network is upgraded to bipolar, ±350V DC. We simulate the fluctuations of local prosumption using 1-minute measurements of the Pecan Street database in 2018 [119] (52 full weeks). This database contains high-resolution consumption data of 25 real households in Austin, TX, USA. Hence, we created a realistic amount of 25 households featuring inflexible consumption and rooftop PV panels. As the Pecan Street data does not represent a futuristic amount of EVs, we adopt the 25 synthetic driving profiles from [124]. We describe the wholesale energy price uncertainty with the ERCOT day-ahead energy price [125].

4.4.2. SCENARIOS

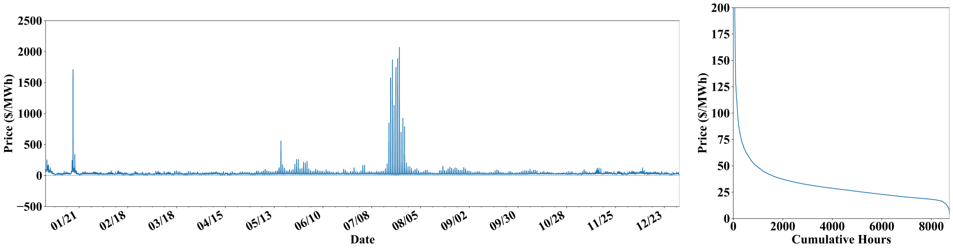
The simulations test the LEM design against high prosumption uncertainty and evaluate how effectively it coordinates EV charging. We consider three scenarios with one, two and even four EVs per household. Two common types of EV owner behaviour are considered: (1) urgent charging, namely charging at maximum power upon arrival until full, and (2) wait-and-see charging. In the latter, the EV owner tries to minimise charging costs, whereas her range anxiety–based bidding strategy is continuously adjusted to guarantee a full charge by departure.

Other scenario parameters remain constant. The DC substation converter has a capacity of 150kW and the cable power rating is doubled compared to Table 3.2, as we switched from unipolar to bipolar DC to serve more loads presented by the Pecan Street data. Since power flow linearisation may introduce an error of up to 5%, we set a 5% reserve margin on the auctionable substation capacity (ASC). Namely, the ASC for EV charging is 95% of the DC substation capacity minus a conservative estimation of the expected inflexible prosumption. The latter is chosen as the maximum inflexible prosumption for each PTU of the same days of the week within ±1 month.



(a) aggregate PV generation and residential consumption from Pecan Street database 2018 [119].

(b) same as (a), cumulative.



(c) ERCOT day-ahead energy price (LZ South) in 2018 [125].

(d) same as (c), cumulative.

Figure 4.2: Aggregate inflexible prosumption and wholesale day-ahead energy price in the simulation. Price peaks above 200$/MWh are not shown in (d).

4.4.3. INITIALISATION AND REALISATION

For each simulation, we create an LMO agent for the DCDS, EV agents who submit bids to the LMO, and a dummy generator/load that represents the supply and demand of the wholesale energy market. We treat household consumption and PV generation as must-served, inflexible prosumption; an agent modelling is unnecessary for them. The value-of-lost-load for inflexible loads is set to 5 $/kWh and the bidding price of PV panels is set to zero, considering the negligible variable costs. Household locations are randomly selected. Regarding EV charging, we assume that all EVs are driven once per day following one of the 25 synthetic driving profiles [124] and charged overnight at home. All EVs' expected SOC by departure is set to 100%. The average EV willingness to pay is initialised at 5 ¢/kWh with a standard deviation of 0.5 ¢/kWh to break ties in market clearing.

The ABM is implemented in Python 3.7. The market operation (the LMO agent), EV charging schedule and energy bidding (EV agents), and the communication needed are implemented using SPADE 3.1 [126]. We verify the ABM in four steps suggested by Deguchi [127]: agent behaviour recording/tracking, single-agent testing, interaction testing and multi-agent testing. The deterministic optimisation benchmark, namely the DSO's optimal decision on behalf of EVs, is modelled according to [2] using Pyomo 5.7 [103] and is solved by Gurobi 9.1. Finally, we test the feasibility of the market outcomes using a physical power system model we developed using PyPSA 0.17 [104].

4.4.4. PERFORMANCE CRITERIA

Table 4.1 presents the criteria for quantifying a market design's goals of economic efficiency and system reliability. Regarding economic efficiency, the energy import cost represents the cost of energy the LMO purchased from the wholesale market (via the DC substation) on behalf of local prosumers. The substation congestion cost covers the difference between wholesale and local energy prices. All local prosumers pay this congestion cost to the DSO for the expansion of DC substations and cables. For scenarios where not all the EV charging demand can be met, we impose an additional fast-charging cost of 1 $/kWh, consisting of a penalty for the inconvenience and a higher energy cost at a commercial fast-charging station. The system reliability goals are evaluated by (1) maximum substation loading factor, (2) maximum cable loading factor, and (3) maximum voltage deviation in the DCDS.

To evaluate the LEM design's impact on different types of prosumers, we also included the weighted average ('wt. avg.') energy price per prosumer group: PV generation, inflexible loads and EV charging at home. Fast EV charging outside the DCDS is offered on-demand at a fixed tariff and is excluded from this wt. avg. EV charging price.

Table 4.1: Criteria for local electricity market design, based on [1].

category	goal	criteria
economic efficiency	efficient production cost recovery efficient allocation	energy import cost ($) substation congestion cost ($) EV energy charged (MWh)
system reliability	sufficient network capacity voltage regulation	max. substation loading (≤ 100%) max. cable loading (≤ 100%) max. voltage deviation (within ±5%)

4.5. SIMULATION RESULTS

This section presents the simulation results of the LEM design. Sect. 4.5 presents four benchmark cases, illustrating the best possible system performance with zero to four EVs per household. By comparison, Sections 4.5, 4.5 and 4.5 illustrate the performance of the LEM under two common charging strategies. Simulations indicate that the LEM design provides sufficiently high economic efficiency and system reliability, also in the challenging scenario with four EVs per household.

BENCHMARK SCENARIOS WITH ZERO TO FOUR EVS PER HOUSEHOLD

We introduce four benchmark cases to indicate the theoretical potential of a market design with complete information (Table 4.2). Here local prosumption, wholesale energy prices and EV availability are known and EV owners are fully collaborative. Although the EV energy demand is only a fraction of the total energy consumption, the flexibility with EVs becomes the primary source of substation congestion, as shown in Figure 4.3(a,d,g).

Under optimal scheduling, the benchmark cases show the lowest possible energy import cost of $6,982 – $14,031. The substation congestion cost is negligible with up to two

Table 4.2: Deterministic optimisation benchmark with zero, one, two and four EVs per household in 2018.

number of EVs per household	zero	one	two	four
energy import cost ($)	6982	8596	10237	14031
substation congestion cost ($)	0	0	115	2242
total system cost ($)	6982	8596	10352	16273
EV energy demand (MWh)	0.00	60.52	121.03	242.06
max. substation loading* (%)	73.60	95.90	118.49	121.99
max. cable loading* (%)	52.57	68.50	94.14	112.26
max. voltage deviation (%)	1.16	1.52	1.96	2.42
wt. avg. PV generation energy price (¢/kWh)	5.60	5.60	5.61	5.94
wt. avg. inflexible load energy price (¢/kWh)	4.68	4.68	4.69	4.86
wt. avg. EV charging energy price (¢/kWh)	-	2.65	2.75	3.74

* Before the DSO redispatch of EV charging. After that, the instant peak loads are shaved by the DSO within the PTU, so that the substation and cable loading is always kept below 100%.

EVs per household. Under the extreme scenario of four EVs per household, this cost is also limited to $2,242; clearly, such an optimum is not achievable under uncertainty. The total system cost, namely the sum of energy import cost, substation congestion cost and EV fast-charging cost (if applicable), is mostly determined by its first part and increases almost linearly as the number of EVs.

Simulations suggest that cable congestion and voltage issues are not limiting an urban DCDS with a short cable length [2]: they did not occur even with four EVs per home. Scenarios with two and four EVs show a risk of instant overloading of the DC substation and some cables; however, such risks are mitigated by the DSO redispatch on EV charging. Although congestion slightly increased the wt. avg. EV charging price (2.65 – 3.74 ¢/kWh), inflexible consumers do not have to pay higher prices. EV charging mainly falls in the low price periods around midnight when inflexible consumption and PV generation are negligible. But in most times, the local energy price is linked to the wholesale price, based on which local prosumers can schedule their energy usage.

LEM PERFORMANCE WITH ONE EV PER HOUSEHOLD

This scenario has one of the two cars of an average household being electric. The energy import costs, $8,112 with wait-and-see charging and $8,570 with urgent charging, are comparable to the benchmark. In early January, the wholesale energy prices are higher than what EV owners are willing to pay. So some EVs (1.40% of the total demand) choose not to bid in the LEM but do fast charging at a fixed price of 1 $/kWh, leading to an additional fast-charging cost of up to $850. LEM is relatively efficient with wait-and-see charging, as the total system cost is only 5.81% higher than the benchmark.

The LEM also ensures system reliability through its implicit auction of substation capacity. The voltage deviation and network loading stay within the safety range. With wait-and-see charging, the substation congestion cost of $223 is an order of magnitude lower than the energy import cost. LEM also offers price signals as efficient as the benchmark for prosumers to behave flexibly. It drives up energy prices when residual demand

Table 4.3: LEM performance with one, two and four EVs per household in 2018.

number of EVs per household EV charging strategy	one WS	one U	two WS	two U	four WS	four U
energy import cost ($)	8112	8570	9305	9903	11783	12515
fast charging cost ($)	760	850	1810	1900	24090	9250
substation congestion cost ($)	223	2550	762	4058	2342	8466
total system cost ($)	9095	11970	11877	15861	38215	30231
EV energy demand* (MWh)	60.77	60.66	119.76	119.97	240.91	242.69
EV energy charged (MWh)	60.01	59.81	117.95	118.07	216.82	233.44
residual EV energy demand (MWh)	0.76	0.85	1.81	1.90	24.09	9.25
max. substation loading** (%)	90.66	83.33	92.50	90.56	101.53	96.95
max. cable loading (%)	71.63	64.73	82.40	68.43	80.62	81.86
max. voltage deviation (%)	1.50	1.50	1.67	1.49	1.75	1.66
wt. avg. PV generation price (¢/kWh)	5.60	5.60	5.60	5.60	5.68	5.66
wt. avg. inflexible load price (¢/kWh)	4.70	5.27	4.74	5.37	4.87	5.76
wt. avg. EV charging price*** (¢/kWh)	2.14	3.96	2.44	4.16	3.06	4.62

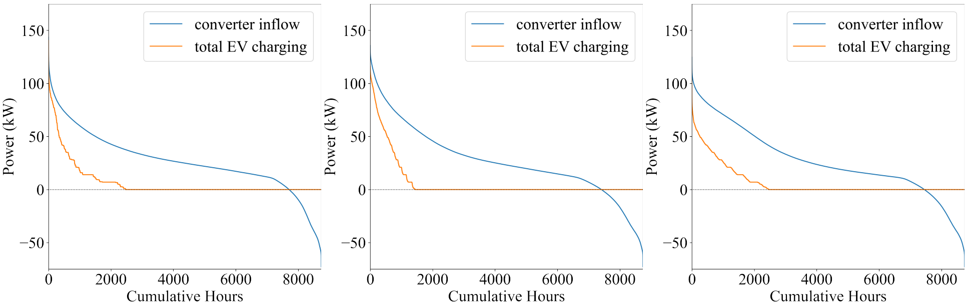
* EV energy demand may vary due to the randomness in EV driving pattern. WS = wait-and-see; U = urgent.
** Potential overload is mitigated by DSO redispatch within the same PTU.
*** Price does not include fast charging costs for the residual EV energy demand.

exceeds the ASC and relieves congestion by postponing less urgent EV charging.

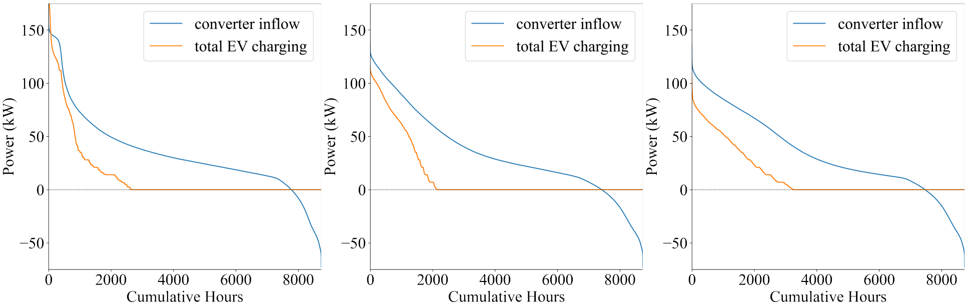
With flexible prosumers (wait-and-see charging), the LEM design creates similarly efficient price signals as the benchmark, confirming our conclusions in [2]. The wt. avg. EV charging price of 2.14 ¢/kWh (excluding fast-charging) is much lower than the price for inflexible loads, as prosumers charge EVs at low-price, off-peak hours. However, price-insensitive prosumers (urgent charging) cannot use DC substation capacity efficiently and result in a congestion cost of $2,550 and a high EV charging price 3.96 ¢/kWh. Such inflexible prosumers also increased the wt. avg. energy cost of inflexible loads from 4.70 ¢/kWh to 5.27 ¢/kWh.

LEM PERFORMANCE WITH TWO EVS PER HOUSEHOLD

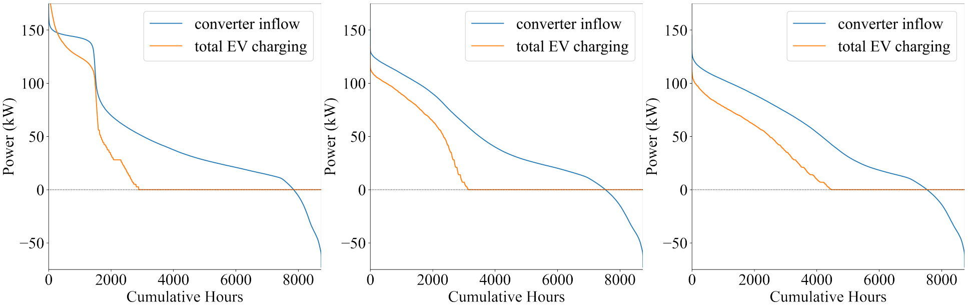
In this scenario, the total system cost of $11,877 (with wait-and-see charging) is only 14.7% higher than the unrealistic benchmark, showing a relatively high efficiency of the LEM design. LEM coordinates flexible prosumers well as indicated by a low substation congestion cost of $762. However, LEM's efficiency depends on prosumer behaviour, as the total system cost can reach $15,861 with price-insensitive (urgent charging) prosumers, 53.2% higher than the benchmark. The prosumer autonomy granted by the LEM has exacerbated the substation congestion in the evening and driven up the congestion cost to $4,058. This congestion also increased the wt. avg. EV charging price to 4.16 ¢/kWh (2.44 ¢/kWh with wait-and-see) as well as the price of inflexible households (5.37 ¢/kWh). Nonetheless, the LEM design ensures DCDS reliability under two charging strategies. Neither overloads of substations or cables nor large voltage deviations occured thanks to a conservative reserve margin of the ASC and the use of bipolar DC.



(a) 1-EV, benchmark (b) 1-EV, wait-and-see (c) 1-EV, urgent

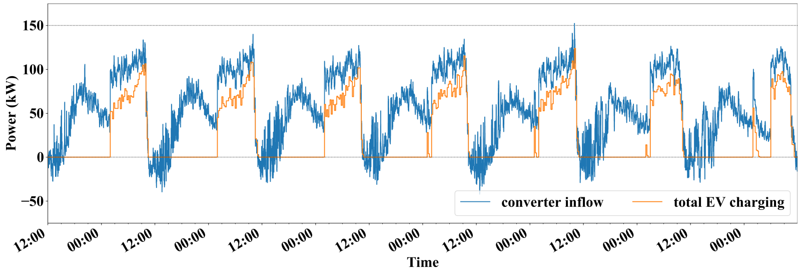


(d) 2-EV, benchmark (e) 2-EV, wait-and-see (f) 2-EV, urgent

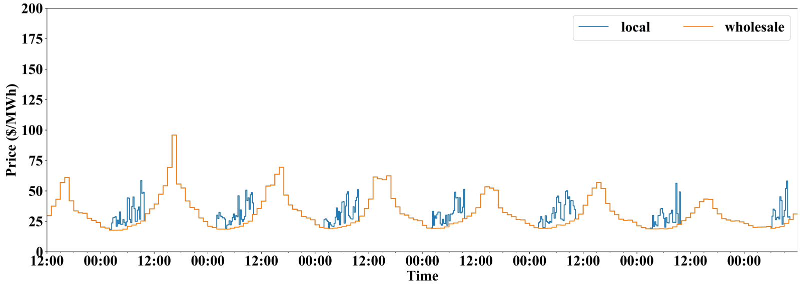


(g) 4-EV, benchmark (h) 4-EV, wait-and-see (i) 4-EV, urgent

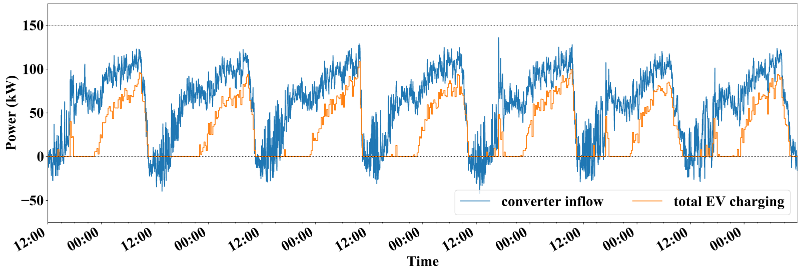
Figure 4.3: LEM simulation: DC substation converter power flow versus EV charging load.



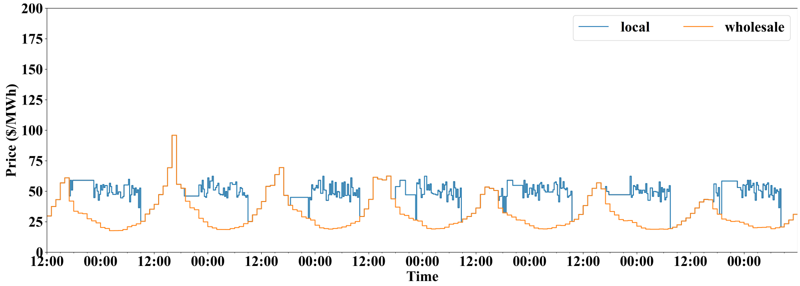
(a) wait-and-see: DC substation power versus aggregate EV charging power



(b) wait-and-see: local energy price



(c) urgent: DC substation power versus aggregate EV charging power



(d) urgent: local energy price

Figure 4.4: LEM simulation with 4 EVs per household: DC substation power, aggregate EV charging power, local energy price between 10–17 June.

LEM PERFORMANCE WITH FOUR EVS PER HOUSEHOLD

This extreme scenario tests the limit of the LEM design: the total energy demand of 100 EVs (242 MWh) is already comparable to the inflexible demand (294 MWh). Even with urgent charging, 9.25 MWh residual EV charging demand (3.81%) must be served with an external fast-charging station at an extra cost of $9,250. The substation congestion cost increases to $8,466 (Figure 4.4(d)), and the total system cost is already 85.8% higher than the benchmark. Hence, the LEM design is not an efficient solution for extreme scenarios; the LMO/DSO should expand the network capacity instead to meet the increased demand. But LEM still guaranteed this DCDS's reliability in this scenario. An instantaneous substation overload of 1.53% (with wait-and-see charging) can be mitigated by DSO intervention (Figure 4.4(a)).

Ironically, the LEM design may perform even worse with flexible than inflexible prosumers in extreme situations. Whereas urgent charging allows charging as many EVs as possible (Figure 4.4(c)), wait-and-see charging encourages EVs to postpone charging until the hour with lower wholesale prices. EV owners do not buy energy before this hour but later face an energy shortage. Hence, the EVs cannot be fully charged by departure, even at higher bidding prices (Figure 4.4(b)). Consequently, a total of 24.09 MWh EV energy demand (10%) must be served by additional fast charging at an extremely high cost of $24,090. The total system cost $38,215 is not only 1.35 times higher than the benchmark but is also much higher than the cost with urgent charging. Hence, the LEM cannot ensure a DCDS's market efficiency in the presence of too much uncoordinated flexibility. An improved LEM design should coordinate local energy prosumption via additional measures in such a case: a viable option is to carefully define, operate and monitor a locational flexibility market [1], [93].

4.6. DISCUSSION

The results indicated that a simple LEM design can enable efficient DCDS operation under uncertainty. In a common scenario with one EV per household, the LEM design's total system cost, $9,095, is comparable to that of the benchmark $8,596 (despite an increased substation congestion cost of $223), as shown in Table 4.3. This means that the relatively simple LEM design yields a nearly optimal DCDS operation with a reasonable degree of prosumer flexibility. It neglects voltage deviations and cable capacity constraints, but such simplifications barely affect the efficiency of a DCDS. This design ensures a technically feasible market outcome even in the extreme situation with four EVs per household. The LEM design's simple bidding format, namely price-quantity pairs, means that prosumers only have to share a minimum of information with the LMO, thus preserving privacy. The simple bidding format and clearing mechanism also increase the LEM design's scalability, making it faster and more reliable than the theoretically optimal IM design. These results are discussed in detail later in the section.

Simulations of stress test scenarios with two and even four EVs per household confirmed the LEM design's reliability under uncertainty, ensured by the real-time DSO intervention in EV charging. As introduced in Sect. 4.1, the key to a reliable DCDS operation is the congestion management for the DC substation, which is challenging due to highly fluctuating, uncertain prosumption. Because the LEM is a real-time energy market, inflexible prosumption prediction and flexible prosumer scheduling are only done

one PTU in advance when uncertainty is further limited. In the simulations, no substation overload occurred in any scenario despite uncertain inflexible prosumption. If uncoordinated prosumption leads to substation overload, the DSO can redispatch part of EV charging within a PTU, thereby relieving congestion without delaying the EV charging. Voltage deviation and cable overloading are not the limiting factors in an urban low-voltage DCDS with thick and short cables.

Simulations suggest that DC substation capacity is the typical bottleneck of a DCDS that requires congestion pricing. Hence, a zonal market with a single price zone behind the substation is usually sufficient. Distribution cables are usually over-dimensioned to meet future flexible demand, avoiding municipal constructions and the associated high costs. The use of bipolar DC cables also helps by providing higher power capacity than AC cables. Hence, we propose to remove cable capacity constraints from a DCDS market design, thereby creating a uniform energy price. Since an extreme case with four EVs per household was feasible, further electrification including heat pumps would also be possible in this scenario. If substation congestion drives up energy prices significantly, the concept of modular DC converters [128] allows the DSO to upgrade the DC substation quickly and at low costs.

The introduction of a LEM allows the wholesale energy market to integrate local energy resources. An LMO/DSO can integrate prosumer flexibility into the LEM design more directly and efficiently than aggregator/retailer-based market designs [2]. Thus, the wholesale market can directly access and use local flexibility for a globally efficient resource allocation. Indeed, such market integration may require an update on wholesale market rules: small prosumers typically do not (or cannot) schedule devices one day in advance, as is common in wholesale day-ahead energy markets. Hence, the challenge is facilitating intraday or real-time energy trading rather than day-ahead. Meanwhile, an LMO should be allowed to participate directly in the wholesale energy market. New regulations should enable such changes.

The LEM design supports prosumer autonomy by facilitating self-scheduling. Its simple bidding format in price-quantity pairs makes it easy for prosumers to understand and follow market rules. The LEM design treats all flexible technologies (generation, consumption and storage) equally as long as they respond correctly to price signals. It also preserves market fairness: prosumers who made flexibility investments benefit from lower energy bills, but it does not mean that the existing, inflexible consumers will see a sharp increase in their energy bills (Table 4.3).

The LEM design is suitable for DCDSs without voltage issues and can apply to radial, ring or even meshed grids in an urban context. It is based on a simplified power flow model and is suitable for urban DCDSs with relatively short cables. In rural networks, voltage deviations may become a limiting factor for reliable DCDS operation. In such cases, an expansion of the LEM design should include dynamic line capacity, considering voltage limits. Albeit designed for DC, the LEM can serve as a stimulus for future low-voltage AC markets by facilitating prosumer participation. However, it does not aim to solve AC-specific network problems such as phase imbalances and high energy losses; such problems are simply solved by switching to DC.

Despite its advantages, the LEM design requires a certain degree of intelligence with prosumers and the LMO/DSO for optimal DCDS operation. With a simple wait-and-see

EV charging strategy [123], price-sensitive EVs can efficiently schedule charging without creating much congestion under the LEM design. In the LEM design, EV owners submit price-quantity bids to the LMO one PTU in advance. When scheduling, they should consider the uncertainty of energy availability and that of the local energy price. With a less price-sensitive (namely urgent) charging strategy, the LEM design ensures a DCDS's reliability despite an increase in energy import costs. prosumers have incentives to share their flexibility as the urgent charging strategy will lead to high energy bills for EV owners. Meanwhile, the LMO/DSO should make sure that sufficient flexibility is available for economic DCDS operation and that local energy prices do not expose prosumers to too much risk. If substation congestion keeps energy prices high, the DSO should expand the DC substation or install additional substations (easier than with AC).

Considerations about the LEM design include market efficiency and system reliability. First, can flexible prosumers bid optimally to meet their energy demand at the least cost? All EVs may plan to charge during low-price hours, but the resulting congestion may prevent some EVs from being fully charged by departure. They may increase their bidding price, but the market-clearing price may also increase. Second, because the LEM is only cleared per PTU, intra-PTU congestion may still occur if the inflexible prosumption prediction contains errors. The simplification of power flow (resulting in an error of up to 5%) further exacerbates this error. The DSO should solve all these problems with intra-PTU redispatch. Third, limited to simple bids, the LEM cannot take into account complex system services such as voltage regulation and energy loss compensation. Such services should be provided by the DSO separately.

4.7. SUMMARY

This chapter demonstrated that a *locational energy market* (LEM) design can enable an economically efficient and reliable operation of a direct current (DC) distribution system (DCDS) under uncertainty. The LEM design, based on our previous work [1], [2], is the first comprehensive energy market design for DCDSs. It works as follows. First, flexible prosumers such as electric vehicle (EV) owners place energy bids for the next programme time unit. Next, a local market operator matches supply and demand under the DC substation capacity constraint, thereby eliminating congestion. If a network problem occurs, a distribution system operator redispatches EV charging in real time. With this design, simple prosumer self-scheduling supported by the LMO can keep the DCDS operation almost as efficient as in a deterministic optimisation benchmark. Since a DCDS usually has only one bottleneck at the DC substation converter, the LEM design operates efficiently if only the substation constraint is respected. Nevertheless, efficient LEM operation relies on a certain degree of prosumer intelligence in self-scheduling.

Using an agent-based model, we tested the LEM design with self-scheduling EVs in a typical European DCDS. This model describes EV charging preferences, energy bidding strategies and their interactions with the market. Two common charging strategies, namely wait-and-see charging and urgent charging, mimic the realistic behaviour of EV owners. We evaluated the influence of the share of EVs, their charging preferences, and the uncertainty of local prosumption. We demonstrated that a range anxiety-based bidding strategy [123] is sufficient to achieve efficient DCDS operation when network constraints are not too tight.

The LEM design performed efficiently and reliably under uncertainty in simulations based on the 2018 high-resolution Pecan Street database. It was tested in a scenario with stochastic local power prosumption, fluctuating wholesale energy prices and unforeseen EV availability. With price-sensitive EV owners (wait-and-see) and one or two EVs per household, the LEM design is completely reliable and the EV charging prices are comparable to the benchmark. Even in the extreme situation with four EVs per household, the DCDS operation is still 100% reliable and the weighted average EV charging price is lower than that of inflexible loads thanks to the real-time intervention of a distribution system operator. Hence, we conclude that the simple LEM design, with only price-quantity bids and the DC substation capacity constraint, is the best feasible option among the three designs proposed in [1].

Assumptions behind the LEM design deserve further investigation. First, the LEM design requires short-term predictions of local prosumption, wholesale energy prices and EV availability. Such predictions are challenging due to the low level of aggregation. Second, we described EV preferences with 25 synthetic driving profiles, a simple range anxiety model and a willingness to pay. More realistic simulations should be based on improved EV behaviour models or a state-of-the-art database with EV charging statistics. Third, the uncertainty modelling in this chapter is limited to household load, rooftop solar generation and wholesale day-ahead energy prices, so the modelling effectiveness depends on the representativeness of the data sources. Future case studies including heat pumps, batteries and other intelligent appliances should verify the general applicability of the LEM design under real-time (or balancing) wholesale energy prices, taxes and levies, as suggested by Stawska et al. [129].

As DC distribution technology is currently under development and standardisation, the DCDS market design is a greenfield study that requires new market goods and trading rules. With an improved agent-based model, further research should evaluate the influence of complex prosumer behaviour—irrationality, learning and gaming—and different flexibility scheduling algorithms [130] on the LEM design. Finally, this market design should be tested in different scenarios with heterogeneous devices and finally be validated through field tests involving real customers.

5

DISCUSSION

Having tested the three DCDS market designs, we now reflect on their performance and briefly discuss the other important factors of the market design. These factors include implementation barriers, investment incentives, strategic behaviour, application areas and disruptive technological developments, all of which can have a profound influence on the operation and implementation of the markets.

5.1. REFLECTION ON THE MARKET DESIGNS

Chapters 3 and 4 demonstrated the potential of the LEM design and two other market designs using a deterministic optimisation model and an agent-based model, respectively. Nevertheless, these promising market designs may face practical challenges in daily operations that have not been addressed in the previous analysis. Below we discuss some of the main challenges and their potential for improvement.

LEM DESIGN

The first and the biggest challenge to any local market design is prosumer involvement. In real life, small prosumers cannot or will not schedule flexible devices such as EVs then bid continuously in a real-time market such as LEM, without the help of a smart bidding agent or aggregator. Prosumers have limited information about wholesale energy markets and local power prosumption. Another challenge is their limited capability and experience in scheduling and bidding compared to players in a mature wholesale energy market. Hence, the LEM design should facilitate the participation of small prosumers through a user-friendly trading platform. Meanwhile, it should preserve information transparency regarding historical, current and future information about the wholesale energy market, local prosumption profiles, congested areas and congestion revenues. Last but not least, it should provide prosumers with easily implementable, automatic (agent-based) bidding strategies that meet their individual needs, as well as a performance dashboard (energy prices, accepted bids and offers, net profit) that they can refer to. To ensure that the LEM design is also compatible with consumers who passively participate in the LEM, the local market operator (LMO) should provide them with a monthly overview of their energy bills, including the weighted average energy prices and tips on how to reduce their energy costs further (e.g., by shifting evening peaks).

The second challenge of the LEM design lies in the high demands on the LMO and the distribution system operator (DSO). With LEM, an LMO/DSO (collaborating closely in this design) is responsible for predicting local inflexible prosumption 15 minutes in advance, which can be a challenge in an urban low-voltage DCDS due to the limited number of households and less aggregated, highly fluctuating power prosumption. Such predictions are an essential reference for the energy trading between local prosumers; limited information availability and potential prediction errors can influence the LEM's judgement on congestion, the auctionable substation capacity (ASC) and the local energy price. If congestion is predicted, the LMO/DSO should make sure that sufficient flexibility is available at the desired time and location, provided by local flexible load, generation or energy storage. According to the LEM design, a DSO should reschedule part of flexible devices in real time when necessary (within the same PTU), but such rescheduling is subject to prosumer consent, computation & communication support (for real-time control), as well as energy laws and regulations.

IM DESIGN

The IM design based on centralised optimisation can be technically, economically or institutionally challenging for distribution grids, as it requires direct control over most of residents' appliances. First, its performance highly depends on the availability and the accuracy of prosumer preferences, but not all prosumers are willing to reveal this information; some may not be able to clearly express their preferences or accurately predict their prosumption. Second, the energy prices calculated ex post may bring uncertainty to prosumers. Third, the IM design may face computational and communication challenges and is less scalable than the LEM design. It adopts a bilinear power flow formulation to mitigate voltage deviations, and it includes mixed-integer operational constraints for flexible devices such as heat pumps, EVs and batteries. Therefore, the IM design presents a non-linear problem that is more difficult to solve than that of the LEM design.

However, such a market design has the potential to integrate the largest volume of flexible power prosumption and may be the only market solution when a DCDS has to be operated under very tight constraints, namely very frequent congestion. This centralised, forward-looking IM design has the potential to see the most efficient resource allocation and can be a promising option for DC microgrids or energy communities. In such systems, direct control of prosumer devices is possible via programmable electric appliances, computation & communication infrastructure, and a centrally optimised control algorithm.

WEP DESIGN

The WEP design is suitable for the market transition phase in which prosumer flexibility is limited. With further electrification in vehicles and residential heating, simply allowing flexible prosumption at wholesale energy prices would lead to much higher power consumption than usual during low-price hours, requiring unnecessarily high investments in flexibility services for congestion management.

The WEP design and other designs based on local flexibility markets can still be improved. First, the authority can issue regulations to restrict the flexibility of high-power devices, such as EVs, heat pumps and E-boilers, so that their total energy consumption can be kept within the DCDS capacity constraints (with a DSO or an aggregator) without affecting the comfort of residents. Second, the WEP design should incentivise prosumers to support optimal DCDS operation by rewarding them not only for providing flexibility services, but also for allowing the LMO/DSO to redispatch their appliances. Third, in case a local flexibility market is required, its limited liquidity can be further improved by a simplified, standardised bidding format [131] that can integrate flexibility sources with different power ratings, energy capacities and temporal constraints.

5.2. IMPLEMENTATION BARRIERS

Despite DC's unique advantages, there exist practical implementation barriers (including social, technical and economic) that stand in the way of widespread adoption of DCDSs and the markets designed for them.

The biggest challenge to DCDS adoption is the chicken-and-egg dilemma between DC equipment manufacturers and DC grid owners/operators [36]. As DC distribution technologies are still under research and development today, only a few, less standardised DCDS demonstration sites exist worldwide [132], typically using customised or modified DC devices. Large electric appliance manufacturers are not interested (for economic reasons) in developing DC or DC-ready devices for a DCDS that does not yet exist, even though such developments may require only minor changes in the circuit design (e.g., an extra DC socket that connects to an air conditioner's DC-link). Communities with small households and commercial buildings may not prefer DC distribution because (1) a mature AC distribution system is already in place and (2) even if they are interested, they will hardly find any DC-ready appliances in the market.

The good news is that many DC initiatives and government funding have noticed this issue and are supporting both DCDS demonstration sites and the manufacture of DC-ready devices as an attempt to break this chicken-and-egg dilemma [133]. One heavily debated strategy, given the dominant position of AC distribution, is to keep the existing networks in AC while developing a separate DC-powered distribution system. This system, for instance based on street lighting systems, can also connect EV charging facilities, large PV panels and battery systems [10], [134], [135], all of which can be more easily integrated into a DCDS than into an AC distribution network.

Another major challenge is a lack of DC standards and regulations, especially in protection and interfaces. As DC distribution technology is still being researched and developed, companies and institutes have been proposing different solutions to real-time converter control and short-circuit protection (using semiconductor DC circuit breakers) [10]. This would result in less compatible DC components and consequently affect the public acceptance of this new technology. To tackle this challenge, associations such as IEEE have been proposing industrial standards for DC microgrids [136], distribution grids and appliances [137], [138] to facilitate the industrialisation of DC power systems.

On the other hand, the local energy markets designed for DCDSs also face challenges from the wholesale energy market due to the complete inter-linkage between the two. The wholesale market should facilitate high-frequency energy trading with DCDS energy markets, for instance by introducing high-fidelity energy products on a 5-minute or even 1-minute basis. Public acceptance of local energy markets also plays a role: in Europe, the concept of locational marginal pricing, or nodal pricing, is not widely accepted by the public (there is a trend towards zonal energy markets as in Poland), let alone in the emerging local energy markets in which different neighbourhood may face different power prices due to congestion.

Another challenge for the DCDS market design is the requirement to update energy market regulations and wholesale energy markets. Though new energy policies such as Clean Energy Package [139] emphasise a need for local energy markets, there is no discussion yet on how local energy market should be organised, and whether local ancillary service markets (e.g., for local congestion management and voltage regulation) can be open to public participation, including household prosumers with EVs and home batteries, without incurring high transaction costs. Meanwhile, policymakers may reflect on whether the taxes and levies system designed for conventional AC systems should be directly applied to DC, and address the social concerns — such as energy poverty — that may accompany the introduction of local energy markets into the neighbourhood.

5.3. INVESTMENT INCENTIVES

An important function of an electricity market is to provide price signals for efficient long-term investment. As electrification continues, an increased volume of local generation and consumption will create higher power prosumption. Hence, future power systems require much system flexibility from network capacity increase or from flexible generators, loads and storage systems. The possibility of market-based DCDS operation may create new business models for DCDS researchers, manufacturers and small prosumers, and help to promote the uptake of DCDS technologies by removing implementation barriers related to market regulations.

SUBSTATION EXPANSION WITH MODULAR CONVERTERS

Chapter 4 has revealed that the main bottleneck of a bipolar DCDS is the DC substation converter. Thanks to the modular nature of converters, substation capacity expansion is relatively easy in a DCDS. A DSO can order extra converter modules from manufacturers as needed and then install these modules on a plug-and-play basis to increase the substation capacity quickly.

Another expansion opportunity is to place additional DC substations at different locations of a DCDS. DC substation converters developed under the plug-and-play concept can be operated in parallel with or without communication (via droop control, etc.). Such additional substation installations would be challenging for AC distribution grids because of phase angle and circular current issues. If parts of a DCDS frequently suffer from congestion or voltage problems, the DSO can install additional DC substations to support the system, provided that the necessary medium-voltage cables are available or can be introduced without high investment.

It is noteworthy that such DC substation capacity expansions will impact local energy prices as they relieve potential congestion. Depending on the market design, a DSO may have an incentive to keep a certain level of congestion to receive congestion revenues, as is the case with the LEM design. To avoid such incentives, the market design should not let the DSO only benefit from congestion revenues. Instead, his revenues should be based on separate network tariffs.

CABLE EXPANSION AND MESHED NETWORK OPERATION

Simulations in Chapter 4 indicated that cable power capacity is not the main cause of network congestion in urban DCDSs compared to DC substations, partly owing to an increased power capacity when a distribution network is converted from AC to DC. However, as electrification progresses, some cables still may become heavily loaded and compromise the reliability of DCDS operations. Voltage swells/sags can also happen in case of a large supply/demand at the nodes furthest away from the substation.

In such cases, an extension of the cable capacity can be considered, e.g. by adding a new parallel cable or new branches connecting the furthest nodes to form a ring or even a meshed DC distribution. In traditional AC networks this was a difficult task because of voltage angles and power flow, but in DC networks such problems do not exist. With new power flow control converters, one can fully control the power flow between different branches in a ring or meshed DCDS grid [10].

However, cable expansion can be more costly in money and time than DC substation expansion, as it requires municipal approval and construction. If a network problem can be resolved temporarily with local flexibility services, such cable extensions can be postponed until the regular maintenance/replacement period. Cable expansion may also lower the weighted average local energy price of the congested area, but the impact would be less as such congestion would occur less frequently.

FLEXIBLE GENERATORS AND LOADS

The introduction of the LEM and real-time local energy prices would also encourage investment in flexible generation and consumption. Although PV panels could become the most popular type of distributed energy source in urban DCDS, their generation flexibility is rather limited, especially on less sunny days and during the night. Other technologies, such as micro-turbines and fuel cells powered by biofuel or hydrogen, can guarantee power output regardless of weather conditions, providing a reliable local energy supply. In case of network congestion or an outage of the main grid, these flexible generators can benefit from scarcity prices in the LEM and explicit local flexibility markets (if available), creating new business models for local flexibility investments. Also, the large energy demand from EVs, heat pumps and water heaters provides an incentive to invest in flexibility, allowing consumers to avoid peak prices and benefit from lower energy prices (thus supporting the global power system operation). Follow-up research should demonstrate the business value of prosumer flexibility for congestion management, system support, or both [129].

STORAGE SYSTEMS

Another key technology in a DCDS energy market would be storage systems. Recent developments in home batteries, supercapacitors and vehicle-to-grid technologies made household energy storage systems not only economically feasible but also attractive in terms of supply security, self-sufficiency and reduced dependence on the distribution networks (and lower network fees). The introduction of local electricity markets will increase the the business value of storage systems. Such systems can provide arbitrage opportunities between local energy price gaps or provide local ancillary services such as congestion management and voltage support to the DSO and aggregators. On a national level, such storage systems can also provide frequency containment/restoration services or other flexibility services to transmission system operators, balance responsible parties and aggregators thanks to their fast response time.

Challenges with local storage systems still exist. First, under imperfect incentives, profit-seeking energy arbitrageurs may create congestion that could have been avoided. Although such incentives can be mitigated by mechanisms such as local energy prices, further regulation might be needed to limit such behaviour, especially when it threatens a DCDS's operational security. Second, the local energy market should suggest an optimal level of investment in storage systems. Because too much energy arbitrage can reduce the energy price gaps to a level that cannot cover investments in storage systems. Third, storage technologies such as batteries have a rather limited energy storage capacity. If a DCDS is mainly powered by PV panels, several consecutive cloudy days can completely drain such battery systems, leaving them unable to cope with congestion or support islanding. To avoid it, the LMO/DSO should monitor the state and availability of local storage systems. Fourth, the deployment of storage systems can reduce a prosumer's demand on a distribution network, which is contrary to the interests of a DSO who profits from network charges. Follow-up studies should address this conflict of interest between a DSO and its network users.

5.4. STRATEGIC BEHAVIOUR

An energy market at the local level may be susceptible to strategic market behaviour [140]. Although the main focus of our DCDS market design is the architecture, namely the choice and arrangement of sub-markets for each tradeable product, we briefly discuss the potential for gaming and strategic bidding in DCDS energy markets. Research on strategic behaviour is regarded as an important future work.

Local prosumers in a DCDS energy market may have an incentive for strategic behaviour. Because a DCDS has physical bottlenecks, resources such as network capacity, locally available energy and local ancillary services such as voltage support can become scarce. The nature of a local energy market, featured by (1) low liquidity (small number of generators and consumers), (2) a high degree of heterogeneity in prosumers' assets, (3) their ability of planning and scheduling, (4) imperfect information in real time and (5) a complex market design with network constraints, may trigger strategic behaviour [141].

Prosumers may have an incentive to make strategic bids to influence local energy prices or reduce flexibility supply for potentially higher profits, if congestion is foreseeable and this leads to higher revenues for them [141]. For instance, a group of such producers may cut the amount of their energy offer, if they are certain that the full-volume participation will trigger congestion (due to too much local generation) and a nearly zero market-clearing price.

Future study of market performance under strategic prosumer bidding can best be done through game-theoretic research. However, game-theoretic modelling involves many behavioural assumptions that could make the DCDS market model less realistic, as it represents a small, local market with very heterogeneous consumers. Hence, we opted for the alternative agent-based modelling, in which adaptive agents update strategies based on their status and preferences. Future work can extend our models by allowing agents to learn from their past experiences or even learn to communicate and collude with other market participants [142].

5.5. DISRUPTIVE DC TECHNOLOGIES

Although our three market designs are based on the current development of DC distribution technology, we foresee two technical breakthroughs that could potentially eliminate the need for certain sub-markets (for network capacity or voltage regulation) or pose new challenges to our proposed market designs.

The most promising breakthroughs in the DCDS technology may be brought by power flow control converters (PFCCs), particularly suitable for bipolar DCDSs with high power flows. PFCCs [10], [128] are typically partially-rated converters (e.g., rated at 10% of the corresponding cable power) based on triple active bridge topology. They can partly or fully route the power flow of meshed DCDSs while achieving an energy efficiency of over 99% and significant material savings. PFCCs could not only address cable overloads within the DCDS, but also efficiently compensate for voltage sags or swells to maximise the utilisation of the local DC grid. Once PFCCs can be widely adopted in (meshed) DCDSs, the system can fully utilise all possible paths of power flow, increasing the power distribution capacity of the entire system. With PFCCs, a DCDS will see much fewer congestion and voltage problems; therefore, we can be more confident of the simplicity of the LEM design, which does not take such problems into account.

Another breakthrough, though not limited to DC, may come from the further development and deployment of distributed optimal power flow. Traditional (wholesale and local) energy markets, while characterised by centralised and potentially more efficient resource allocation, place high demands on real-time information exchange, metering and billing, and rapid market clearing. Decentralised energy markets based on distributed optimal power flow [102] are suitable for remote areas where stable communication or high-performance computing infrastructure does not exist. Another promising application field is large urban areas with high requirements for market reliability and scalability. Recent research [21] suggests the potential of distributed market clearing in DCDSs with lower or no communication requirements (e.g., billing based on local voltage measurements).

5.6. BROADER APPLICATIONS

DC distribution technology has shown its high potential in urban power distribution but also in other applications. These applications, such as data centres, ships and aeroplanes, DC lighting and charging systems, and remote standalone power systems (under the concept of microgrids) are a greenfield for the development of new business models. Below we briefly discuss some promising application areas, where conflicts of interest among local prosumers can be solved by market designs.

MEDIUM-VOLTAGE DC GRIDS

The LEM design also applies to medium-voltage DC networks. The larger the scale, the more it resembles (AC) wholesale energy markets. Prosumers at higher voltage levels, including factories, small wind farms and aggregated small prosumers, typically have more experience with predicting, scheduling and energy trading. Therefore, consumption becomes more controllable and predictable, and market participants can take on more risk and responsibility, as is the case today in wholesale markets. Hence, medium-voltage DC markets may look similar to the existing wholesale markets except for their increased flexibility (focus on intraday than day-ahead), limited intelligence (trading agents than traders) and availability at critical locations (locational flexibility). Concepts such as day-ahead markets, balancing markets, forward contracts and even derivatives may be introduced at the medium-voltage level.

RURAL NETWORKS

Another promising application field for DCDSs is where there is no AC grid infrastructure, such as in remote areas and on islands. Various DC projects and initiatives have focused on the electrification of rural areas in Africa and India [143]. Typically, such new systems are supported by PV panels and batteries that run on DC, whereas the loads including LED lighting, computation & communication infrastructure, and appliances with variable speed drives work with DC as well. Hence, a DC-powered distribution system is economically more efficient as it requires fewer investments in diesel generators and synchronisation controllers and lower operation and maintenance costs.

ISLANDED NETWORKS

Islanded DCDS and their markets present new challenges and opportunities. The absence of the utility network means that a DCDS must balance power supply and demand by itself at all times, which can be especially challenging if the main energy source is intermittent renewables. The introduction of storage systems and controllable generators (such as hydrogen fuel cells) may further increase the reliability of the local power supply. One should define different levels of demand flexibility (or supply security) and prioritise essential loads for instance based on voltage-based demand response (thanks to DC's wide range of operational voltage).

MESHED URBAN GRIDS

Even under interconnected grid operation, DCDSs may outperform conventional AC distribution systems thanks to lower energy losses, fewer power components (no additional inversion and reactive compensation) and higher underwater performance (rivers, seasides). As suggested by [10], low-voltage DC distribution is well suited for efficient and reliable power delivery in *systems with bidirectional power flow that consist of multiple sources and multiple loads*, and can provide a power increase of up to 20% compared to radial operation.

6

CONCLUSION

This dissertation aims to develop a market design that is tailored to DC distribution systems. Although both DCDS technologies and the concept of local energy market are still under development, we proposed viable market design solutions based on the best practices in the emerging DC technology. Compared to AC systems, a DCDS has higher power capacity, energy efficiency, reliability and no need for synchronisation – positioning it well for a future in which large volumes of renewable power is generated and consumed locally. However, its unique features such as low system inertia, strict power limits and power–voltage coupling require a custom market design, featured by short response times, precise congestion management and a different approach to voltage regulation.

We developed a comprehensive design framework for local electricity markets to structure alternative options. To our knowledge, this dissertation represents a first attempt to marry the promising DC distribution technology with the emerging concept of local electricity markets, thereby removing the market-side implementation barriers to widespread application of DCDSs.

We designed an efficient and technically feasible market, namely the LEM design, for urban DCDS applications. To resolve DC converter congestion, the LEM design features fast market clearing and real-time control over flexible devices. Other market designs, namely the IM and WEP designs, were proven to have practical limitations. In the future, the LEM design should be further tested, improved and verified by demonstration sites and field tests with real prosumers various sources of flexibility.

6.1. ANSWERS TO THE RESEARCH QUESTIONS

We briefly summarise the answers to the research question and sub-questions below.

Which market designs that are both technically-feasible and prosumer-friendly facilitate efficient and reliable operation of a DC distribution system under uncertainty?

We identified and verified a *locational energy market* design that is technically feasible, prosumer-friendly and economically efficient, and guarantees DCDS reliability in real-life situations under uncertainty. We achieved this through a systematic market design framework, with which we identified three DCDS-tailored market designs with a high potential to meet the above goals, namely the *integrated market* (IM) design, *wholesale energy price* (WEP) design and *locational energy market* (LEM) design. We further evaluated the performance of these market designs in three steps, namely qualitative assessment, quantitative assessment without uncertainty (using optimisation modelling) and quantitative assessment under uncertainty (using agent-based modelling). These steps allowed us to verify the LEM design's economic efficiency and system reliability under uncertainty. They also pointed out the limitations of the IM design (large-scale information processing) and WEP design (inefficient price incentives).

Q1 Which design variables determine a DCDS market's performance in economic efficiency and system reliability? Which design offers high potential for such performance?

This sub-question was answered in Chapter 2, where we identified the key market design options for DCDSs in two categories: market architecture and sub-market rules. The main elements of a DCDS *market architecture* are energy delivery, the provision of substation capacity, and voltage regulation. The sub-markets for these commodities should be properly interlinked to meet DC operational requirements. Next, for each selected *sub-market*, we analysed the design options regarding the general organisation, bid format, allocation and payment, and settlement.

Following our design framework, we identified three promising DCDS market designs, each with a unique architecture. The first one is a IM design, which incorporates all system costs into energy prices. The second is a WEP design[1], which passes wholesale prices directly to prosumers while letting the distribution system operator resolve congestion. The third is a LEM design, which relieves congestion with nodal prices but leaves the voltage regulation to the system operator.

Q2 Which DCDS market design has high economic efficiency and system reliability in the presence of complete information?

Chapter 3 presented a quantitative assessment of the above DC-tailored market designs, assuming complete information availability. It demonstrated with an optimisation model that the LEM design has nearly optimal economic efficiency and system reliability in theory. Considering the complexity of the market design, Q2 represents an intermediate step in the research where we neglect the influence of uncertainty and evaluate the theoretical potential of the market designs under ideal conditions. Recognising that both total demand and demand flexibility may increase significantly in the future, we included a high proportion of electric vehicles to test the robustness of the market designs in the presence of a large volume of flexible demand. Simulations based on a realistic urban DCDS demonstrated that all the three market designs can mitigate network congestion and voltage deviation even in extreme situations with a large share of electric vehicles. In contrast, even under ideal conditions, the WEP design was shown to lead to severe congestion and significant grid or flexibility investments and has therefore been disqualified. We conclude that a simple LEM design, even if it neglects voltage deviations and cable power constraints, preserves system reliability and computational feasibility and remains almost as efficient as the optimal but hardly implementable IM design.

Q3 Is there a market design that preserves a DCDS's economic efficiency and system reliability, given the influence of prosumer behaviour under uncertainty?

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[1] Also referred to as locational Flex market design in Chapter 2.

Using agent-based modelling (ABM), Chapter 4 demonstrated that the LEM design verified by Q2 can facilitate an economically efficient and reliable operation of a DCDS in the presence of uncertainty and realistic prosumer behaviour. The ABM represents small prosumers' preferences and their autonomous behaviour in DCDS energy markets, in which multiple sources of uncertainty exist. It describes realistic EV charging preferences and energy bidding strategies (such as range-anxiety-based bidding). The LEM design performed efficiently and reliably under uncertainty in simulations based on the high-resolution 2018 Pecan Street database and with the EULV network. It was tested in various scenarios with stochastic local power prosumption, fluctuating wholesale energy prices and unforeseen EV availability. We conclude that the simple LEM design, considering only price-quantity bids and the DC substation constraint, is the best feasible option among the three designs put forward in Chapter 2. This conclusion holds only when network constraints are not too tight, as is typically the case in urban networks. In rural networks, distribution lines can be relatively long and voltage drops should be considered in the market design.

6.2. LIMITATIONS AND FUTURE WORK

As this dissertation focuses on the fundamentals of local energy market design, we made assumptions and simplifications on both the technical system and the market operation, thereby leaving room for further development. Below we suggest future research directions that can further validate the DC-tailored market designs and bring them closer to large-scale applications.

First, further enhancement of the optimisation model and the ABM should enable more realistic market simulations. Such simulations depend on detailed prosumer behaviour models and/or a state-of-the-art database of EV charging statistics. Case studies including heat pumps, batteries and other flexible appliances should verify the general applicability of the LEM design in urban, rural or even islanded DCDSs. The inclusion of a wholesale energy market model (possibly with real-time or balancing markets) can deepen our understanding of the interaction between wholesale and local markets.

Second, the LEM and other DCDS market designs require high-frequency, high-fidelity trading. Such trading can be enabled by automatic agents, which could bid in the local energy market in real time on behalf of prosumers. A simple, user-friendly but efficient agent module, such as an app on a smartphone, should enable such energy transactions in a DCDS. Alternatively, energy service providers such as aggregators, smart EV charging providers and energy communities can support prosumers with their market participation. New business models and contract templates should be developed tailored to DC and local energy markets. In both cases, such high-frequency energy trading in a DCDS also poses high requirements for the LMO/DSO, as they are responsible for short-term forecasting of the less aggregated, local prosumption. All of these topics should be addressed by follow-up research.

Third, our local energy market design excluded the influence of some price components of a prosumer's final energy bill, including transmission system costs, distribution system costs, taxes and levies. Although these components are typically set by national or regional energy policies and are out of our research scope, their existence may largely influence a prosumer's incentives and bidding strategies. Because these extra costs can add up to a considerable amount compared to the 'optimal' price incentive set by the LEM design. Further studies should estimate the impact of such price components on prosumers' incentives on bidding and investment decisions. Innovative, dynamic network tariffs such as capacity subscription [144] can help handle congestion, in which a DSO can limit prosumers to their subscribed (power) capacity bandwidth in case the converter is at threat of being overloaded.

Fourth, follow-up studies should explore the influence of prosumer value – including privacy, energy equality and energy self-sufficiency – on the local energy market design. As we mainly focused on the economic side of prosumer interaction, we made many assumptions about prosumers' preferences. However, more realistic numerical studies and the eventual field tests should evaluate the role of such values in the market design and its daily operation. A social market design aiming at higher fairness can be designed.

Finally, as DCDSs will co-exist with the legacy AC power systems, the cooperation between DCDS markets and AC energy markets should be enhanced at both local and wholesale level. Thanks to DC systems' fast response, DCDSs have a high potential in providing valuable ancillary services, such as second-level congestion management and frequency containment reserve, to AC power systems. Follow-up research should reveal this potential and develop new business models for DCDSs in AC ancillary services markets [42]. New, DC-friendly market regulations should be proposed accordingly to enable such cooperation and business models.

6.3. FINAL THOUGHTS

Our research on DCDS market design initiated from the DCSmart Project, which aims to enable a *straightforward integration of smart grid system technologies, the creation of market opportunities and stakeholders adoption through the development and implementation of DC distribution smart grids* [145]. This dissertation presents an investigation of the potential energy market options for this young DC distribution technology. In the absence of mature residential DCDS demonstration systems, many assumptions and initial estimates had to be made, and the first findings from pilot projects are still pending. Such assumptions may limit the representativeness of our research on DCDS market design, but but we hope that we have been able to shed some light on the economic operation of DCDS in the context of energy market regulation.

Since our goal is to tailor a local energy market to a DCDS, the main challenge is to distinguish the unique technical features of DC and, correspondingly, specify the design requirements from the beginning. Much effort has been made to understand the principles of the DCDS operation and control, including DC converter control, optimal power flow and different collaborative operation strategies between renewable sources, DC loads and batteries, all necessary for an efficient and reliable DCDS operation. The main conclusion of this research is that the adoption of DC helps us to avoid typical AC grid issues such as voltage issues and phase imbalances. However, the key design challenge for DCDS markets is to mitigate substation converter overloading, because the use of converters lowers a DCDS's ability to withstand even an instant of overload.

Noticing the complexity of the design problem, we proposed a comprehensive energy market design framework and conducted three rounds of market design using framework. The markets are designed and tested according to the agile development principle, using in each step a qualitative analysis (Chapter 2), a simple optimisation-based model (Chapter 3) and a more realistic agent-based DCDS market model (Chapter 4).

During the PhD journey, the candidate has gone through a rough but rewarding journey to the completion of his dissertation. In the first two years, he was not fully prepared to work as an independent researcher; he struggled and finally managed to determine his research focus and defend his proposal. Recognising the complexity of the DCDS market design required him to focus not only on detailed trading rules for energy, but also to take a step back and review all tradable commodities that can and should be traded, following a top-down approach. The interactions and discussions with peer researchers also greatly inspired his research. Not only did he receive valuable feedback from the Power Rangers peer meetings, but he also attended ICDCM and EEM conferences, where he met the right audience who understand the lesser-known DC market concept. It could have helped him even further had he managed to attend other top conferences such as IEEE PES General Meeting. If he had asked for more support when designing agent-based models and developing Python codes, he could have completed his PhD faster. An important lesson learned is that he will continue sharing ideas with his colleagues for better collaboration and higher productivity.

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LIST OF PUBLICATIONS

Related to this dissertation:

1. L. Piao, L. de Vries, M. de Weerdt and N. Yorke-Smith, *Electricity Markets for DC Distribution Systems: Market Design Under Uncertainty*, submitted to Energy.
2. L. Piao, L. de Vries, M. de Weerdt and N. Yorke-Smith, *Electricity markets for DC distribution systems: Locational pricing trumps wholesale pricing*, Energy 214, 2021.
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6. L. Piao, M. de Weerdt and L. de Vries, *Electricity market design requirements for DC distribution systems*, IEEE International Conference on DC Microgrids, 2017.

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1. S. Fan, Q. Ai, and L. Piao, *Bargaining-based Cooperative Energy Trading for Distribution Company and Demand Response*, Applied Energy, 226:469–482, 2018.
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12. L. Piao, Q. Ai, and X. He, *Microgrid Energy Scheduling Strategy Using Distributed Energy Resources and Electric Vehicles*, Electrical Appliances and Energy Efficiency Management Technology, 5:53–58, 2015.

CURRICULUM VITÆ

Longjian PIAO

1990	Born in Anshan, Liaoning, China.

EDUCATION

2008-2011	Bachelor of Science in electric engineering Shanghai Jiao Tong University, Shanghai, China
2011-2013	Master of Science in electric engineering Technische Universität Berlin, Berlin, Germany
2013-2015	Master of Science in electric engineering Shanghai Jiao Tong University, Shanghai, China
2016-2022	PhD candidate in electricity markets Technische Universiteit Delft, Delft, The Netherlands

WORK EXPERIENCE

2015	Modeling intern, real-time digital simulation for AC-DC microgrids Xi’an High Voltage Apparatus Research Institute, Xi’an, China
2016-2020	Doctoral researcher, smart distribution DC grids project Technische Universiteit Delft, Delft, The Netherlands
2020	Technical consultant, magneto waste-heat-to-power project Technische Universiteit Delft, Delft, The Netherlands
2021-	Portfolio manager for power transmission systems TenneT TSO GmbH, Bayreuth, Germany